



**School of the Built Environment**

***Rethinking Innovation in Computational Design***

***A Theoretical Framework for Innovative Strategies to Enhance the Efficiency  
of the 'Digital' in Architectural Design***

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## Abstract

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Between the potential for ‘digital’ in architectural design that is demonstrated in a minority of architectural practices, and its marginalisation in the remaining majority, there is a need to enhance the efficiency of ‘digital’ in architectural design. The vast array of digital technologies alongside the rapid evolution of these technologies show the dynamism of the situation that requires the simultaneous and continuous re-evaluation of design theory and the continuous development of innovative design strategies in practice. Therefore, the research aims to develop a theoretical framework that will underpin the development of innovative strategies in practice and will act as a roadmap for future research towards producing a mature and comprehensible theory for computational design.

In order to achieve this aim, a critical review of the literature is conducted where the potential of computational design methods is explored, the centrality of parametric design is examined and recent phenomena in computational design are classified and explained. Subsequently, a case study strategy is adopted to investigate the practical context of those phenomena. This explores the digital technologies utilised, the computational design methods applied and the factors that restrict efficient use of those technologies and methods within different practical contexts and real-life design processes and project scenarios. In order to ensure reliability and a multi-perspective investigation, the firms included as case studies are varied in terms of the location, discipline, and advancement of digital technologies. The data was collected through semi-structured interviews with architects who had a high level of experience and knowledge in computational design and hold leading positions at their firms. The data is analysed based on the computational design phenomena in order to establish new links between architectural design practice and its related theory.

Based on these established links, the research concludes with a theoretical framework that identifies the criteria for selecting the right digital tool for the right purpose, and the real contexts in which those digital tools can be adapted including the purpose of this adaption. The framework also identifies different approaches for the development of experience and knowledge in practice, the problems within integrated work caused by the contradiction in mindsets and the imbalance in experience and knowledge, the permanence and temporality of the emergent roles, the levels of collaboration in architectural practice, and the potential of data in architectural design. In addition, the framework identifies aspects of complexity in architectural design and the relationship among those aspects whilst identifying the

absorption forces of complexity in architectural design. Furthermore, the framework investigates the impact of the ‘digital’ on design creativity and identifies different types and purposes of practice-based research. The framework demonstrates the centrality of parametric design in developing innovative strategies by showing its potential in supporting collaborative and integrated work, driving data across different platforms and design stages, adapting tools, and supporting design creativity. In addition, a new understanding for sustainability is revealed by introducing the terms ‘sustainable processes’ and ‘recycling processes’ and investigating the role of parametric design in supporting this type of process, and its appropriateness in enabling the implementation of the ‘building seed’ concept. The research also introduces the ‘Wiki Seed Library’ as an innovative design strategy and uses the theoretical framework to evaluate its potential impact. Finally, the research provides a series of recommendations for architects in practice that offer different views, ideas and inspiration to enhancing the efficiency of the ‘digital’ in architectural design.

**Keywords:**

Architectural Design Process, Architectural Practice, BIM, Building Seeds, Computational/Digital Design, Innovative Strategies, Parametric Design

# CHAPTER ONE

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## 1 Introduction

### 1.1 Introduction

This chapter will provide a background to the research, and outline the main research problem. Based on this problem, the research rationale will be discussed by identifying the main requirements for architectural practice in relation to design theory. From this basis, the chapter will introduce the scope of the research, including its aim and objectives. The chapter will also identify the frameworks developed to guide this research and will explicate how those frameworks will be developed. Furthermore, an overview of the research methodology will be provided, and finally a brief description of the thesis structure.

### 1.2 Background

In parallel to the rapid evolution of digital technologies, architectural practice is similarly undergoing unprecedented, rapid transitional changes (De Rycke et al., 2018; Haidar, Underwood, & Coates, 2017; Kocaturk, 2017). New design tools, techniques and methodologies are being developed that are shifting the design processes from an individual to a collaborative process (Fok & Picon, 2016; Kocaturk, 2013; Kocatürk & Medjdoub, 2011), from disciplinary to interdisciplinary (Bhooshan, 2016; Hesselgren & Medjdoub, 2010; Sprecher & Ahrens, 2016), and from implicit to explicit (J. E. Harding & Shepherd, 2017; Jabi, Soe, Theobald, Aish, & Lannon, 2017; Oxman, 2006). The tools are becoming more adaptable (Burry, 2013), the processes are becoming more iterative and flexible (Imbert et al., 2012; Tamke & Thomsen, 2018; Wortmann & Tunçer, 2017), and the traditional form-based models are being abandoned in favour of data-rich and performative models (May, 2018; Mueller, 2011; Tamke, Nicholas, & Zwierzycki, 2018; Thomsen, Tamke, Gengnagel, Faircloth, & Scheurer, 2015).

The continuous evolution of CAD systems (Bhooshan, 2017; Holzer, 2015; Penttilä, 2006) and modelling techniques (Kocaturk & Kiviniemi, 2013; Kocaturk, 2017; Whitehead et al., 2011) has resulted in the emergence of novel design approaches, such as scripting (Burry, 2013; Katz, 2010), algorithmic design (Frazer, 1995; Oxman, 2017b), performative design (Becker, 1999, cited in Turrin et al., 2011; Oxman, 2006), BIM-based design (Eastman,

Eastman, Teicholz, & Sacks, 2011; Garber, 2014) and parametric design (Haidar, Underwood, & Coates, 2019; Jabí et al., 2017). These novel approaches are challenging the limits of architectural practice, by shifting the design process beyond the sphere of geometry (Hesselgren & Medjdoub, 2010), where different processes, such as materiality and fabrication, structural analysis, and environmental performance, are becoming integral parts of the design process (Bhooshan, 2016; Fok & Picon, 2016; Mueller, 2011; Thomsen et al., 2015).

Furthermore, parametric design is emerging as a unique and distinctive model of design thinking (Oxman, 2017b, p. 4). This is due to the capability of parametric design applications to automate the generation and evaluation of a large range of alternative design solutions (Barrios, 2005; Bernal, Haymaker, & Eastman, 2015; Chaszar & Joyce, 2016a; Hudson, 2010; Mueller, 2011; Turrin, von Buelow, & Stouffs, 2011), which enables designers to quickly explore a much wider design space (Aish & Woodbury, 2005; Anton & Tănase, 2016; Wortmann & Tunçer, 2017) that is beyond the reach of traditional methods (Harding & Shepherd, 2017).

This rapidly changing situation is inciting the production of a large body of literature in an attempt to create a theoretical foundation for these new tools, methods and cultures in architectural design (Bernal et al., 2015; Kolarevic, 2004; Oxman, 2006; Oxman & Gu, 2015b), resulting in a series of challenges to the maturity of design theory; the increasing multiplicity, variety and complexity of digital technologies, and the difficulty in ensuring an efficient use of those tools in architectural design.

### **1.3 Research Problem**

The main issue in current architectural practice is the rapidity in which digital technologies and design methods are evolving (De Rycke et al., 2018; Haidar et al., 2017). This speed is resulting in the emergence of a vast array of complex digital technologies that need new types of experiences, and a wide range of heterogeneous knowledge that lies beyond the scope of the traditional cognitive base of the architect (Oxman, 2017b). From a practical perspective, this situation is resulting in difficulties in ensuring the effective and efficient use of these new technologies. This can be traced in various studies (Eastman et al., 2011; Harding & Shepherd, 2017; Holzer, 2015; Jabí et al., 2017; Oxman, 2006; Schumacher, 2017; Thomsen et al., 2015; Wortmann & Tunçer, 2017), which report: the misunderstanding and

marginalisation of new computational design methods; the absence of sufficient practical examples to show the mature implementation of different new methods; the complexity and cognitive barriers caused by the adoption of the digital technologies in design; and the immaturity of the computational design theory that underpins these technologies and methods. For instance, parametric design is emerging as a unique and distinctive model of creativity and innovation (Oxman, 2017b, p. 4), which has demonstrated significant potential in many recent projects (Bhooshan, 2017; J. Harding, Joyce, Shepherd, & Williams, 2012; Imbert et al., 2012; Oxman, 2017b). This is due to its ability to automate different activities in the design process (Jabi et al., 2017; Turrin et al., 2011), and the seamlessness and flexibility in which a wide range of design possibilities can be generated and evaluated (Aish & Hanna, 2017; Hudson, 2010). Despite the significant potential of parametric design, it is still misunderstood and overlooked in the majority of the architectural practices. Instead, it is seen as a new style of ‘blobby architecture’ (Jabi et al., 2017), and as an expression of artistic or technophilic exuberance (Schumacher, 2016) rather than a method to facilitate, automate and accelerate the design process (Haidar et al., 2019).

From a theoretical perspective, this rapid evolution of digital technologies is resulting in the emergence of a large body of design theory, that lacks maturity and specificity in discussing the real impact of digital technologies on the architectural practice. For instance, the literature shows that digital technologies are increasing the complexity of design processes (Oxman, 2006; Thomsen et al., 2015). In contrast, the role of parametric design in automating processes (Holzer, 2015), and the role of BIM in automating the information flow across disciplines (Eynon, 2016) should be understood as methods to simplify the design process. Furthermore, the new roles that are emerging within design teams are widely discussed (Holzer, 2015) without analysing the time factor that might affect the permanence of these roles. In addition, a variety of theories are emerging that show the potential for parametric design in automating processes (Aish & Hanna, 2017; Jabi et al., 2017; Woodbury, Mohiuddin, Cichy, & Mueller, 2017). Meanwhile, analysing the real scope of parametric design and its relationship to BIM and other technologies are often overlooked to a certain level.

In general, architecture needs greater efficiency in the utilisation of the new technologies and methods. One way of increasing efficiency is to harness the new technologies to support sustainability in architectural design. In fact, this rapidly changing situation in the architectural domain coincides with an increase in natural disasters (Snell, 2018), the growing



limitations of global resources (Mueller, 2011), evidence of climate change (Kwok & Grondzik, 2018), and population growth (Carlile, 2014). Therefore, the focus is shifting towards enhancing sustainability (Wright, 2018), where concepts like energy efficiency and recyclability (Bashir, Ahmad, Sale, Abdullahi, & Aminu, 2016) are becoming essential in building design, and sustainable design is increasingly associated with design innovation (Kocaturk, 2017). This coincidence illuminates the potential for parametric design to facilitate and automate the evaluation of the environmental performance of buildings at the early design stages (Hudson, 2010; Turrin et al., 2011). Thus, parametric systems are becoming cornerstones within more complex performative digital environments (Oxman, 2006, p. 253).

The potential for parametric design to support energy-efficient and hence sustainable design solutions is well covered in the literature (Anton & Tănase, 2016; Eltaweel & Yuehong, 2017; Ercan & Elias-Ozkan, 2015; Imbert et al., 2012; Turrin et al., 2011). However, some valuable aspects are still overlooked. This includes the potential of parametric design in accelerating the design process, and hence, to save energy and support sustainability within the design process, and the distinction between the merits of parametric design as a design methodology and the merits of the tools and applications that are used in parametric design. This is added to the potential of the reusability of parametric design definitions across different projects.

In general, these advances in digital technologies seem to be more attractive to theoreticians than practitioners. This can be seen in the imbalance between the large body of theory (DeLanda, 2016; Kocatürk & Medjdoub, 2011; Oxman, 2017b) and the minimal use of these advanced digital technologies in practice, where the majority of architectural practitioners still rely on traditional methods to develop design projects (Eastman et al., 2011; Harding & Shepherd, 2017; Jabi et al., 2017; Schumacher, 2016).

## **1.4 Rationale and Scope**

The new advances in digital technologies are not only changing the way a design project is being approached; they are in fact, resulting in paradigm shifts in the design process (Oxman, 2006), where the structure of the design process and the sequence of its stages are changing. This results in digital continuity in the design process, from conception through to production (Kolarevic, 2004; Oxman, 2017). Oxman (2006) asked whether these novel design methodologies are valid for the majority of the architectural community, or only for the elite;

unfortunately, according to the current situation, the latter seems to be more realistic. Although the new advances in digital technologies, and the utilisation and development of new methods are resulting in positive results, this can only be seen in a limited number of architectural practices (Bhooshan, 2017; De Kestelier, 2013; Whitehead, de Kestelier, Gallou, & Kocatürk, 2011). Meanwhile, the majority of architectural practices around the world are still anchored in the traditional approaches to design projects (Holzer, 2015; Schumacher, 2016). To address this problem, architectural practice needs to develop innovative design strategies that can enable a wider range of architectural practitioners to make more effective and efficient use of these technologies. This could support the development of highly effective, smart, and automated design processes, and could enable such innovative methods of working to ‘travel downstream’, and potentially become the norm in architectural practice. This should arguably be the general overarching aim for architectural practice as a whole (Figure 1).

One of the main restrictions on the development of such strategies is the lack of maturity in design theory, as discussed in the previous section. This lack of maturity results from the rapid evolution of digital technologies and novel design approaches. For instance, within the current decade, hundreds of smart software applications, plug-ins and other technologies were developed with the potential for ground-breaking impacts on the way a design project could be approached. Thus, a vast array of plug-ins has recently developed to expand the scope of parametric design. These technologies enable the automated evaluation of a building’s environmental and structural performance in the early design stages (J. E. Harding & Shepherd, 2017; Oxman, 2017b). In addition, several applications are being developed to enable an automated and seamless flow of information across applications and disciplines, and to link different applications used in architectural practice to diverse social media and map websites (Flux.io, 2015; Grasshopper, n.d). The plethora of existing digital technologies, alongside their continuous and rapid evolution results in increasing difficulty in generating an appropriate and mature design theory that can effectively articulate, explain, and predict the real impact of such technologies on architectural design.

Therefore, the research is not focused on a static situation. Instead, it is focused on a rapidly changing and highly-dynamic situation that requires the continuous reevaluation of design theory within short periods of time through a series of research projects. To respond to this intensity and dynamism, the research will develop a theoretical framework that will act as a guide for future research projects involved in digital technologies and their impact on

architectural design. More precisely, the framework will contain a series of well-structured and taxonomical concepts, aspects, and categorisations with their relationships. Each of these concepts represents one aspect of the impact of digital technologies on practice. Therefore, the framework will be used to facilitate the structure of any future research, and hence, to enable a more broad and profound investigation into the real impact of technology in order to develop innovative design strategies.

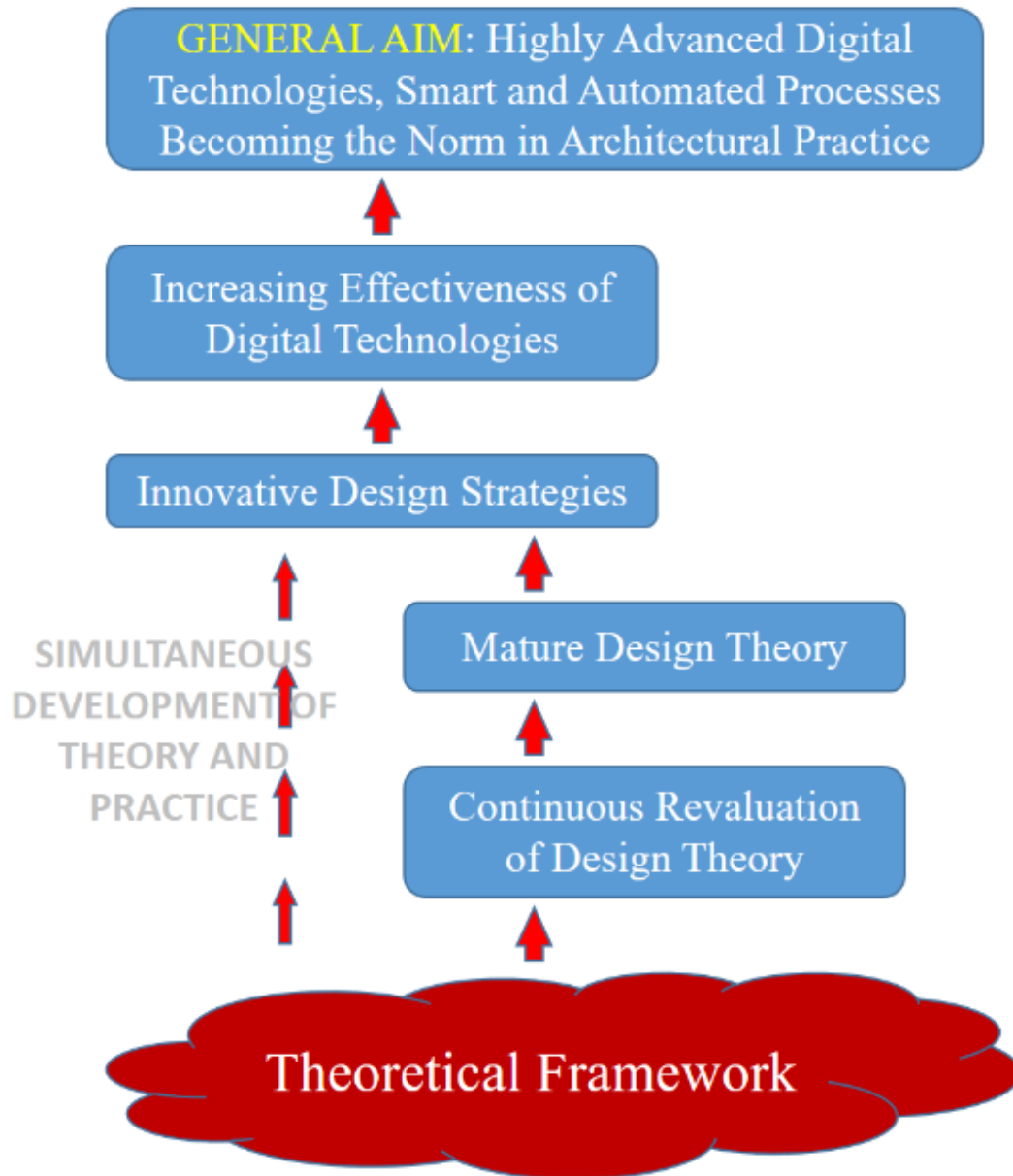


Figure 1: General Aim and Research Aim

The research will identify the real impact and potential of digital technologies on architectural practice, the factors that restrict the effective use of technology in practice, and the centrality of parametric design in developing innovative strategies. Furthermore, to demonstrate the effectiveness, reliability and applicability of the theoretical framework, the study will place the framework within a practical context by suggesting an innovative design strategy and by applying the theoretical framework to evaluate this strategy. In addition, the research will rely on the framework to provide a series of recommendations, ideas, and inspirations for architects in practice in order to support the more efficient employment of technologies amongst practitioners. The framework, will therefore contribute to the simultaneous development of design theory and architectural practice, which will help in developing innovative strategies to enhance the efficiency of the ‘digital’ in architectural design.

## **1.5 Research Focus**

Within this rapid evolution of a wide range of digital technologies and methods, parametric design is emerging as a unique and distinctive model of design thinking (Oxman, 2017b, p. 4). It is the only design methodology that takes full advantage of digital technologies (Schumacher, 2016). Parametric design has become a seminal medium in the evolution of new processes in digital design across a broad range of design fields (Oxman, 2017a, p. 1). This is due to the capability of parametric design applications to automate repetitive tasks within the design process (Holzer, 2015; Turrin et al., 2011), and to similarly automate the generation of several design possibilities of a basic design idea. This enables designers to explore a much wider design space that is beyond the reach of any other method (Aish & Hanna, 2017; Jabi et al., 2017). Furthermore, a vast array of parametric design applications and plug-ins have recently been developed, such as Karamba, Honeybee, Ladybug, Embryo and Kangaroo (J. E. Harding & Shepherd, 2017; Oxman, 2017b). These applications are enhancing the integration between architectural design and neighbouring fields, where different processes, such as materiality, fabrication, structural engineering, and environmental design, are becoming integral parts of the architectural design process (Bhooshan, 2017). As such, an emerging body of concepts is being developed to produce a theoretical basis of parametric design thinking. This body of concepts is becoming the nexus for the theoretical production of digital design (Oxman, 2017a, p. 1).

Despite the considerable potential of parametric design to automate the design process, and to push its scope beyond the sphere of geometry, it is still undervalued or misunderstood by the majority of architectural practices (Jabi et al., 2017; Schumacher, 2016). This contradiction between the significant impact of parametric design, and the underestimation of its potential for practice suggests the need to investigate the factors resulting in this misunderstanding and marginalisation. This would help to reformulate the potential for parametric design within a mature theoretical context, as an essential part of the theoretical framework.

Another aspect that motivates the focus on parametric design is its relevance to BIM (Building Information Modelling), which is a novel method of managing a building project throughout its lifecycle, that is based on automating the flow of information across different disciplines and project stages (Eynon, 2016; Sacks, Eastman, Lee, & Teicholz, 2018). This automation is enabled through the parametric principles, which are the main feature of all BIM applications (Holzer, 2015). With the same parametric principles, parametric design applications (such as Grasshopper and Dynamo) have the potential to act as BIM tools, and to go beyond the capacity of current BIM applications. They offer flexibility by tweaking BIM tools to enable the integration of new types of information into BIM models. This potential is often overlooked in BIM-related literature, and will therefore be an important aspect of the theoretical framework.

## **1.6 Research Questions**

Considering the significant potential of the ‘digital’ (digital technologies and computational design methods) in architectural design and the minimal use of these technologies and methods in the majority of architectural practices, the main question that arises is:

*How can architects in practice enhance the efficiency of the ‘digital’ in architectural design?*

Answering this question requires a mature and sophisticated understanding of both the real impact and the true potential of these new technologies and methods, and the challenges that architects encounter when adopting these tools in practice. Therefore, the following sub-questions are raised:

- How is the adoption of digital technologies in current architectural practice reshaping the architectural design process?
- What is the true potential of the ‘digital’ in architectural design process?

- What are the factors that restrict the efficient use of technology in architectural practice?

## 1.7 Research Aim and Objectives

### 1.7.1 Aim

*The aim of the research is to develop a theoretical framework for innovative strategies to enhance the efficiency of the ‘digital’ in architectural design.*

A theoretical framework is a set of related concepts and theories that underpin the author’s understanding, planning, development and structure of a study (Grant & Osanloo, 2014). This research aims to develop a theoretical framework that can act as a ‘roadmap’ for future research projects that, in turn, aims to produce a mature and comprehensible theory that can underpin the development of highly effective innovative strategies within architectural design.

The Oxford Dictionaries (n.d) define a strategy as ‘a plan of action designed to achieve a long-term or overall aim’. In this research, the ‘long term’ and ‘overall aim’ are to enhance the efficiency of digital technologies in design. This will be achieved by developing innovative strategies that will be facilitated by a theoretical framework. According to Cambridge Dictionary (n.d), a strategy is ‘a detailed plan for achieving success in situations such as war, politics, business, industry or sport’. In relation to this research, the ‘situation’ is the limited use of existing digital technologies and methods despite the wide variety available and their significant potential. ‘Achieving success’ means making efficient use of these technologies and methods within real practice. The ‘detailed plan’ is the innovative strategy that stems from the theoretical framework which offers the components, relations, and structure for more detailed plans and more mature strategies.

The verb ‘innovate’ is defined in the Oxford Dictionary as ‘make changes in something established, especially by introducing new methods, ideas, or products’ (Oxford Dictionary, n.d). The ‘established thing’ in this research are the digital technologies which appear to be well developed and mature. Therefore the study will suggest new ‘ideas’ that will uncover different aspects of these new technologies which are overlooked in the literature. From an architectural perspective, Kocaturk (2013, p. 24) argues that, “innovation is usually hidden in

the process of bridging the gap between the possibilities and the constraints offered by the very same technology”. From the perspective of this research, the ‘possibilities’ can refer to the potential for ‘digital’ as demonstrated by the minority of architectural practices, while the constraints refer to the factors that restrict the efficient use of the ‘digital’ within the majority. In this case, ‘bridging the gap’ means suggesting ideas and developing a framework to enhance the efficiency of the ‘digital’ in design. This will eliminate the ‘constraints’ with a view to gaining the benefit from the ‘potential’.

According to the Oxford Dictionary, ‘efficiency (of a system or machine) means achieving maximum productivity with minimum wasted effort or expense’. In this research, the efficiency of the ‘digital’ can be achieved by using the new technologies and methods to facilitate, automate, and accelerate the design process in order to minimise efforts and cost. In architectural literature, the term ‘efficiency’ is closely related to building sustainability, where the term ‘energy efficiency’ is widely used (Bashir et al., 2016; Levenson, 2018) to highlight the need to respond to climatic challenges and energy poverty (Snell, 2018; Wright, 2018). This shows an essential aspect of the enhancement of the ‘digital’ efficiency, namely through ensuring that new technologies and methods support sustainability.

The term ‘digital’ is an adjective that is associated with computer technology; however, in many publications involved in computational design theory, the term ‘digital’ is used as a noun to refer to the digital technologies and computational design methods that are used in architectural design. Digital technologies can be split into hardware and software technologies. Hardware technologies involve the rapid prototyping tools (3D printers, 3D scanners, laser cutters) in addition to servers, network systems, virtual reality systems, etc. Software technologies involve the different software applications used in design, such as CAD, BIM, visualisation and parametric design applications.

### **1.7.2 Objectives**

- 1- To determine how digital technologies and computational design methods are reshaping the architectural design process and resulting in radical changes to architectural practice;
- 2- To identify the factors that restrict the efficient use of the ‘digital’ in architectural practice;
- 3- To demonstrate the centrality of parametric design in developing innovative strategies in architectural design;

- 4- To develop a theoretical framework for innovative design strategies through the establishment of new links between design theory, architectural practice and digital technologies;
- 5- To demonstrate the applicability and reliability of the theoretical framework by suggesting an innovative design strategy and evaluating it based on the theoretical framework.

## **1.8 The Framework**

The framework explains and grounds the path of the study in order to make the research findings more meaningful, acceptable to the theoretical constructs in the research field, and generalisable (Adom et al., 2016). According to Grant and Osanloo (2014), a theoretical framework is the ‘blueprint’, guide, or ‘roadmap’ for the entire research inquiry. It consists of selected and related concepts and theories that underpin the author’s understanding of how research is understood, planned, and developed, and how it is structured through an organised flow that moves from one chapter to another. This definition suggests that the framework consists of components that guide a researcher’s mind in structuring the study so that each part is related to one of the components. From a different perspective, Camp (2001) focuses on the relationships among the components by defining a theoretical framework as a set of theoretical assumptions that explain the relationships among a set of phenomena. In this case, each phenomenon represents a component of the theoretical framework where the research can be structured on the relationship among those phenomena/components.

The importance of theoretical frameworks is addressed in different studies that explain theoretical frameworks and their role in research. This essentiality can be traced to Mertens (1998) who states that every decision made within the research process has to be guided by the theoretical framework. Similarly, Adom et al. (2016, p. 16) advises that a theoretical framework should guide and resonate with every aspect of the research process, from the definition of the problem, the literature survey, methodology, presentation and discussion of the findings as well as the conclusions drawn.

Adom et al. (2016) state that the theoretical framework is derived from existing theory in the literature that has already been tested and validated by others and is considered a generally acceptable theory in scholarly literature. In this regard, they explain two ways in which a theoretical framework can be formulated. Firstly, as the concepts, theories, and definitions that represent the components of a theoretical framework together with their relations can be



extracted from the theory through the literature review. Secondly, as a structured or potentially less structured theoretical framework can be adopted from another study to guide the current research.

Between these two ways to formulate a theoretical framework, a question may arise concerning the stage at which the theoretical framework is developed to guide the study. In this regard, Camp (2001) argues that the related theories in the framework are identified from the literature to form the conceptual point of departure for the study. Adom et al. (2016) refers to this view as a traditional way of developing a theoretical framework where the framework is developed a priori, or before the data collection. He asserts that, when a research design begins with a structured or less structured theoretical framework that is borrowed from another study, the framework often emerges in the data analysis phase. Moreover, Ennis (1999), cited in Chukwuedo and Uko-Aviomoh (2015) highlights the emergent nature of the theoretical framework, stating that it grows out of the research focus, guides the design of individual studies, and structures the research presentation and publications.

This research will combine all three views regarding the different stages at which a theoretical framework can be developed and the emergent nature of the framework. Therefore, this research will rely on the development and the emergence of two frameworks; the first will be referred to as the ‘initial framework’ and the second will be referred to as the ‘theoretical framework’. Both frameworks are derived from the theory, albeit at different stages. In fact, the literature review in this study is conducted in three stages that correspond with conventional design, computational design, and the transitional changes in architectural design. The following two sub-sections will explain the purpose of each of the two frameworks, the stages at which they will be developed, and how the theoretical framework will be derived from the initial framework.

### **1.8.1 Initial Framework**

According to Adom et al. (2016, p. 18),

... the problem statement in a research establishes an interaction by two or more factors that produce a dilemma or quandary that can cause for further examination. The problem statement defines the root problem as well as the other variables and constructs inherent to the problem. It identifies an area that needs further research or helps to resolve/address an existing problem in the field.

In this research, the ‘problem’ was identified by discussing the rapid evolution of digital technologies and their potential impact on architectural practice as well as on design theory. This discussion revealed that the problem emerges from the ‘interaction’ of three ‘factors’: digital technologies and methods, architectural practice, and design theory. This results in a multi-faceted ‘dilemma’. The first aspect of the dilemma lies in the challenges to the adoption of new technologies and methods in the majority of architectural practices despite their success amongst a minority of practices. The second aspect of the dilemma lies in the difficulty in formulating a mature design theory. This is due to the unprecedented speed in which a vast array of digital technologies are evolving. The third aspect lies in the need to bridge the gap between theory and practice and hence to allow the simultaneous evolution of design theory and architectural practice.

Thus, the initial framework emerged from the correlation of three aspects; the first aspect is the ‘Digital’ (digital technologies and computational design methods), the second is architectural practice, and the third is design theory. Each of these aspects are represented as a node as shown in Figure 2. In this case, the connecting line between ‘Theory’ and ‘Practice’ represents the context in which design is conducted in practice, regardless of the adoption of digital technologies. This relates to conventional design where sketching and drawing are the main method of communicating design ideas. This will be addressed in the first stage of the literature review (Chapter 2). The connecting line between ‘Digital’ and ‘Theory’ represents the potential of ‘digital’ for architectural design regardless of the practice. This will be addressed in the second stage of the literature review, which will investigate the potential impact of different digital technologies and computational design methods on the design process. This will be achieved by juxtaposing the features of the design process explored in the previous chapter with those of computational design. The connecting line between ‘Digital’ and ‘Practice’ represents computational design, and emerges from the practical context in which the ‘digital’ is utilised regardless of design theory. This will also be addressed in the second stage of the literature review.

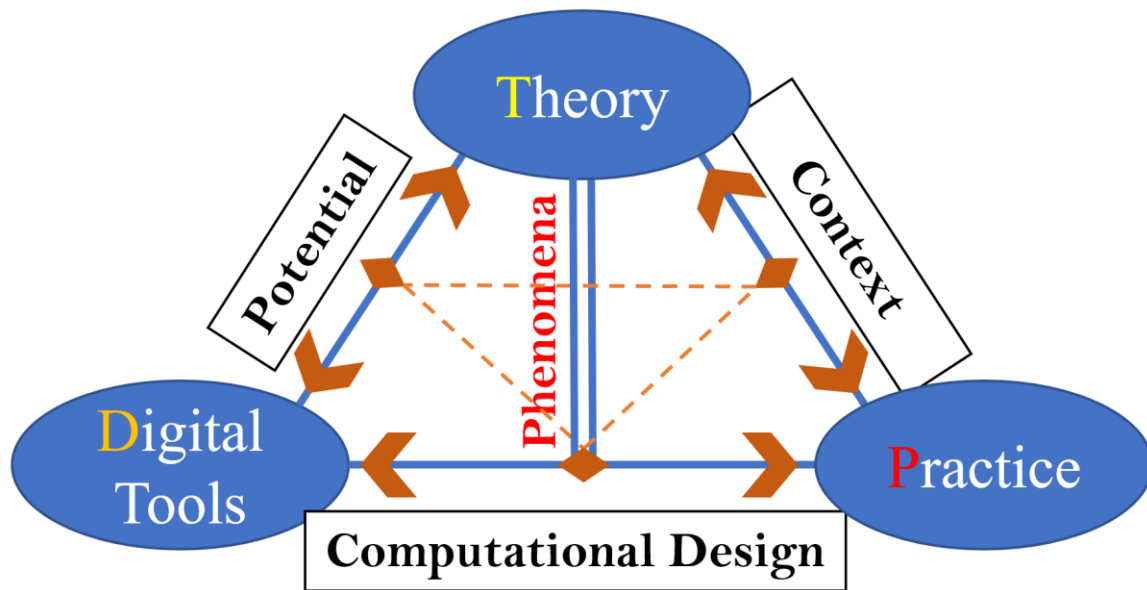


Figure 2: Initial Framework

### 1.8.2 Theoretical Framework

The formulation of the theoretical framework starts with the third stage of the literature review. In the first two stages of the literature review, the impact of the ‘digital’ on architectural design was investigated through the juxtaposition of the process, methods, activities, and practice of conventional design with those of computational design. This impact will help to identify the transitional changes and shifts in architectural design caused by the adoption of digital technologies and computational design methods in architectural practice. Each of these shifts represent a phenomenon that represents one component of the theoretical framework. Therefore, this part of literature review relies on the outcomes of the previous two stages alongside additional literature that describes and classifies these phenomena in order to establish the relationships among them. The result of this literature review stage will be an interim version of the theoretical framework. Subsequently, the theoretical framework will guide the remaining parts of the research, where the nature of these phenomena will constitute the philosophical stance, the research strategy, and the way data will be collected and analysed in the research. Therefore, the theoretical framework will help in achieving in-depth and broad investigation of the research problems and a highly-structured and mature articulation of the research outcomes. The final version of the theoretical framework will act as the ‘map’ or the ‘blue print’ (Adom et al., 2016) that can be adopted to guide in future studies in order the develop mature and highly structured

innovative design strategies towards enhancing the efficiency of the ‘digital’ in architectural design.

## **1.9 Overview of the Research Methodology**

The nature of the phenomena investigated, and the knowledge required to understand these phenomena will inform the ontological and epistemological assumptions that will influence the adoption of subjectivism. In fact, most of the impacts of technology on practice are subjective and rely on people’s opinions that may differ from one architectural practice to another as well as from one design project to another. In addition, most phenomena can only be understood through their social context within the architectural practice. However, some few aspects are objective and rely on facts that can be obtained through few examples, such as the use of parametric design tools as BIM tools.

The novelty of the digital technologies utilised and developed in architectural practice and the lack of specificity in relevant design theory have led to the adoption of the case study as a research strategy to investigate the phenomena within a recent practical context. Variations in the case studies (in terms of the location, discipline, and advancement of digital technologies) will help to enhance the reliability of the research by investigating the practical context from different perspectives. The interim version of the theoretical framework will help to: facilitate the definition of the themes of each case; structure the questions of each case, and categorise the themes when analysing the case studies. Therefore, the framework will be simplified in order to identify the main themes identified.

Furthermore, the nature of the phenomena investigated requires the exploration of narrative materials and explanations in order to develop a theoretical framework. This will involve a purely qualitative, detailed, and nuanced account of data; therefore, the research will deal with qualitative data that will be collected through semi-structured interviews. This simplified framework will represent the frame of reference for the case studies when writing the interview questions.

The data analysis will be based on a thematic data analysis technique. The analysis will be conducted in two stages; the first stage will be the thematic narrative analysis that focuses on the context of each individual case. The analysis in this stage will rely on the interviews’ verbatim transcript, where the data will be coded and categorised in order to formulate an individual analysis for each case. The codes will be derived from the same frame of reference

as that previously used to identify the case study themes. The second stage will be a cross-case thematic analysis that focuses on the phenomena investigated in the literature review as well as in the case studies. The analysis at this stage will rely on the individual case analysis developed in the first stage, where the data will be coded and categorised in order to formulate the final research discussions. The codes will be derived from the interim version of the theoretical framework that was developed in the literature review chapter in order to establish new links between theory and practice.

### **1.10 Thesis Structure**

The thesis will be structured in the following chapters:

Chapter 1 provides the background of the research, and identifies the main research problem. Consequently, the research sets the general overarching aim for architectural practice and, based on this general aim, sets the scope of this research. The chapter also outlines the objectives and the two theoretical frameworks that will guide this study. This encompasses how these frameworks will be generated, and the stage at which each will emerge. Furthermore, an overview of the research methodology is provided, and the conduct of the research is explained

Chapter 2 provides a literature review that explores conventional design theory and practice. With regard to theory, the research will investigate the historical shift from craft-based design to ‘design by drawing’. It will analyse different definitions for design and profoundly explore the design process (its stages, its nature, its main features), in addition to the exploration of the activities conducted and the methods applied by designers. With regard to practice, the chapter will explore the social dimension of architectural practice. This includes, the different roles in architectural practice and their relationship to architects and design projects. Therefore, the practical context of architectural design will be explored in this chapter.

Chapter 3 follows on from the literature review in Chapter 2 by discussing the historical evolution of computational design, while juxtaposing the features of architectural design explored in the previous chapter to those of computational design methods. This will aim to identify the paradigm shifts in the design process that result from the adoption of these new methods. It will investigate the benefits, impact, potential, and limitation of each design method starting from CAD to scripting, algorithmic design, performative design and through to BIM and parametric design. Furthermore, the chapter will also demonstrate the centrality

of parametric design by exploring the robust links between parametric design and all the other design methods discussed in this chapter.

Chapter 4 will start to develop the theoretical framework based on the initial framework. This will involve the development of a taxonomy for the recent phenomena in architectural design that result from the utilisation and development of highly advanced digital technologies and computational design methods in practice. The chapter analyses the literature that addresses the transitional changes and shifts in architectural design. Moreover, it uses the outcome of the previous two chapters to specifically identify the impact of the ‘digital’ on architectural design. The outcome of this research represents the interim version of the theoretical framework that will be used in the following chapters to inform methods and to enhance the depth and breadth in the understanding of technologies and methods in a practical context.

Chapter 5 is the research methodology chapter. In this chapter, the philosophical stance, the research approach, strategy, data collection and data analysis techniques will be identified. These will be based on the nature of the research objectives, and the nature of the phenomena investigated.

Chapter 6 is the case study chapter, where the case studies are analysed individually. The themes are derived from the phenomena explored in Chapter 4 which allow for the investigation of the same phenomena throughout all cases in relation to the outcome of the literature review.

Chapter 7 will provide the final theoretical framework while at the same time showing the process of its development. Within this chapter, the final discussions of the research will be provided based on the cross-case analysis. The chapter’s structure is consistent with the phenomena explored in Chapter 4; these are explored and further exemplified in a practical contexts within Chapter 6. Therefore, each of those phenomena will be shown as a section in this chapter where the sub-sections derive from the cross-case analysis.

Chapter 8 introduces the ‘Wiki Seed Library’ (WSL) as a proposed innovative design strategy. The chapter will identify the seed library and then suggest different methods to enhance its validity and motivate experts to contribute to the development of the library. Subsequently, the chapter adopts the theoretical framework in order to evaluate the potential impact of this new strategy on architectural design.

Chapter 9 is the conclusion chapter, where a summary of the whole research process is provided. The chapter outlines the final outcomes of the research aligning with the key themes, and considering both the aim and objectives set in Chapter 1. The chapter will offer recommendations for firms and architects in practice in order to help practitioners to enhance the efficiency of the ‘digital’ in practice. The chapter also explains how the research contributes to the production of new knowledge. In addition, it identifies the limitations of this study and suggests future research areas and approaches that can further apply and develop the theoretical framework provided in this research.

### **1.11 Chapter Summary**

The chapter identified the dilemma encapsulated in the potential of ‘digital’, as demonstrated in a minority of practices, and the poor reliance on ‘digital’ in the majority of practices. Moreover, it also considers the difficulty of developing a mature theory due to the rapid evolution and broad range of digital technologies and methods available to designers. Therefore the chapter emphasised the need to develop innovative strategies to enhance the efficiency of ‘digital’ in architectural design. It highlighted the need to deal with the dynamics of the situation by continuously reevaluating theory and moving towards the simultaneous development of design theory and architectural practice. Therefore, the scope of the research has been identified, including its aim to develop a theoretical framework that will underpin the evolution of innovative strategies in future research. From this basis, the main objectives that will achieve this aim have been identified, and the theoretical frameworks that will guide this study were explained as well as the way in which they will be developed. The chapter provided an overview of the research methodology and a summary of the research structure.

# CHAPTER TWO

## 2 Architectural Design (Theory and Practice)

### 2.1 Introduction

This research suggests that new computational design methods utilised in current architectural design practice are not being developed to replace existing conventional methodologies. They are novel methods that tend to enrich the profession by enabling a wider range of possibilities in design methodology, a higher level of freedom for designers, and more feasible design processes. Oxman (2006) insists on the importance of re-visiting and re-examining precedent design methodologies, as current phenomena in computational design methodologies can be understood with reference to their previous, paper-based counterparts.

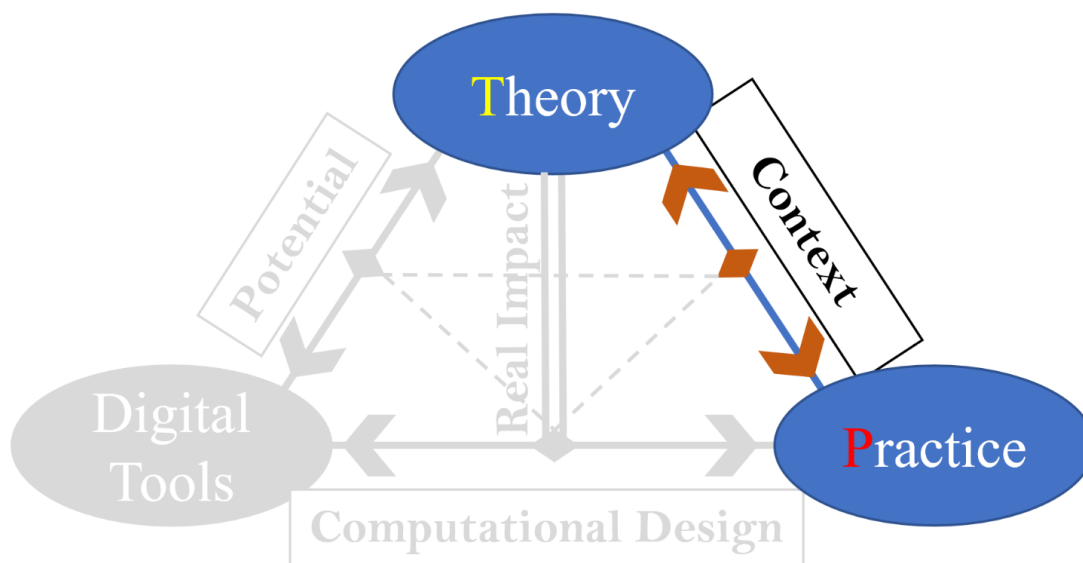


Figure 3: Chapter Focus in relation to the Initial Framework

Therefore, this chapter discusses a variety of definitions for ‘design’, and explores the structure of the design process - its stages, nature, and different features - in addition to the different activities and methods applied to solve design problems. Furthermore, the chapter explores the practical context in which the design process is approached, and the challenges, constraints and difficulties that designers encounter in practice when different voices start to become involved in design decisions within a collaborative, business-led work environment (figure 3). The outcome of this chapter will later be juxtaposed with the digitally-driven



computational design processes in order to form the basis of the investigation into the impact of computational design on the design process.

## **2.2 From Vernacular and Craft Design to ‘Drawing-based’ Design**

Cross (2011) and Lawson (2006) believe that everyone is capable of designing, and refer to general daily activities as design tasks that humans perform by instinct, such as arranging living rooms, cultivating and maintaining gardens, arranging desktops work spaces. It is only fairly recently in the industrialised world that the ability to design has been regarded as a professional activity that requires training, special education and a kind of exceptional talent (Cross, 2011; Lawson, 2006). Historically, objects were designed and crafted simultaneously in a ‘vernacular manner’ (Lawson, 2006) as part of a craftsman’s work (Jones, 1992), where objects were crafted to the required shape without the need to provide a ‘scale drawing’ in advance. Furthermore, any problem was solved directly on the final product. Later, it was possible to evolve the shape of a product through a ‘scale drawing’ that was provided by a ‘designer’ before the making starts. This shift resulted in a separation between thinking and making, which, according to Jones (1992), represents both the strength and weakness of an industrial society.

Jones (1992) outlines a wide range of merits that design by drawing has over craft-based design, or what Lawson (2006) terms ‘vernacular design’. Jones (1992, p. 3) states that scale drawing offers a medium for experiments and changes that enable the specification of accurate dimensions in advanced of manufacture, which enables advance planning. More specifically, scale drawing gives a much greater ‘perceptual span’ than that which was achievable to a craftsman, as it gives the freedom to alter the shape of the product as a whole, instead of being restricted to minor changes, as was the case with craft design (Jones, 1992, p. 28). In other words, providing drawings in advance of making enhances the modifiability of the design object, which can reduce the cost and time needed to explore different possibilities and options. This can help to provide the most optimal design product form in relation to the desired function of a product.

In addition, Jones (1992, p. 28) states that scale drawings represent ‘a rapidly manipulatable model of the relationship between the components of which the product is composed, especially when the desired object is larger than what a single craftsman can make on their own’. This indicates that designing by drawing enables the production of larger and probably

more complex design shapes than that which is achievable with vernacular and craft-based design. Indeed, Jones (1992, p. 28) ensures that,

... the speed with which drawings can be perceived and modified offers the capacity to store provisional decisions about the different parts of the design product, which enables designers to cope with high degree of complexity that is unmanageable and unimaginable in crafts-based design.

Therefore, in comparison to vernacular design, design by drawing allows the whole design and production process to be accelerated, and this offers designers access to otherwise unachievable levels of complexity.

In addition, the separation between design and drawing makes it possible for different people to become involved in the production process by splitting the production work into pieces, or standardised components that can be made simultaneously by repetitive hand labour or by machines over a shorter time (Jones, 1992). Therefore, design by drawing is an essential step towards shifting design and production from an individual activity into a collaborative activity, where participants with different experiences can assume a portion of the work to produce one single product.

In summary, design by drawing enables the exploration of a wider scope of design alternatives in comparison to what is explorable in vernacular design. This same benefit enables a designer to accelerate the design and production process, which helps in the representation and production of larger and more complex forms. This is enhanced by the ability offered by drawings to split up the production process into pieces and components to enable several participants to become involved in the process, and hence, to support collaborative work. This significant impact of design by drawing has resulted in the emergence of drawings as the main method for design. Thus, 'the typical design is believed to be an individual's creative effort, conjuring up images of late nights at the drawing board' (Cuff, 1992, p. 13). Based on this image, this type of design will be referred to as 'conventional design' or 'paper-based design' in the following chapters.

While in vernacular design process, design is closely associated with making (Lawson, 2006), design by drawing can be seen as a method that breaks this association. This is a significant change that requires critical investigation about the problematic issues that can result from this change. This will, in turn, form the basis for an investigation into the role of digital technologies and computational design methods in addressing those issues.

## 2.3 Defining Design

Many authors have tried to define ‘design’ and to illustrate its process and stages. In this section, a variety of definitions by authors from different design disciplines are considered. In this regard, Cuff (1991, p. 11) raises a debate about ‘design as decision making’ as opposed to ‘design as making sense of solutions’. This distinction enables a better understanding of the various definitions of design, where some are product-oriented and others are process-oriented. Besides, the following definitions differ in terms of the level of abstraction, where some definitions are very short and abstract and refer only to the general aim of design, while others are more detailed and refer to the activities within the design process, its main features, and its relation to the future.

According to the Oxford Dictionaries (n.d), ‘design’ is “a plan or drawing produced to show the look and function or workings of a building, garment, or other object before it is made”. This definition seems extremely product-oriented and does not refer to the process that may result in this ‘plan’ or ‘drawing’. Moreover, it emphasises the value of design in producing a future image of a currently non-existent object. Another definition that emphasises this value is provided by Page (1966, cited in Jones, 1992, p. 4), who defines design as ‘the imaginative jump from present situation to future possibilities’. A similar definition that highlights the same value however, with more focus on the ‘process’ is provided by Archer (1965) (a product designer) who defines design as, “the formulation of a prescription or model for a finished work in advance of its embodiment”. This value in design highlights an important area of investigation; thus, the role of computational design methods should support future expectations about the design product, and in enhance the resolution of future images to a greater extent than that achievable with traditional methods.

Other definitions highlight different features of design. For instance, Reswick (1965, cited in Jones, 1992, p. 4) defines design as ‘a creative activity that involves bringing into being, something new and useful that has not existed previously’. In this case, creativity is highlighted as the main feature of design. Similarly, Asimow (1962, cited in Jones, 1992, p. 4) defines design as, ‘decision making in the face of uncertainty, with high penalties for errors’. Asimow highlights the uncertainty of design, where critical decisions should be taken despite their subjective nature and the significant impact on results. In this regard, Chaszar and Joyce (2016b) definition of design highlight this uncertainty; they state that design is a ‘messy’ activity, where designers rely on “incomplete knowledge and use imperfect

methods” in order to conduct “iterative attempts’ to solve ‘wicked’ and ‘ill-defined’ problems”. Such a description reveals the complexity, uncertainty and ambiguity of the design process, its methods and its related knowledge, raising questions about how different digital tools are utilised to deal with this complexity and ambiguity.

Some authors provide simple definitions. For instance, Matchett (1968) (an engineer) simply defines design as “the optimum solution to the sum of the true needs of a particular set of circumstances”, Meanwhile, Luckman (1967) (an architect) provides an even simpler and more abstract definition. stating that, ‘design is a man’s first step towards the mastering of his environment’. Krippendorff (1989), in turn, defines design as ‘making sense (of things)’. Similarly, Archer (1965) states that design is ‘a goal-directed problem-solving activity’. The previous four definitions capture the essence of design in terms of it being a ‘problem-solving activity’ dedicated for finding ‘the optimum solution’ for a design problem that should be based on specific ‘needs’ and ‘circumstances’ in order to ‘making sense of things’ towards ‘mastering the environment’; however, they are more philosophical rather than descriptive. In contrast, Lawson (2006, p. 14) (an architect) provides a more detailed and process-oriented description for design,

“design involves a sophisticated mental process capable of manipulating many kinds of information, blending them all into a coherent set of ideas and finally generating some realisation of those ideas that normally take the form of drawings”.

Lawson’s description seems applicable for any sort of design, regardless of the discipline. Ultimately, any design process involves blending information to generate ideas regardless of the tools used or the methods applied. However, Lawson’s description raises questions about the type of information used to inform ideas in design as well as computational design. For example, how is information ‘blended’; how is the blending achieved between automated and human/machine-centric designs; how are these ideas realised, represented and communicated; do they take the form of ‘drawings’, or other forms, such as models, and finally, how achievable, feasible, and popular are these new methods. Nevertheless, a more comprehensive understanding of ‘design’ is required before these questions can be addressed. Thus, the following sections discuss the ‘design process’, its stages and components, the design methods, and some problematic issues that are criticised in the literature.

## 2.4 The Design Process

It is important to understand and critically explicate the ‘design process’ and to differentiate it from the ‘design product’, as more has been said about design products (buildings) than how such products or buildings were designed (the design process) (Cuff, 1992; Lawson, 2006). In response to this imbalance in architectural research, Lawson (2006) clarifies a variety of uses for the term ‘design’, where he insists on recognising whether it is related to the end product or to the process, which can be based on the context. An example of this insistence can be traced in his description of ‘Sydney Opera House by Jørn Utzon’ Lawson (2006, p. 6):

*“... fascinating not just as a product but also as a process that has been well-documented and teaches us many lessons about designing...”*

Similarly, Ampatzidou (2014) eloquently articulates this critical recognition by arguing that architecture narrates stories about present and past, while architectural design narrates stories about the future. Moreover, Peter Eisenman in Ampatzidou (2014) suggests that a classical architect’s work should be read and understood based on the “traces of the design process” and not on “previous formal analysis”. In other words, Eisenman, like Lawson, urges a focus on the “stories hidden in the process of giving shape to the space around us” (Ampatzidou, 2014).

These arguments urge a focus on the design process as an essential step to investigate the impact of digital technologies on the different aspects of architectural design. While design refers to a valued quality in architecture, the design process concerns what designers do at the ‘drawing board’ (Cuff, 1991). It is about the steps taken to arrive at a conclusion (Plowright, 2014). Therefore, the following sections will investigate the steps and stages of the design process and the methods utilised to achieve those steps. In addition, the complexity and ambiguity in the design process highlighted in previous definitions of design will be explored further.

### 2.4.1 The Structure of the Design Process

To enhance the understanding of a design process, it is necessary to explore its structure, i.e. its stages, activities, components and sequence. This will later enable more specificity when investigating the impact of the ‘digital’ on the design process, where this impact can be investigated on specific stage or activity within the whole design process.

In RIBA's (1980) 'Handbook of Architectural Practice and Management' provided by the Royal Institute of British Architects (RIBA), the architectural design process is outlined in four stages: 1. Accumulating general information and specific information for the problem in hand. 2. Understanding the nature of the problem and providing possible solutions. 3. Developing one or more solutions that were isolated in stage (2). 4. Communicating the optimal solutions to other stakeholders. In architectural literature, those stages and their sequence receive a lot of criticism, which state that they contradict the complex nature of design. For instance, Lawson (2006) highlights the difficulty for the designer in specifying the information needed in stage 1 without conducting some investigation of the problem in stage 2. Moreover, there is an apparent inability of the detailed development of solution in stage three to go smoothly to one inevitable solution. Despite the honesty of RIBA in declaring the likely necessity for unpredictable jumps between the four phases, no specific explanation is offered to determine the frequency of these jumps and how they can be made (Lawson, 2006). In this light, Bernal et al. (2015) list a number of design 'actions' that designers perform iteratively during the conventional design process. These actions are:

- "Interpreting design situations;
- Co-evolving problems and solutions;
- Recalling patterns of organisation;
- Storing and reusing expert knowledge from specific design domains;
- Dividing tasks in distributed cognitive systems" (Bernal et al., 2015, p. 163)

Similar to the RIBA stages, this classification of design actions strictly divide the design process into linear stages, where the completion of each stage seems to be required before the next stage can begin. This same strict division can also be traced to the more recent RIBA 'Plan of Work', which is 'a bedrock document for architects' profession and the construction industry, providing a shared framework for the organisation and management of building projects' (Sinclair, 2013, p. 2). This framework consists of the following eight stages, which are:

- Stage 0 (Strategic Planning): Identify the client's Business Case and Strategic Brief and other core project requirements;
- Stage 1 (Preparation and Brief): Develop the project objectives, and the initial project brief. In addition to undertaking feasibility studies and review the site information;

- Stage 2 (Concept Design): Prepare the concept design, including the outline proposals for the structural design and other services- and cost-related information;
- Stage 3 (Developed Design): Prepare the developed design, including the coordinated and updated proposals for structural design and other more detailed services and cost-related information;
- Stage 4 (Technical Design): Prepare the technical design in accordance with the design responsibility matrix and project strategies;
- Stage 5 (Construction): Offsite manufacturing and onsite construction;
- Stage 6 (Handover and Close Out): Handover of the building and conclusion of the building contract;
- Stage 7 (In Use): Undertake the in use services in accordance with schedule of services (RIBA, 2013).

A comparison between the design stages and actions discussed in this section, and the complex and uncertain nature of the design process as highlighted in some of the definitions of design (section 2.3), reveals that these stages represent an excessive simplification of the reality of the design process. Therefore, the following sections will further clarify the complex nature of the design process, the origin of this complexity, its results, and how designers can cope with such complexity while designing. This will enable the later investigation on changes to the structure of the design process and the chronology of its stages when different computational design methods are applied.

#### **2.4.2 Design as a Problem Solving Process**

The previous two sections accentuate that ‘problem-solving’ as the main activity in the design process, and emphasise the complex nature of this activity that contradicts the design process stages outlined by RIBA (1980). This section will clarify the nature of the design problem and how it can be identified and solved in order for the different aspects of design complexity to be explored.

In general, design is understood as a problem-solving process in which the designer understands the requirements of the client and critically defines the problem(s). From this basis they develop solutions for this problem(s), and appropriate criteria are then set to inform the selection of the optimum solution for further development (J Christopher Jones, 1963; Lawson, 2006; Luckman, 1967). However, Lawson (2006) prefers to speak about ‘situations’ in which the problem and the solutions merge within the design process, where a

well-illustrated and acceptable solution is needed to fully understand the problem. He describes this simultaneous merging as a “negotiation between problem and solution”, in which the design process activities are involved (Lawson, 2006, 2011). By contrast, Jones (1963) insists on the need to separate the logical analysis (problem) from creative thought (solution) in order to leave the mind free to produce ideas and solutions, and to avoid confusing the process of analysis. This kind of argument that separates the problem identification and problem solving processes are highly criticised in the literature. They overlook the difficulty of fully describing design problems at the outset of the design process (Hudson, 2010), and the interactive nature of identifying and solving design problems, where loops, circularity and back-tracing are required within the problem solving process (Jones, 1992). For instance, Cross (2011) emphasises the tricky relationship between a problem and its solution, where the understanding of the problem (what is required) and solving the problem (how to satisfy the requirements) are ‘interwoven processes’. Therefore, the development of a solution-concept is usually matched with the development of problem-concept. Similarly, Richard MacCorma in Cross (2011) ensures that defining a problem can be achieved through attempting solutions. Within this context, Hudson (2010) cites different authors to demonstrate this interactive relationship. This includes the equivalency of the efforts required to find the problem and solve it (Schon, 1991, cited in Hudson, 2010); the circularity between a problem and solutions; and the inclusion of solution seeds within the problem statement (Wade, 1977, cited in Hudson, 2010). This is in addition to Heath’s (1984, cited in in Hudson, 2010) summary of the reciprocal nature between a design problem and its solution, who stated that ‘a problem well stated is a problem solved’.

The previous discussion shows that no mature understanding of the nature of design problems can be achieved until a solution is attempted or even conceived. In fact, most authors involved in learning and teaching and the level of understanding required within a learning process, seem to agree with such concept. This idea can be traced in many articles and books related to learning and teaching in academia, which argue that no learning can occur without reflection (Moon, 2004), and that a ‘student’ cannot fully understand their own ideas without writing them on a computer screen (M. Saunders, Lewis, & Thornhill, 2007). Similarly, it could be argued that a designer cannot have a comprehensive understanding of the design problem without providing some solutions. Therefore, the design process can be understood as a learning and teaching process in which a designer learns the requirements from the client, develops a design solution and then teaches the design proposal to other project



stakeholders. In this case, for the designer to learn the requirements and understand the problem, they need to reflect on their understanding by providing some solutions. This situation sheds light on the more specific aspects of the impact of digital technologies on the design process, and raises questions about how digital technologies can be used to improve the negotiation between the problem and the solution, and how this improvement can result in a more efficient and seamless design processes.

### **2.4.3 Complexity, Ambiguity and Uncertainty in the Design Process**

Having clarified the nature of design problems and the interactive relationship between the problem identification and problem solving processes, this helps to clarify one aspect of the complexity of the design process. The following discussion will explore the complex nature of design activity (Cross, 2011) in more depth in order to understand the ambiguity and uncertainty that designers confront within the design process.

In general, the design process is described in the literature as a ‘messy’ activity (Chaszar & Joyce, 2016). It requires designers to take critical decisions within a high level of uncertainty (Asimow, 1962, cited in Jones, 1992) in order to deal with complex and ill-defined problems (Heath, 1942, cited in Hudson, 2010) by undertaking complex cognitive activities (Cross, 2011) based on ‘imperfect methods’ (Chaszar & Joyce, 2016) and unlistable, unclassifiable and unmeasurable knowledge (Lawson, 2011). In an attempt to understand the roots of the complexity, uncertainty and ambiguity in the design process, the following discussion identifies four aspects in the process that result in this complexity.

The first aspect stems from the nature of design problems, which are ‘wicked’ (Chaszar & Joyce, 2016). There can be incomplete, contradictory and changing requirements over the process, together with no obvious procedure to test solutions. This may result in a situation where it is very hard to specify the point at which the design process should stop (Rittel & Webber, 1973, cited in Hudson, 2010). In addition, design problems are unique in every situation and this prevents the use of existing solutions to inform current problems. It results in a situation where previous solutions can only solve parts of the current issues, which may reveal or suggest other more complex problems (Rittel & Webber, 1973, cited in Hudson, 2010). This discussion emphasises the question raised in the previous section about the ability of computational design methods to enhance the negotiation between design problems and their solutions. In addition, it is important to find the appropriate computational method to enable greater efficiency by using precedents to inform current solutions.

The second aspect stems from the obscurity of the knowledge needed to solve design problems, which are ‘tacit knowledge’ that is difficult to document and transfer (Plowright, 2014). In this regard, Lawson (2011) affirms that the sort of knowledge and cognitive support needed for designers is wide, subjective and ambiguous, and hence, cannot be listed, classified or measured. This raises questions as to what happens to such knowledge and cognitive support when highly advanced digital technologies are utilised, and what new sort of knowledge is needed to adopt these new technologies.

The third aspect stems from the experiences needed to conduct a design process, which are subjective and unclassifiable (Lawson, 2011). For more specificity, Lawson and Dorst (2009) argue that the activities undertaken by individual designers within a design process substantially differ based on the designer’s experience. More precisely, expert designers do different things to novice designers, and require different kinds of cognitive support; in other words, experts think less. This last argument highlights the difference in the design activities based on their experience. While the focus in Lawson and Dorst’s (2009) argument is on a designer’s ‘level’ of experience, it is also worthwhile to relate the design activities to the designer’s ‘type’ of experience rather than just to the level of general design experience. This point becomes more critical in computational design processes, where the multiplicity and complexity of tools and processes require highly collaborative work environments, and hence, different types of unique experiences need to be coordinated to realise efficiency in collaborative work.

The fourth aspect stems from the fact that the design process is linked to future design products or future buildings, where designers need ‘to use current information to predict a future state that will not come about unless the predictions are correct’ (Jones, 1992, pp. 9-10). Therefore, the final design outcome needs to be sufficiently crystallised before the means needed to reach this outcome are explored. In such cases, designers are required to work backwards in time, and trace the intermediate difficulties every time unforeseen difficulties are revealed (Jones, 1992, p. 3). This shows the ambiguity of design problems more clearly and how they grow in clarity as the design progresses. Furthermore, it shows the difficulty in dealing with these problems, especially at the outset of the design process, which might result in back-tracing and repeating some activities when the problem starts to crystallise. Therefore, as mentioned earlier, it is important to search for a new computational design methodology that enhances the future predictions of the design product by reducing the level of ambiguity at the early stages of the design process.

The previous discussion reveals the importance of investigating the impact of computational design methods and the different digital technologies on the complexity of the design process. It also raised the need to examine how these technologies help designers to tackle this complexity at various design stages. In addition to highlighting complexity as one of the main aspects of the design process, other related aspects have emerged from this section. These include: the uniqueness of the design problem and the resulting difficulty in adopting precedent solutions; the subjectivity and implicit nature of the knowledge and experiences of designer; and the difficulty of taking early decisions due to the ambiguity of the design problem at the outset of the design process. While each of these aspects represent one specific focus when investigating the impact of computational design methods, the last aspect shows the ambiguity at the early stages, which is one of the main challenges for designers. Therefore, the following section will discuss the criticality of these early stages in the design process.

#### **2.4.4 Criticality of Conceptual design**

This section focuses on conceptual design, and sets the foundation for the further investigation that will involve in the impact of digital tools on the conceptual stage of the architectural design process. In fact, one of the major roles of the new computational design methods is to shift the provision of performative criteria into the conceptual design stage (Eastman et al., 2011; May, 2018).

Pahl et al. (2007) define conceptual design as the phase in the design process in which the “requirements and design objectives defined in the first phase are synthesised into conceptual alternatives”. Another definition, which focuses on the activities and steps within the conceptual design stage, is provided by Okudan, 2008 in Turrin et al. (2011, p. 657) who defines conceptual design as a “series of divergent and convergent steps, completed at different levels of solution abstraction” where a set of acceptable solutions is provided for assessment and selection in the divergent phase. With this type of conception, Jones (1963) classifies the process where the designer’s mind moves from problem-analysis to solution-seeking in three stages: firstly, the *analysis* lists all the design requirements in relation to the performance specifications. Secondly, the *synthesis* finds solutions for the specifications and builds up a complete design. Finally, the *evaluation* of the accuracy of the design solution and selection of the final design completes the process. Lawson (2006) suggests that these

three stages operate in the design process as a loop in order to allow the iteration of the problem solving process until a final decision is achieved.

The criticality of the conceptual design stage is highly regarded in the literature. In this respect, Mueller (2011) argues that the conceptual stage of a conventional design process lacks sufficient timely information, delays the performative feedback of the building until the later stages where the design is already developed and any change can be substantially expensive. Similarly, other authors use quantitative information to describe the sensitivity of the conceptual design phase where immature decisions often result in unaffordable costs; this is because the majority of costing is decided within the conceptual phase (Chong et al, 2009; Duffy, 1993; Wing, 2001; Wing, 2002 in Turrin et al., 2011). Similarly, Harding and Shepherd (2017) state that, during the conceptual design phase, limited information, and few constraints and objectives are known about the projects, and yet, the most important design decisions have to be taken at this stage. Oxman (2017b) attributes this dilemma to the non-explicit nature of the representational methods applied in conventional design processes, where the focus is placed only on visual representation. This situation results in a lack of communication between designers and other project stakeholders, or in other words, a total separation between architects and builders (Garber, 2014).

In summary, the criticality of the conceptual design stage stems from the contradiction between the essentiality of the decisions needed (Chong et al, 2009; Duffy, 1993; Wing, 2001; Wing, 2002 in Turrin et al., 2011), and the ambiguity of the design problem (Jones, 1992). This contradiction prompts an indispensable need to emphasise the impact of computational design methods on this early stage of the design process, and how they can enable designers to reduce ambiguity to better inform the critical decisions needed at this early stage.

#### **2.4.5 Creativity in Design**

The previous sections explain how most creative activities are conducted in the conceptual design stage, whilst at later stages more technical activities are required to communicate with other stakeholders. Moreover, despite the extreme difficulty of conducting a design process, due to its complexity, ambiguity and uncertainty, many architects and authors of architectural theory consider this difficulty as an integral part of designing that requires a specific type of talent. For instance, Cross (2011, p.12) states that within the design process, designers generate proposals that remain uncertain until a late stage of the design process, while at the

same time, they need to generate early tentative solutions that are often imprecise and inconclusive. He describes this uncertainty as the frustration and joy of designing, that requires designers to have the ‘talent of living in a world of uncertainty’ (Cross, 2011, p. 29). In other words, to survive through extreme complexity and ambiguity, designers need to be creative.

One notable impact of designing by drawing, in comparison to vernacular design, is that it can take away much of the intellectual difficulty and ‘fun’ from manufacture and pass them to a new class of persons who make drawings (Jones, 1992, p. 21). In other words, it pushes the creative aspect of designing to the ‘designer’ and hence, changes craftsmen or fabricators into technicians, who only have to realise drawings given by a designer and transform them into a final product without intervening in design decisions. In this regard, Jones (1992, p. xxv) states that creativity involves ‘being able to change one’s view of things, and of oneself, to the point of attempting something you thought was impossible or beyond you’. This highlights another aspect of design that appears to be overlooked in most of the previous definitions; ‘attempting the impossible’ reveals the tendency of designers to explore the unexplorable and scrutinise design solutions that may not have precedents. Indeed, Cross (2011, p. 8) criticises the definition of design as ‘the optimal solution to a given problem’. Instead, he prefers to describe design as an exploratory process conducted by a creative designer who ‘sets off to explore and to discover something new rather than to reach somewhere already known, or to return with another example of the already familiar’. This could be the difference between engineering and architectural design, where engineers ‘interpret the design brief as specification for a solution’, while architects use the brief as a ‘starting point for a journey of exploration’, i.e. architects tend to innovate in every design situation.

Understanding design as a ‘technical’ and ‘science-based’ activity of searching amongst the possible solutions of a pre-defined problem as opposed rather than a creative exploratory process of uncertain situations is highly debatable in architectural research. Within this context, Plowright (2014, p. 2) identifies ‘two camps of architectural designers’ with different opinions concerning ‘how events in the world are interpreted’. The first camp consists of those who see the world in terms of ‘art’, and therefore, ‘resist any documentation of how to design’. This view is based on a belief that documentation will undermine the sense of artistry, exploration and innovation. The second camp consists of those who see the world in terms of ‘science’, and therefore look for ‘a single, strict, and repeatable structured method

that can be applied in all applications of design' regardless of the specific situations in the design process. This latter view contradicts the previous discussion concerning the uniqueness of design problems and the difficulty in adopting precedent solutions to solve current problems (Rittel & Webber, cited in 1973 in Hudson, 2010). In addition, the view of the second camp represents an attempt to reshape the design process into rational, systematic and science-based design activities, which are seen as 'a strong desire to impose order on design thinking'. This suggests disrespect for the natural design ability (Cross, 2011). In fact, a natural design ability is viewed by some theorists as 'the most valuable part of the design process that goes inside the designer's head and partly out of reach of their conscious control' (Jones, 1992, p. 46). From this basis, Jones (1992, p. 46) concludes that creative activities in design are 'skilled actions governed by the skilled nervous system with no intervention of conscious thought' and therefore, 'it is rational to believe that skilled actions are unconsciously controlled and irrational to expect designer to be wholly capable of a rational explanation'. This shows the difficulty in providing a general description of the structure of the design process and to identify design activities that work in all situations.

The discussion about creativity in design appears to be highly subjective and open to a wide range of conflicted and contradicted arguments. Therefore, identifying the impact of computational design on creativity appears to be relatively challenging and highly subjective, as it is open to diverse interpretations and highly differentiated mindsets and cultures.

#### **2.4.6 Design Activities and Methods: What a Designer in Action Does? And How?**

Identifying the real impact of computational design methods on the architectural design process is subject to a mature understanding of the design process. Having identified the main features of the design process in the previous sections, this section will explore specific activities that designers undertake within the design process and identify the specific tasks they conduct and how they conceive those activities and tasks.

According to Jones (1992), the design process is driven by a set of actions or methods that are carried out in a series or in parallel in order to move from an initial brief to a finished design. While the 'actions' in this statement represent 'what' designers do to achieve the design product, the 'methods' represent 'how' those actions are undertaken. The previous section provides answers about 'what' designers do to solve complicated design problems, and the skills and mental abilities that designers need to confront the complexity and uncertainty of the design process. In addition, some arguments were provided to show how this complexity

is confronted. This section will focus more on the ‘How?’ question; it shows different approaches and methods that designers apply to provide solutions for design problems.

#### ***2.4.6.1 Generating Ideas (Incubation and Ideation)***

At the outset of the design process, a designer starts exploring possible solutions for design problems through ‘incubation’, where he/she spends long periods of time doing nothing but ‘taking general information, working rather fruitlessly at seemingly trivial aspects of the problem or giving attention to unrelated matters’ (Jones, 1992, p. 29). Usually, within this situation, an original idea starts to emerge and this will often lead to a sudden ‘leap of insight’, where a dramatic change occurs in the way in which the problem is perceived. This ‘leap’ normally results in turning a complicated problem into a simple one (Jones, 1992). Based on this argument, a link can be established between the design ideas and design complexity, where the emergence of new ideas result in a ‘leap of insight’ that results in the reduced complexity of a design problem. This leap of insight can be provoked by a better understanding of the problem, or a potential approach to solve this problem. Therefore, it could be argued that the complexity of design problems can be reduced by understanding them better. This relationship can be investigated further when computational design methods are applied. However, a question remains unanswered, namely how this idea can be emerged in order to get this magical impact of simplifying design problem in a sudden manner?

In order to facilitate the emergence of original ideas, the designer needs to avoid ‘mental rigidity’, which, according to Broadbent (1966b, cited in Jones, 1992), represents the enemy of originality. This mainly occurs when a designer acts in a far more regular way than the situation demands. Cross (2011) investigated another interesting way through interviews with different designers in which they were asked how they believed they came up with creative insight or concepts. One theme that recurred in their responses concerned their heavy reliance on ‘intuition’, so that rather than following technical steps to develop concepts and reach their goals, they rely on a natural and unconscious ways of thinking to intuitively generate design concepts.

It is not straightforward to identify the impact of computational design methods on ideation, as a wide range of digital technologies are used that require various technical activities, experiences and knowledge to generate ‘intuitive’ and ‘unconscious’ design concepts. Ideation is a process that is totally generated from a designer’s mind and cannot be replaced by a machine. However, many digital technologies and methods might exist to aid designers

at this critical stage of the design process by reducing the time needed for incubation and to immerse the designer's imagination with precedents and possibilities beyond the capacity of his/her mind.

#### ***2.4.6.2 Communicating Design Intentions (Sketching and Drawing)***

While the discussions in section 2.2 define drawing as an activity that designers do to communicate design ideas with other participants in the design process, the architect Santiago Calatrava cited in (Cross, 2011) emphasises the merit of drawing. However, he adds another dimension; he states that the design idea is, at first, generated in the designer's mind, then the designer makes simple sketches that help in 'organising things'. They then start to develop drawings that help to explore the details with more accuracy. These sketches and drawings instigate internal dialogue inside the designer's mind that enable them to better understand the design problem and discover the layers of the design project. In fact, it is difficult to interact with complicated design situations purely through internal mental processes due to the 'cognitive limit of the amount of complexity that can be handled internally' (Jones, 1992). This requires the designer to develop external presentations, which normally take the form of sketches and drawings to provide 'a temp, external store of tentative ideas' (Cross, 2011, pp. 10-12). Therefore, sketches and drawings are not only provided to communicate design ideas with others as they also allow an internal dialogue inside designer's mind. However, the sketches and drawings only show the final results of the designer's intention, but not the progressive stages that can hold valuable evidence of a designer's thinking. This is an important aspect that requires a search for a specific digital technology that is capable of documenting the process of developing a drawing or a model and not just the final result.

#### ***2.4.6.3 Coping with Complexity***

The way in which designers cope with complexity was already discussed in section 2.2. This shows the benefits of designing by drawing over vernacular design when dealing with complex design products. Moreover, section 2.4.1 also discussed the link between understanding and the reduction of complexity, alongside the use of intuition to generate concepts in complex situations. This discussion attempts to deepen this notion by exploring the thoughts, and mental abilities required by a designer to cope with complexity. In this regard, Cross (2011) cites different interviewees who identify the relationship between a designer's capabilities and the complexity and uncertainty within the design process. One of the interviewees argues that a designer needs to be 'sensitive to nuances in their internal and



external environments'. This sensitivity will enable designers to intuitively note 'particular coincidences' that other people fail to notice, and then recognise those coincidences as opportunities that 'offer prospects and risks in attaining some desirable goal' (Cross, 2011, pp. 12,13). This highlights the complexity of the design process and its reliance on a wide range of aspects and situations. Furthermore, it reinforces that designers need to exceptional mental abilities to establish links between aspects in order to enhance their understanding of the design problem and offer solutions.

Another way to cope with the uncertainty in the design process is to try to 'impose order' on the rather 'nebulous problems'. This order can take the form of 'guiding principles' that offer 'starting points' to enable the designer to 'limit the problem to something manageable' (Cross, 2011, p. 15). This need to limit the design problem is also emphasised by another interviewee, who states that the designer needs to reduce and narrow down the range of problem solutions early in the design process through providing a 'conjecture' of possible solutions and then to test these conjectured solutions against a limited set of objectives in order to establish an idea about the building form that will later act as means of substantiating a solution concept (Cross, 2011). Within the same research by Cross (2011), Bryan Lawson argues that an effective way to cope with uncertainty in the design process is to conduct 'parallel processes' that rely on 'parallel lines of thought'. The efficiency of this method was verified by Robert Venturi's description of his design for the Sainsbury Wing extension, where two sets of ideas were generated. While both sets of ideas were equally important, they were merged into one single solution. This way of thinking can be linked to the divergent and convergent stages of conceptual design that were discussed earlier. Based on Lawson's concept and Venturi's example, the divergence emerges through the conduct of parallel processes to provide possible solutions, while the convergence is enabled by merging two solutions into one rather than selecting one single optimal solution.

The previous discussion explains the complexity and uncertainty in the design process. In fact, the extent of this complexity and uncertainty can be conceived by observing the terminology that previous interviewees use, such as, sensitivity to nuances, particular coincidences, opportunities for possible solutions, risks, nebulous problems, limiting problems, solution range reduction, possible solution conjecture, and parallel lines of thought. This situation indicates that computational design methods should mainly focus on reducing complexity and uncertainty in the design process by offering: a more sophisticated way of

imposing order, an automated manner for generating and testing possible solutions, and smart methods to conduct parallel processes.

#### ***2.4.6.4 Coping with the Creativity and Rationality of the Design Process (The Blackbox and Glassbox Methods)***

Discussing how designers cope with the creativity and rationality of the design process informs the debate about whether the design process is based on ‘science’, consisting of ‘technical’ activities that are ‘rational’ and ‘describable’, or on ‘art’, consisting of ‘creative activities’ that make it more internal and hence ‘indescribable’ (Jones, 1992; Lawson, 2006; Plowright, 2014). In this regard, Lawson (2006) states that the design process activities are a mix of creative and technical activities, while Jones (1992, p.45,46) notes two design methods to drive these two types of activity. He states that the ‘mysterious creative leap of a designer’ comes from the ‘black box’ method, while a ‘completely explicable rational process’ can be discerned through the ‘glass box’ method.

The black box method is based on the assumption that the brain deals with current situations by analysing similar situations encountered in the past, where past experiences are re-patterned based on the current situation. This mental process takes place inside designer’s head and partly out of reach of their conscious control. Thus, a designer produces successful and creative outputs without having the ability to explain how those outputs were obtained (Jones, 1992). Therefore, a more efficient method to save and recall previous experiences and situations is necessary to partially replace the full reliance on the designer’s internal memory. This can be a computational design method that enables the digital documentation of a process that deals with complex design situations and enables automated recall in similar future situations.

Within the blackbox method, a designer (or a group of designers) conduct a ‘brainstorming session’, where every designer contributes to a free conversation in which criticism is ruled out and social inhibitions are removed in order to enable the early and quick generation of a wide range of data which are relevant to the yet, unstructured design problem. In this case, the brainstorming results are fed into the ‘black box’ of a single person to enable the provision of a coherent pattern out of the random ideas generated during the brainstorming session (Jones, 1992). This coherent pattern can be obtained through ‘synetics’, which represents the feedback of the brainstorming outputs, where designers carefully choose some types of analogy in order to transform outputs into meaningful inputs. This may enable a

group of designers to collectively re-pattern original conflicting inputs in order to develop patterns capable of resolving the conflict (Jones, 1992).

The glassbox method is concerned with the need to externalise design thinking; this is based on the assumption that the design process is entirely explicable, where a designer has a full knowledge of what they are doing and why they are doing it. Within this method, the designer absorbs the information given to them and conducts a cyclical process of analytical, synthetic and evaluative steps until the best possible solution is recognised (Jones, 1992). These circular steps appear to be repetitive and cumbersome and require a convenient mechanism to automate those repetitive tasks. Therefore, a search through computational design methods is needed to identify a way to partially or entirely automate such steps.

#### ***2.4.6.5 Solving Design Problems***

Newell et al. (1957, cited in Hudson, 2010) state that, within the problem solving process, the designer moves from a ‘task environment’ (the context in which the problem exists) into a problem space, where the problem solving is conducted as a search for possible solutions. Within this space, the designer produces a series of solutions, which are tested for their compliance with the problem requirements. Based on an understanding of the complexity of the problem solving process gained from the previous sections, this description does not seem to address complexity. A designer in this situation needs to move back and forth to the ‘task environment’ to gain a better understanding of the problem context after the solution search is initiated.

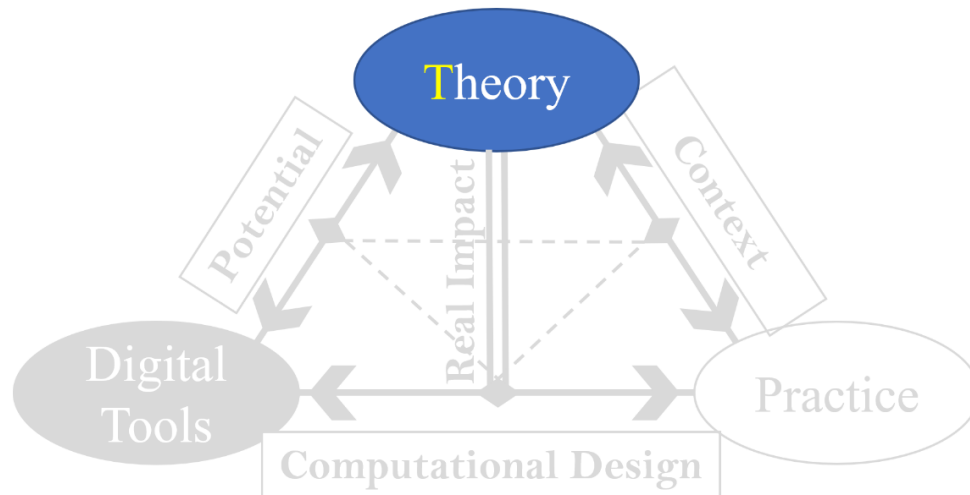
In contrast to Lawson’s parallel processes to generate possible design solutions (Cross, 2011), Simon (1996, cited in Hudson, 2010) suggests another approach, where the designer identifies a starting state, then the search for a solution is conducted by operators that allow the designer to move from one state to another. This situation shows that the problem solving process consists of one path where a design solution is continuously developed, and, rather than being conducted as parallel processes, it grows in maturity as the design progresses,. In general, a combination of linear and cyclical problem solving approaches are shown in the literature as attempts to articulate how a designer’s mind operates within the design process.

Another important aspect of the problem solving process that is highlighted by many design theorists is the design space or problem space. According to Rowe (1987, cited in Hudson, 2010) this is ‘an abstract domain’ that contains different elements holding possible solutions

for the design problem. In this regard, Simon (1975, cited in Hudson, 2010) attributes the success of problem solving in design to the existence of a ‘large design space’. According to Newell et al. (1957, cited in Hudson, 2010) this requires a ‘heuristic search’, where the number of design alternatives is reduced through a set of constraints using experience and rules of thumb rather than theory. Moreover, Lawson (2006) states that the boundary of the design space and, hence, its size, can be defined by the problem constraints. Therefore, an important aspect for investigation is how computational design methods enable designers to provide a wider design space than that achievable with conventional design methods. These methods should allow smart search engines to enable a designer to search more effectively for optimal designs within this large space. This could be an automated solution search that can eliminate part of the difficulty in a heuristic search.

Within this problem space, the designer explores alternative solutions and relies on rational choice and subjective interpretation to select the optimal solution (Simon, 1996, cited in Hudson, 2010). Jones (1992) argues that the generation and evaluation of design alternatives are conducted through an ‘iterative process’, where a series of unstructured tasks are conducted inside the designer’s mind in tandem with an ‘internal feedback mechanism’. This process appears to be cumbersome and complicated. Therefore, it is essential to find the appropriate computational design method to automate this iterative process, and hence, accelerate the process of generating and evaluating design alternatives.

The previous sections have discussed the architectural design process from a theoretical perspective (figure 4). It explored the different stages of the design process, including its complex and creative nature. It also explored how designers work, how they generate ideas, sketches and drawing, and the ways in which they address complexity and creativity in order to solve design problems. Meanwhile, a wide range of questions have been raised for answering when exploring the different computational design methods. For a more in-depth understanding of the design process, and to enable mature questions and answers, it is important to explore the design process within its practical context, so that the same design features identified can be explored within architectural practice, through which new aspects may emerge.



**Figure 4: Focus of the previous sections in relation to the initial framework**

## 2.5 Architectural Practice

As previously mentioned, it is only in fairly recent times that design has been regarded as an activity that requires special abilities (Cross, 2011, p. 4). In fact, architecture is identified as an art, profession or business (Cuff, 1992), that requires management. This view started to emerge as an essential aspect of architecture in the 1960's (Emmitt, 2014). This section will focus on the practical context of architectural design, and identify the social environments in which designers work, communicate and interact, including how architectural projects are approached and managed. This will enable the establishment of the context within which the architectural design process can be approached. The utilisation of highly advanced digital technologies and applications of new computational design methods will also enable an investigation of this practical context.

### 2.5.1 The 'Profession' of Architecture and its 'Business Aspect'

Architectural practice involves the professional activities that architects undertake and how these are customarily performed as routine activities within commonplace experiences (Cuff, 1992). Architectural practices, in turn, are project-driven organisations that undertake the task of identifying how risks, costs and programmes are going to be managed in order to set the value of their design and hence, deliver high quality services for their clients (Emmitt, 2014). Therefore, the business aspects of architecture involve a wide range of managerial, financial, legal, and co-ordinational activities and tasks, such as staying on schedule, adhering to a construction budget, establishing a realistic fee structure, writing legally competent

specifications, and securing effective coordination between external consultants, in-house staff and clients (Cuff, 1992).

As discussed earlier, design implies a set of complex and uncertain activities (Chaszar & Joyce, 2016a; Cross, 2011) that require the designer to rely on limited information to predict an ambiguous future state (Jones, 1992). Similarly, Cuff (1992, p. 4) states that ‘architectural practice emerges through complex interaction among different parties, from which the documents for future buildings emerge’. This indicates that the complex nature of design is naturally inherited by architectural practice, and raises the importance of management. According to Emmitt (2014), ‘management is seen as a way of coping with the chaos of design’, that can enhance the significance of an architect’s role in the realisation of creative buildings. The following sections explore different practical and managerial activities and tasks that architects undertake within the social and interactive environment.

### **2.5.2 The Social Environment of Architectural Practice**

The previous discussions on design regarding ‘science vs art’ (Plowright, 2014), ‘rational vs creative’ (Lawson 2006), and ‘blackbox vs glassbox’ (Jones, 1992), are reflected in architectural practice-related research. In this regard, Cuff (1992) observes a series of dualities in which architectural practice is viewed. This includes the duality that counterposes the individual with the collaborative, and the contrast between ‘architecture’s fundamental respect for the autonomous artist’ and ‘its use of teams of professionals to do the actual work’ (Cuff, 1992, p. 11). This duality highlight contradictions that oscillate between those who prompt the enhancement of collaboration to improve business and design quality (Blau, 1984, cited in Cuff, 1992) to enable the development of new design methods that effectively respond to the current industrial evolution (Jones, 1992), and those who view the involvement of ‘countless voices’ in design decisions as constraints that often overwhelm architect’s intention, resulting in decreased artistic quality (Cuff, 1992). Nevertheless, collaboration and collective work in architectural practice appear to be inevitable. In this context, Cuff (1992) states that artefacts and buildings are socially constructed in practice by a wide range of contributors and stakeholders that, in addition to individual architects, include draftsmen, engineers, consultants, contractors, fundraisers, and clients. All of these participants form socioeconomic forces who need to operate as a unit through the effective coordination of efforts, knowledge and experience. Cuff refers to this aspect in practice as ‘the social dimension of architecture’.

### **2.5.3 How Architects in Practice Work (Roles, Relations and Interaction)**

In order to understand this ‘social dimension’, the following sections will examine the different roles within architectural practice, and investigate the way in which they interact. This will enable a later investigation into the way in which computational design methods change or improve the nature of this interaction.

#### ***2.5.3.1 Roles in Practice***

One of the series of dualities observed by Cuff (1992, p. 11) is the question of ‘whether architecture is best created by mosaic of specialists or is inherently the comprehensive task of qualified generalists’. This highlights the necessity to explore the specific roles that are associated with these specialities and qualifications. In this regard, Cuff (1992, p. 169) observes the recurrent patterns of activities and values that hold a particular significance in architectural practice. These recurrent patterns represent the roles in architectural practice. They are typified responses to typified expectations. Such expectations are built on individual specialisation, expertise, and knowledge which help to identify individual strengths and weaknesses in order to allocate duties within practice (Emmitt, 2014).

Although the roles and their associated duties may vary amongst different architectural firms, Cuff’s observation of the ‘recurrent patterns’ can help to form a general understanding of the main roles in architectural practice. The roles in practice include architects, clients, contractors and consultants, as well as a wide range of specific occupational roles, such as draftsmen, project architects, designers, partners, principals or model makers (Cuff, 1992). Each role describes the way in which each individual is expected to act, the values they will hold, and the significance they will add to the practice (Cuff, 1992).

#### ***2.5.3.2 Role of Architect and their Relation to other Participants***

In addition to the multifaceted role of architects in dealing with complex design problems (Cross, 2011; Jones, 1992), they are required to have the capability to communicate effectively with other professionals in an environment of collaboration and integral work (Emmitt, 2014). They need to coordinate their work with other participants whose input will frame their design solutions by providing wilful choices that have implications for the building’s design (Cuff, 1992). The building design emerges from this interaction, and in order for this to be effective, architects require greater knowledge and expertise; thus, architects are required to not only build aesthetic and functional knowledge, but also other

knowledge on building structures, mechanical systems, graphic conventions, and so forth. Moreover, architects are required to have the capability to continuously nurture the scheme of design projects throughout the stages of development without compromising the design quality (Cuff, 1992). Furthermore, it is important for architects to understand the commercial environment in which they work and the added value that results from consistent and efficient design management (Emmitt, 2014).

In addition, Cuff (1992) observes different sorts of behaviour amongst architects within practice. Architects frequently spend their time on drawing boards - drafting, filing, writing memos - this is coupled with intensive informal discussions with other architects and participants within the organisation. In addition, some architects solely make models for others, while others spend the majority of their time communicating on the phone. This is an interesting observation that shows how, in some cases, architectural practice shifts some architects to narrower areas of specialisation, or away from their creative work. This highlights similar possible shifts when computational design methods are applied. This might shift the focus towards more narrowed specialisations in particular computational methods, or particular communication technologies.

### ***2.5.3.3 Role of Client and their Relation to Architects***

The role of the client is central in architectural practice, as is their relation to architects. In fact, the appropriateness of the services provided by the architectural practice can be threatened without the continuous involvement of the client, who can identify constraints, give advice and provide approval (Cuff, 1992). Clients have an essential voice that can transform the architect's role and significantly affect design decisions. Both architects and clients need to negotiate throughout the design project in order to plan the work, discuss the different aspects of the design, and (in some cases) terminate the project (Cuff, 1992). The relationship between the architect and client is critical and can significantly affect the flow of projects. Thus, according to Cuff (1992), any client wants their input to be significant; however, the architect is expected to have a greater capability to foresee the consequences of different decisions. From this basis, a client may become frustrated when an architect accepts all their decisions and might question the feasibility of hiring them (Cuff, 1992). This is a critical point in the relationship between the client and architect and emphasised by different architects interviewed by Cross (2011). For instance, Denys Landua (architect) states that an 'architect's job is to give the client, on time and on cost, not what he wants, but what he never



dreamed he wanted; and when he gets it, he recognises it as something he wanted all the time' (Cross, 2011, p. 3). Similarly, Richard MacCroma (architect interviewed by Bryan Lawson) ensures that '... in competitions, the winning scheme is the one that tells the client something that they never knew before... something that is terribly important to them and was not in the brief' (Cross, 2011, p. 14, 15). In fact, going beyond the brief and providing more work than required suggests further exploration of the psychology of architects in order to understand what motivates this. Cuff (1992, pp. 70-71) attributes this phenomenon to the 'widely held notion' that the best work comes from offices that adopt the 'Charrette ethos' in which 'good architecture requires commitment beyond the allotted time, accountant's ledger, and normal hours.' This ethical phenomenon incites architects to work overtime to achieve high standards regardless of the fee, which is based on their belief that 'good architecture is rarely possible within the fee'. According to Cuff (1992), this phenomenon represents the architect's 'reaction to and rejection of the client's control by working without pay or longer that is reasonable to create a building beyond the client's subsidy'. Cuff argues that this could be connected to the tendency of the architect to 'own' some part of the project.

The previous discussion highlights an essential aspect that requires consideration, namely the ownership of the design product. This poses questions about how the use of highly advanced digital technologies and methods can change the notion of ownership, especially when working in highly collaborative, integrated and digitally-immersed work environments.

#### **2.5.3.4 Power**

Each of the previous roles come with power that can be gained gradually within a practice's hierarchy, which can be formally and informally constituted. Zartman, (1976, cited in Cuff, 1992, p. 167) defines power as 'the ability to move someone or something within the organisation in a desired direction'. Through her observation of different architectural practices, Cuff (1992) explains how the power of individuals in architectural practice can be gained. She highlights two types of power; firstly, the formal power structure of the practice is identified in the politics and procedures manual. This clearly identifies the status of each individual and their decision making authority, alongside the hierarchy of seniority and the official channels through which individuals interrelate. Secondly, informal power is formed through daily interactions and decision making throughout projects. Cuff (1992) observes an example of this informal power, where a novice architect can gain power by associating with a powerful individual member. Through this connection they may closer and hence, inherit

part of their power. Cuff also states that power can be gained through the ‘persuasive ability’ of individuals undertaking specific types of tasks or the strength in one’s ideas within design projects. Similarly, Blau (1984, cited in Cuff, 1992, p. 169) asserts that one of the main aspects that enable an individual to acquire power in their office is to possess an ‘esoteric experience’, such as knowledge of CAD or lighting. This highlights another aspect to investigate in terms of the impact of digital technologies in design, namely the power that individuals can gain through esoteric knowledge and experience in utilising digital technologies.

#### ***2.5.3.5 The Role of the Design Manager***

Within architectural practice, a design manager is normally appointed to champion the design and to promote its values to other project stakeholders. They achieve this by understanding and responding to different perspectives in order to effectively coordinate ‘the harmonious weaving together of people, materials, technologies and place’, and hence deliver a quality service for clients (Emmitt, 2014, p. 33). A design manager takes informed decisions on a strategic and operation level; the strategic level concerns the long-term direction of a project or an organisation, where the design manager sets the agenda for the effectiveness and profitability of each project, and works alongside the business owners to ensure the project and business deliverables are met. The operational level concerns day-to-day problem solving in the workplace, where they manage the flow of resources (people, technologies, information), liaise with designers, and form the interface between the design team and contractors in order to ensure tasks are completed (Emmitt, 2014). The division of the design manager’s tasks into two levels stimulates a new way of thinking, where the impact of computational design methods can be investigated on each of these levels. This will be addressed in the following chapters, which will show how digital technologies affect the design process within projects, and how they may help in developing new methods or patterns of designing that are applicable to different projects.

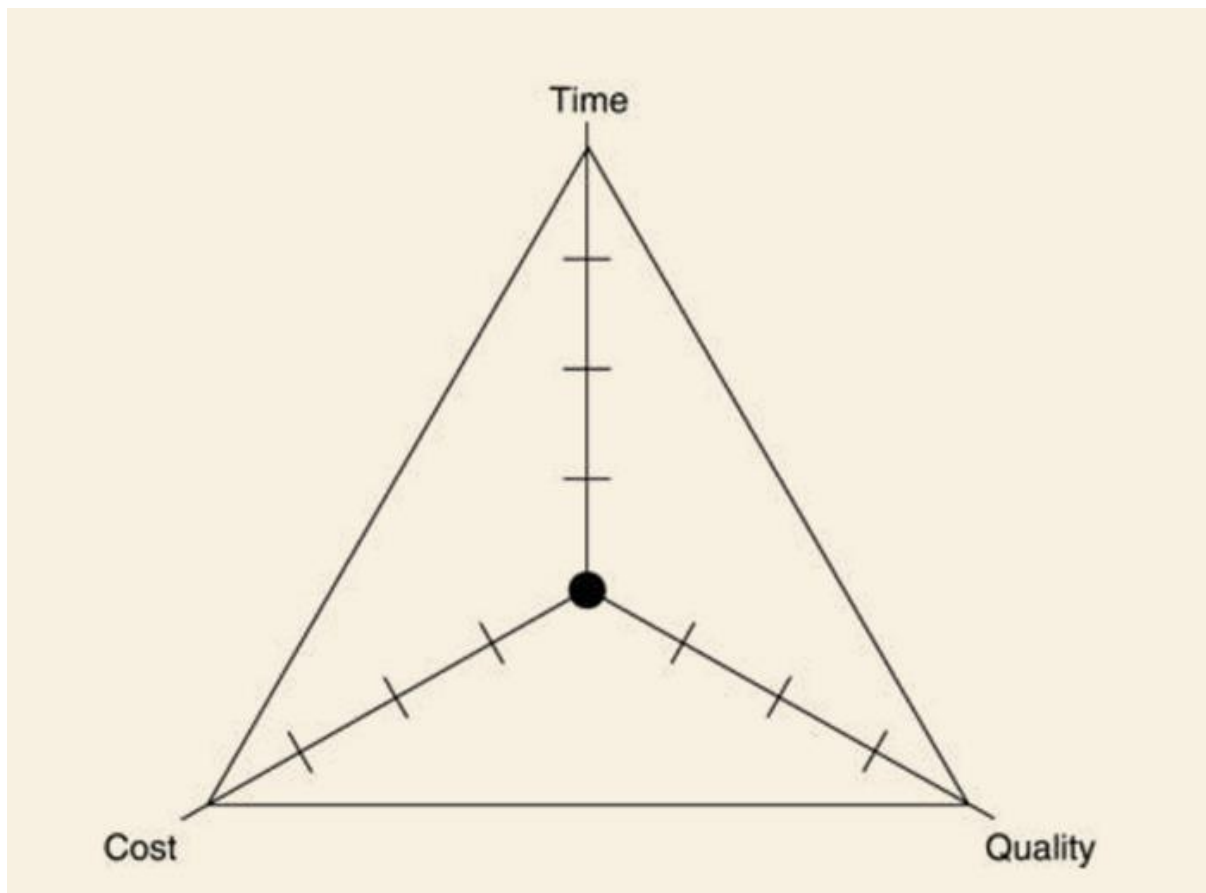
#### **2.5.4 Design Projects in Practice**

While Emmitt (2014) identifies two levels in which a design manager operates (strategic and operational), Cuff (1992) refers to those levels as the ‘organisational level’ and ‘project level’. This section focuses on the project level, and explores different ways in which architects and other project stakeholders interact within the conduct of a design project.

According to Emmitt (2014, p. 46), architectural projects in practice represent a ‘temporary overlap of authority’ and may result in rivalry for power within the project teams’.

#### 2.5.4.1 Project Deliverables

Conducting projects in practice requires the identification of three project deliverables which are cost, time and quality (Figure 5). Therefore, project stakeholders should be careful in managing the balance between these deliverables as an emphasis on one can cause problems within the other two (Emmitt, 2014).



**Figure 5: Project Deliverables in Architectural Practice (Emmitt, 2014)**

Emmitt (2014) asserts that a great deal of responsibility in controlling the cost of the development and the realisation of an architectural project falls upon the shoulders of the design team, and their design decisions throughout the life cycle of the project. He highlights two critical points; the first point concerns designers’ control over the budget, which decreases quickly as the project progresses. The second point concerns the cost of design changes that increase as the project develops. This highlights another aspect of the aforementioned difficulties in conducting a design project, namely the necessity of using

insufficient information to solve ambiguous design problems that cannot be clarified until a late stage, when it is too late and costly to change (Jones, 1992). Therefore, within a practical context, design changes at late stages are not only difficult, but also expensive. This places extra emphasis on the criticality of early decisions and the need to find the appropriate computational design method that enables a high level of maturity in design decisions at earlier stages.

Time is highly related to cost. According to Emmitt (2014), the financial return of projects in any commercial enterprise are highly related to earlier work completions. Moreover, building designers can gain competitive advantage when they have the capability to minimise the time required to assemble a building, and as such, most clients are willing to pay a premium for quick services. This highlights the need to search different computational design methods and explore the range of ways in which they can accelerate the design process. In doing so they can save time, which will automatically result in cost savings. However, the dilemma in the time deliverable is not only the pace of the design process. In real projects, designers need to coordinate their work with the construction team, which means negotiating a contradiction between the iterative nature of design and the linear nature of construction. This leads to clashes between the design programme and that of contractor (Emmitt, 2014). Design problems are complex, uncertain and ambiguous (Chaszar & Joyce, 2016a). Thus they require the generation of different alternative solutions (Lawson, 2006) and iterations of regeneration and retesting (Bernal et al., 2015) until the optimal solution is developed. The previous discussion highlights the practical context of design complexity and reveals another difficulty, where, in real projects, designers have the additional challenge of coordinating their programmes with construction programmes that are different in nature. This issue places extra emphasis on the need to identify a computational design method that can reduce iteration in the design process by automating the generation and testing of design alternatives. From a managerial perspective, Emmitt (2014), states that design programmes need to be relatively flexible and hence, should be able to accommodate the iterative design process, and at the same time, respond to the sequence of construction. He also attributes the clashes between the design and construction teams to the inability of both to recognise the different requirements of the other party. This suggests that, in practice, architects need to have more knowledge about construction in order to achieve a seamless coordination to ensure greater time and cost efficiency in building projects.

Furthermore, architects need to secure quality control over their design throughout the project in order to ‘ensure work conforms to predetermined performance specifications and adherence to current codes, standards and regulations’ (Emmitt, 2014, p. 34). This includes continuous checks to secure consistency between all project documents, drawings and the agreed standards. This consistency raises an important aspect of design complexity in its real-project context, namely the coordination required for effectiveness amongst all participants within a project in order to enhance the quality of buildings and ensure time and cost efficiencies. In general, Emmitt’s (2014) emphasis on the balance between time, cost and quality prompts a need to investigate the capability of computational design methods in changing this equation. This could be achieved by utilising new methods to enable architects to save time while at the same time, maintain quality and save cost, rather than sacrifice one deliverable to enhance the other.

#### ***2.5.4.2 Collaboration in Architectural Projects (Control, Effectiveness and Conflicts)***

The previous discussion about project deliverables raises an important aspect, which is collaboration, where the design team need to collaborate and coordinate work with the construction team and other project participants. Emmitt (2014) emphasises the criticality of architectural practices in providing clear identification of the positions, roles and responsibilities of each team and each team members within the project. He introduces a spectrum that represents different levels of involvement within the design team in the construction process, and hence the different levels of control over the building. At one extreme, some architectural practices provide ‘design-only services’, where the architect’s influence over the progress of the design project may be negligible. In such cases, the image of the completed building might shift from the architect’s design intention as the progress would be driven by other participants with different objectives. At the other extreme, some architectural practices maintain continuous involvement and interaction throughout the project life cycle from inception to completion. This gives a design team full control over the design quality, resulting in consistency between the architect’s design intention and the completed building. This suggests the need for an investigation into the level of control of computational design specialists when highly-advanced digital technologies are utilised in design projects.

In general, knowing one’s own roles, tasks and responsibilities and those of other participants appears to be essential for effective collaboration within design projects. According to

Emmitt (2014, p. 49), this effectiveness can be enhanced through the ‘early involvement’ of different participants within the decision making. This early involvement provides all actors with the opportunity to contribute to the design, detail and planning stages prior to the finalisation of decisions. This can result in the considerable elimination of waste at the later project stages. The importance of early involvement and early decisions shows the practical criticality of the initial design stages, where the most key decisions need to be taken (Chong et al, 2009; Duffy, 1993; Wing, 2001; Wing, 2002 in Turrin et al., 2011) despite the ambiguity of the problem at these stages (Cross, 2011; Jones, 1992). In between this criticality and ambiguity, computational design methods are required to address this contradiction by reducing ambiguity in early stages and hence, enabling better informed decisions in collaborative work.

Nonetheless, the effectiveness of collaborative work can be threatened by conflicts, which normally take place when different participants in an architectural project offer their own sets of values and objectives. Therefore, it is the difference and contradiction amongst these various objectives and values that incite conflict (Becker, 1982, cited in Cuff, 1992). Cuff (1992, p. 62) attributes these conflicts to the fact that ‘placing a high priority on design requires trade-offs in other domains’. For instance, a small budget places limits on the amount of time that the architect can spend on the design and affects their design freedom, which can affect the design quality. Similarly, within an architectural project, a design manager may try to champion design quality, while participants working on behalf of the contractors might be highly sensitive to, and influenced by, the financial implications of design decisions (Emmitt, 2014). Therefore, it is important to investigate the impact of computational design methods and different digital technologies and their ability to omit these conflicts to improve the effectiveness of collaborative work.

#### ***2.5.4.3 Knowledge Acquisition in between ‘Project Level’ and ‘Organisation Level’***

Different stakeholders can gain valuable learning opportunities within collaborative work environments in architectural projects, through their involvement in discussions, agreements, and approvals. Furthermore, they can participate in the evaluation of the project progress at its various stages (Emmitt, 2014). In the previous sections, the social dimension of architectural practice was explored at the ‘strategic/organisation’ level, and at the ‘operational/project’ level (Cuff, 1992; Emmitt, 2014). With this in mind, the aforementioned learning opportunities represent the link between those two levels, where the knowledge and

experiences gained from projects can feed into the general knowledge and experiences of the organisation or practice and its strategic plans. This can result in more mature decisions and more effective work in future projects. In this context, Emmitt (2014) accords some of the success of architectural practice to their ability in establishing a synergistic relationship between the office and projects, where the development of projects helps to fuel organisational knowledge. Therefore, different digital technologies need to be explored in terms of their ability to provide more effective digital documentation of the experiences and knowledge gained from projects in order to enable greater effectiveness in later projects.

### **2.5.5 Design Complexity in Practice**

The previous sections show the collaborative nature of architectural practice, which according to Cuff (1992), emerges through complex interactions among interested parties, where designers need to move their project through the various stages of approval and construction management. This highlights the increasing complexity of the design process (Jones, 1992; Lawson, 2006) when it is approached from a practical context; thus, extra emphasis should be placed on managing this complexity. According to Emmitt (2014), ‘design management is often seen as a way of coping with the chaos of design’. This requires a mature understanding of design complexity in its practical context. In this respect, Cuff (1992, p. 62) attributes the complexity and difficulty of design projects in practice to the fact that such practice is dynamic where the responsibilities, procedures, authorities, allegiances, and expertise in a project are ambiguous. Furthermore, the reliance of design decision on incomplete information often results in a perpetual process discovery. This, in turn, may result in unlimited design possibilities that create challenges when predicting the outcome, and thus lead to ‘surprising endings’. This situation supports the need for a computational design method that can reduce the impact of ‘surprising endings’ or enable ‘positively surprising endings’.

In addition, Emmitt (2014) states that the practice relies on interaction with a diverse range of project stakeholders, where the main challenge for architects is to deal with the heterogeneity of the construction sector that includes a fluid and dynamic collection of specialists. This is added to the nature of the architectural and the construction industry where, unlike manufacturing, no established supply chains can be developed. This results in difficulty when repeating building types and emphasises the uniqueness of design problems, which makes it difficult to use previous solutions to inform current problems (Rittel & Webber,

1973, cited in Hudson, 2010). This shed lights on an important aspect of the potential capability of computational design methods when dealing with the uniqueness of architectural projects. This could be achieved by enabling the extraction of smart patterns from design projects, which could automatically adapt themselves to the unique requirements and features of each design project.

### **2.5.6 Design Creativity in Practice**

The previous sections reveal the business aspect of architectural design and the collaborative nature of architectural practice where architects need to coordinate their work with a wide range of contributors, which places constraints on an architect's design decisions. This highlights a need to discuss the impact of such constraints on design creativity within this practical context.

Unlike in academic institutions, where design is always prioritised, in practice, design and business are in 'constant battle'. Architects tend to view business developers as individuals who lie outside the architectural culture and usually override design priorities to favour economic priorities (Cuff, 1992). On the other hand, business developers tend to view creative designers as individuals who lie outside the bounds of managerial control, and therefore, need pushing to respond to management procedures (Emmitt, 2014).

A high level of conflict can be traced in the literature, which attempts to identify the impact of practical constraints on design creativity. In this respect, many authors in architectural literature refer to creativity as the main feature of design; indeed, Reswick (1965, cited in Jones, 1992, p. 4) defined design as 'a creative activity that involves bringing into being something new and useful that has not existed previously'. In addition, Lawson (2006, p. 12) insists on the need for architects to have a 'well developed aesthetic appreciation' that should add to their technical competence. Nevertheless, Cuff (1992) asserts that, despite the view that business managers tend to work against design quality to ensure profit, an architectural office without good business practices will not survive. Similarly, Emmitt (2014) argues that it is difficult for architects to adopt a creative role outside the management culture. Therefore, the main challenge of business owners is to secure the quality of their services while supporting the creative process, and to effectively manage the administrative constraints placed on creative individuals (Emmitt, 2014).



The literature emphasises the subtle relation between collaborative work in practice and design creativity. Blau, (1984, cited in Cuff, 1992, p. 77) indicates that the more participatory the office, the more effective it can be in terms of both business and design quality. In contrast, Cuff (1992) observes a general belief amongst architects that the design quality decreases in proportion to the number of people involved in its creation. Therefore, the simultaneous management of design and business is essential, and it is only when practitioners recognise this essential link, that mutual cooperation can be assured (Cuff, 1992, p. 11). This accentuates the responsibility of the new digital methods to provide better harmony between design creativity and business efficiency in architectural practice.

## **2.6 Chapter Conclusion**

This section summarises the main findings from this chapter, and explains how they contribute to the development of the theoretical framework. In addition, it summarises the main questions that emerged from the discussion in this chapter, in order for these questions to be answered in the following chapters.

### **2.6.1 The Framework**

Within the discussion about the design process and architectural practice, the theoretical framework started to emerge. This was informed by the identification of different concepts from diverse perspectives and contexts and an exploration of some relationships between these concepts. The first concept is design complexity, which was explored from a theoretical perspective by identifying its roots, and discussing how designers cope with complexity. Moreover, complexity was explored from practical perspectives, where the need to coordinate with other participants results in increasing design complexity. Another concept that was identified in this chapter is design creativity; this was discussed from a theoretical perspective that showed how creativity can be challenged by the complexity and ambiguity of the design process. It was also discussed in practice by discussing the various ‘voices’ involved in design, and the financial and other managerial constraints that could affect creativity. This led to another concept, namely collaboration. In this regard, the chapter shows how different participants collaborate and interact on a practice level as well as a project level. Between these levels, an important concept emerged, namely knowledge acquisition. This concept allows knowledge and experiences to be transferred from project to project. Design knowledge and experiences represent further concepts that were considered in light of their ambiguity and indeterminacy from a theoretical perspective. The discussion

identified the need for further knowledge and experiences amongst architects to enable effective coordination in collaborative work within practice. These concepts can be added to others that also emerged, such as design alternatives, design space, future expectations, and roles and power. Those concepts represent items of the theoretical framework, and will act as a road map that will help to enable more specificity when identifying the potential of the ‘digital’ on architectural design.

## **2.6.2 Questions Raised**

Many questions were raised from this chapter that require discussion in relation to the capabilities of the new computational design methods. Therefore, the following sub-sections outline the anticipated capabilities that computational design methods need to address. These capabilities emerged from an exploration of the limitations of conventional design. The capabilities are classified based on the emerging concepts that will form the theoretical framework, as discussed above.

### **2.6.2.1 Complexity**

- Reducing complexity in the design process;
- Improving negotiations between the design problem and solution, resulting in a more efficient and seamless design processes;
- Dealing with the uniqueness of design problems and design projects by enabling greater efficiency by using precedents to inform current solutions .

### **2.6.2.2 Processes**

- Changing the structure of the design process, its activities, stages, and the chronology of those stages;
- Reducing the time needed for incubation and the immersion of the designer’s imagination in precedents and possibilities that could be beyond the capacity of designer’s mind;
- Enabling the exploration of more design alternatives and providing a wider design space so that more efficient design solutions to emerge;
- Automating the repetitive tasks of generation, evaluation and synthesis;
- Supporting future expectations about the design product, and enhancing the resolution of future images to an extent that is unachievable with traditional methods;
- Enabling more informed decisions at the early stages of the design process;

- Offering a more sophisticated way of imposing order, and providing an automated way of generating and testing possible solutions and smart methods in order to conduct parallel processes;
- Accelerating the design process to facilitate greater time and cost efficiencies;
- Documenting the design process and the steps involved in generating a design object to support the designer's cognitive processing, rather than relying only on memory;

#### **2.6.2.3 Collaboration**

- Allowing better coordination to improve efficiency in collaborative work;
- Enabling the earlier involvement of different participants in design projects;
- Minimising conflicts in order to enhance efficiency in collaborative work.

#### **2.6.2.4 Information**

- Changing the type of design information used and the way in which it is exchanged.

#### **2.6.2.5 Knowledge and Experiences**

- Changing the sort of knowledge and experiences required by the designer;
- Providing more effective digital documentation of the experiences and knowledge gained from projects to facilitate better effectiveness in subsequent projects;

#### **2.6.2.6 Roles and Power**

- Changing roles in architectural practice and changing the power associated with these roles;
- Shifting architects towards narrower areas of specialisation;
- Changing the relationship between the architect and client, and enabling greater client involvement in the design process;

#### **2.6.2.7 Management**

- Allowing designers to save time without sacrificing cost and quality;
- Changing the level of control of the designer over the project;

#### **2.6.2.8 Creativity**

- Influencing design creativity;

- Providing better harmony between design creativity and business efficiency in architectural practice;

### **2.6.3 Summary**

In forming the basis for the investigation into the impact of digital technologies and computational design methods on architectural design, this chapter explored different features of architectural design. This was achieved in different stages; firstly, the shift from vernacular to drawing-based design was outlined. This was explained through showing the benefits of providing ‘drawings’ prior to ‘making’, which allows for the design of larger and more complex shapes and splits the work into pieces for multiple contributions to the design and realisation of the product. Secondly, a range of definitions of design were discussed and categorised in different ways. From this basis, the chapter explored the design process, considering its different stages, nature, and features. It identified the interwoven relationship between the problem identification and problem-solving, and the complexity and ambiguity of this relationship. Moreover, it explored the roots of complexity. This highlighted the criticality of the conceptual design stage, and how this can challenge a designer’s creativity. Furthermore, the chapter provides an understanding of the design process by exploring its activities and methods, i.e. what designers do and how they generate ideas, communicate design intentions, cope with complexity, cope with design rationality and creativity, and solve design problems.

Thirdly, the chapter explored the business aspect of architectural design, and how the design process is conducted within the context of architectural practice. In this regard, the social dimension of architectural practice was explored by identifying range of roles in practice and how different participants work, communicate and interact. In addition, the impact of the multiplicity of voices involved in design decisions, and the financial and business-related priorities in relation to an architect’s creative work were investigated. These were considered alongside the increasing complexity of design in practice that mainly results from the need for continuous coordination. Finally, the chapter explored both organisational and project levels and examined their connection through knowledge acquisition.

# CHAPTER THREE

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## 3 Evolution of Computational Design

### 3.1 Introduction

The digital processes that facilitate the creation of buildings today offer a unique opportunity to redefine architectural practice (Bernstein, 2016). Consequently, large bodies of research and theoretical knowledge are being produced to prototype the new methods and understand their potential (Oxman, 2006; Tamke & Thomsen, 2018). While the new technologies of computational design are the central keystone of the production of new methods and theories (Oxman, 2006; Tamke & Thomsen, 2018), they are also acting as a catalyst to drive design innovation (Kocaturk, 2017), and so the theoretical basis of parametric design is becoming the nexus of theoretical production of computational design (Oxman, 2017a, p. 1).

This chapter explores the historical evolution of computational design methods, considering CAD (Computer-Aided Design), scripting, algorithmic and performative design, BIM-based design, and parametric design. It explores the way that tools are being tweaked and adapted to match the designer's intent through scripting, and how such technologies have resulted in the emergence of novel design approaches, such as generative/algorithmic design and performative design. The chapter then explores different definitions of BIM (Building Information Modelling), its tools, dimensions, and maturity levels, together with its benefits, potential, and problematic issues. Finally, the chapter broadly explores parametric design, its definition and tools. It scrutinises its benefits and potential as opposed to the problems of the other approaches. Moreover, the problems and limitations of parametric design and the barriers that may restrict its potential are investigated from different perspectives.

In addition to identifying the benefits and problems of each design approach, this chapter investigates the impact of each on the design process, and examines the significance of each impact. In this case, the term 'paradigm shift' is used to refer to the impacts that result in changes to the structure of the conventional design process defined in the literature. This can include changing the sequence of the design stages, automating specific stages or specific activities within the design process, integrating some stages, incorporating non-architectural activities into the design process, or any impact that may result in the migration of some activities to earlier stages.

The term computational design will be used in the following sections to refer to approaches that enable design possibilities that are beyond the reach of any paper or CAD-based methods. Thus, in computational design, digital technologies and methods are not only used as a means for drafting, representing or communicating design ideas as in CAD, but also as integral part of the design itself, allowing design possibilities and solutions that are impossible to be achieved using traditional methods. More precisely, the term ‘computational design’ in this research refers to scripting-based, generative/algorithmic, performative, parametric and BIM-based design. Each of these design approaches will be discussed in the following sections within this chapter.

### **3.2 CAD (Computer-Aided Design)**

The impact of digital technologies on the architectural design process started to crystallise in the 1980s and 1990s as CAD was adopted by a wide range of architectural practices throughout the world (Penttilä, 2006). At that time, CAD was used as a representational medium for the 2D and 3D modelling and visualisation of design geometry by providing designers with an interface to modify views, and to enable walk-throughs within the limitations of Euclidian geometry (Oxman, 2017b). While Jones (1992) asserts that the most frustrating aspect in design is the need to provide cycles of modification and re-modification throughout the design process, the improved modifiability in CAD helps to reduce this frustration. It offers designers the capability of using digital technologies to facilitate design. Moreover, Holzer (2015) states that CAD proved its efficiency in project delivery due to its ability to speed up replication within the design process. In comparison to conventional, paper-based design, the ability of CAD to speed up replications offers designers time to generate more design alternatives. This was highlighted in the previous chapter by Simon (1975, cited in Hudson, 2010) who claimed that all design problems can be solved by searching for a large range of possibilities. In addition, this capability can be enhanced through new features that were later added to CAD systems, such as Bezier and NURBS curves and surfaces. Those features allowed a certain degree of interactive and precise control over smooth, doubly-curved, and complex spaces and geometries (Bhooshan, 2017). The term ‘complexity’ in this context should not be mixed with the complexity of the design process that was discussed in the previous chapter. In this context, Bhooshan refers to the complex geometries that are more controllable through CAD, while the previous chapter discussed the complexity of the problem solving process that increases when more participants become involved in this process in practice (Cuff, 1992; Emmitt, 2014). The

ability to control and interact with more complex geometries in CAD can provide a way to expand the design space by giving access to geometries that might not be controllable with paper-based design. From a more recent perspective, CAD systems are co-evolving with BIM (Building Information Modelling) and CAM (Computer-Aided Manufacturing), which enable a higher level of interoperability (Bhooshan, 2017). This further help to bridge the gap between designing and making, which is the main disadvantage of the reliance on drawings in design (Lawson, 2006).

The previous discussion shows the merits of CAD in improving the level of presentation, and speeding up replications. Hence, this allow more time to explore a greater range of design alternatives and hence, the expansion of the design space with the ability to control and interact with more complex geometries. This is added to the capability of CAD systems in bridging some of the gap between designing and making. However, none of the previous benefits represents a paradigm shift in the design process. They are just merits that facilitate and accelerate the design process without affecting its structure, i.e. they do not result in changes to the sequence of design stages nor do they result in the integration of processes from other disciplines into the design process. Therefore, CAD is not seen as a computational design method. The following sections explore more advanced digital technologies and methods, where the investigation of the benefits of those advanced methods will enable greater maturity when identifying the problems and limitations in CAD systems

### **3.3 Scripting**

The previous section explains the tendency to expand the level of tractable geometric complexity, which is enabled by the ‘new’ CAD features. This tendency appears to be a main factor that instigated the development of new software and modelling techniques to enhance the generation, presentation, and evaluation of complex forms. For this reason, architects have started to shift from using technology as a tool to facilitate design, to interact with their tools in order to expand the functionality of traditional CAD applications. Most software applications, including CAD, that are currently used by designers are provided with scripting platforms that allow a user to modify the application, build more commands or write a chain of commands to form a ‘plug-in’ that can fit specific design purposes. (Burry, 2013, p. 8) defines scripting as ‘the capability offered for almost all design software packages that allows the user to adapt, customise, or completely reconfigure software around their own predictions and modes of working’.

The role of scripting in current architectural practice is highly regarded within practical literature. For instance, Ceccato (2010) states that, in ZHA (Zaha Hadid Architects), scripting is one of the main roles of the research group, which provides teams specialised in scripting for many design platforms during different projects. According to Ceccato (2010), the utilisation of scripting in ZHA helps to increase the level of interoperability between different design and production teams. This means that scripting helps to reduce the loss of information and geometry when drawings and models are exported from one software application to another. Moreover, Katz (2010) argues that scripting can support comparative analysis as the variation of parameters can automatically generate a new model for each value with the ability to generate multiple possibilities for each model. From a theoretical perspective, Burry (2013) argues that scripting has the potential to extend design experimentation by providing both more time for design thinking and a platform for the designer to optimise the design tools. As a result, by adopting scripting, a designer can act as a tool builder. This shows a significant paradigm shift in the design process, where designers move away from using existing tools or technologies to facilitate design, and instead, design or redesign the tools themselves to match their specific intentions in a specific project context. In addition, scripting can be seen as a new level in the design process; this can be traced to Mueller's (2011) definition of the levels of 'designing a facility', where 'designing the tools from which the facility will be designed' is referred to as one of those levels. However, getting the potential of scripting can be threatened by the difficulty of learning scripting by architects as its reliance on programming and coding that contradict with the visual nature of design representations (Lawson, 2006). Indeed, Oxman (2017b) argues that scripting represents a new way of thinking in design, that represents a cognitive barrier for designers.

Having explored the benefits of using scripting and its significant impact on the structure of the design process, it is important to recognise the practical situations in which designers need to modify their tools, the sort of knowledge and skills that are required for scripting, and how designers can deal with these additional cognitive skills. Thus, it is important to explore whether designers themselves can provide scripting, or whether they need to hire specialists from different backgrounds to participate within design teams.



### 3.4 Generative/Algorithmic Design

In addition to the impact of digital technologies and tools on various aspects of the architectural design process, these technologies have resulted in the emergence of new approaches that depend entirely on digital means, and require a totally new sort of knowledge, new experiences, and unique methods of thinking. For instance, the scripting ability has enabled the development of algorithms to generate architectural forms. Meanwhile, Aish and Hanna (2017) use the term ‘direct manipulation’ to refer to the way in which design forms are modified and manipulated within traditional CAD systems. Therefore, using algorithms to generate forms can be described as ‘indirect manipulation’, where designers shift from directly manipulating design forms, to manipulating algorithms in order to automatically generate and edit forms. In this context, Oxman (2017b, p. 10) defines an ‘algorithm’ as “a set of rules written by a source code of explicit instructions that initiate computational procedures that generate digital forms”. Meanwhile, she states that generative models in digital design involve setting generative rules, relations and principles from which shapes and forms can be derived (Oxman, 2006). These two statements are very similar, and in fact, the algorithm in the first definition is referred to as rules, relations and principles in the second definition. Similarly, Frazer (1995) defines generative design as “the expression of architectural concepts as a collection of genetic rules and the digital encoding of their evolution”. These definitions indicate that generative design represents a paradigm shift in the design process, where an algorithm is developed to act as a ‘mediator’ between the designer and the design form in order to enable smart form generation in the design process.



Figure 6: Generative Design: Serpentine Gallery Pavilion (Itō and Belmond, 2002)

One of the projects that effectively exemplifies such a design approach is the ‘Serpentine Gallery Pavilion’ designed by Toyo Itō and Cecile Belmond in London (2002) (Figure 6). In this project, Ito and Belmond provide a very simple algorithm to generate a complex ‘mess of lines’ that in turn, forms the structure of the pavilion (Itō, Arup, Balmond, & Gallery, 2002; Meredith & Sasaki, 2008).

The purposes, benefits and potential of adopting such a design approach is widely discussed in the literature. From a general perspective, Chaszar and Joyce (2016a) state that generative design helps in mitigating some of the limitations of conventional design by providing designers with the capability of harnessing computational power to afford higher levels of speed, accuracy and complexity. Meanwhile, H. Liu (2010) simply identifies the main benefit of generative design as enabling the generation of novel design solutions that might be impossible to achieve when traditional methods are applied. This ability to enable the ‘impossible’ leads to the hypothesis that the potential of generative design can exceed the ‘aiding’ potential of CAD by augmenting the inventiveness of designers (Chaszar & Joyce, 2016a), which results in the ability to discover unprecedented levels of complexity. In this regard, and with more specificity in articulating the potential of generative design in architectural practice, Kolarevic (2004) argues that these kind of processes can shift the emphasis from the external form to the inner logic of the project. This shift can be traced to the previously discussed difficulty in describing design, where the most valuable part of the process occurs inside the designer’s mind and out of the control of their nervous system (Jones, 1992). Therefore, developing an algorithm to generate designs could shift the focus of the designer’s mind into a generative process, facilitating a greater opportunity to describe the design process, rather than just the final product. Furthermore, Chaszar and Joyce (2016a) state that generative systems support two levels of freedom in the design process; on the first level, designers define the generative system itself that determines the global freedoms and what is possible, and on the second level, designers manipulate this generative system to identify local freedoms, and hence, specific design solutions. Thus, unlike CAD, generative design can be seen as a totally new design method that, in most of the cases, has no paper-based counterpart. This is the point at which the concept of computational design starts to emerge, whereby the digital technologies and computational methods are not only used as representational mediums for design forms, but also as integrated parts of the design process itself. In other words, generative design represents a shift from ‘computer-aided design’ to ‘computational design’.

It is, therefore, useful to understand the real impact of this novel design approach on the structure of the design process, and how applicable it is within real practice. Furthermore, it is necessary to identify who can apply this method, and whether it requires a new sort of participant who is purely a specialist in generative design. Besides this, it is important to appreciate whether this is solely enabled by scripting, or whether there are some specific software applications that are dedicated to generative design without the need to mastering scripting. Finally, it is also necessary to recognise the ‘side effects’ of adopting such kind of processes, and more specifically, how designers in practice are dealing with the additional cognitive load required to implement generative design.

### **3.5 Performative Design**

Having explored scripting and algorithmic design, and identified their significant impact in altering the structure of the design process and in allowing access to unprecedented levels of complexity, a key question arises. How is it possible to harness these new digital technologies and methods to mitigate some of the difficulties in architectural design? The main difficulty in design stems from the ambiguity of the design problems (Chaszar & Joyce, 2016); this requires designers ‘to use current information to predict future state, that will not come about until the prediction are correct’ (Jones, 1992, pp. 9-10). This difficulty can be exaggerated at the conceptual design stage where the greatest level of uncertainty is associated with the need to take the most critical decisions (Chong et al, 2009; Duffy, 1993; Wing, 2001; Wing, 2002 in Turrin et al., 2011), with the highest penalties for error (Asimow, 1962, cited in Jones, 1992), and the risk of expensive bills for late changes (Mueller, 2011). Therefore designers may end up thinking, “if we had known at the start what we know now we’d never have design like this” (Jones, 1992, p. xxv). This situation prompts the need to find a computational design method that is capable of reducing this ambiguity and provide sufficient information at earlier stages in order to improve the future expectations. Hence, this could better inform any critical early decision, and potentially reduce the risk of expensive bills for late decisions. Therefore, it is arguably easier to predict the future building form; however, the difficulty lies in providing a reliable and highly-informed prediction for the performance of a future building. Reliable predictions are becoming more critical with the current increase in: natural disasters caused by climate changes (Snell, 2018), carbon emissions (Wright, 2018) and population growth (Carlile, 2014). Thus, a mature and early prediction for the environmental performance of a building alongside its compliance with sustainability requirements is becoming an indispensable necessity. Thus, architectural

practice is moving into performance-based practice, where the observation of structural and environmental building behaviours are shifting into the early stages of the design process, and becoming the main criteria in evaluating the quality of a building (Thomsen et al., 2015). This tendency in architectural practice is referred to as ‘performative design’, which is “a design approach in which building performance, broadly understood, becomes a guiding criteria” (Becker, 1999 in Turrin et al., 2011, p. 658). Oxman (2006, p. 257) defines performative design as, “a process of formation that is driven by a desired performance”. She claims that the current ‘digital tools’ can effectively support performative design due to their ability to connect design and materialisation in the conceptual design stage. In a number of studies, the process of performative design is understood as (amongst others) a set of structural, environmental, acoustical, thermal, and financial information from different disciplines that are incorporated into the conceptual phase of the design process. This information can be represented by a digital simulation, which can provide an early analytical evaluation, allowing for an early selection of solution that offers the optimal performance (Kolarevic, 2004; Oxman, 2006; Turrin et al., 2011). As a result, the focus is shifting away from form-based modelling to performance-based modelling. This results in increased complexity at the conceptual design stage where designers need to deal with a large amount of conflicting and heterogeneous information (Turrin et al., 2011).

Some built projects exemplify this kind of design approach, such as ‘Kunsthau in Graz’ in Austria, designed by Cook and Fournier (2003). According to Kolarevic (2004), the form of this building was slightly modified in the conceptual phase to improve the structural performance of the building. These modifications were based on the structural analysis conducted by ‘Bollinger and Grohmann Ingenieure’, which involves an engineering practice that focuses on technological innovation and sustainable building structures (Bollinger+Grohmann, n/d). Another example is the ‘London Authority (GLA) Headquarters’ in London, designed by ‘Foster & Partners’ (Figure 7), where the pebble-like form of this building is heavily influenced by the energy-performance analysis and acoustical simulation conducted by Arup (Kolarevic, 2004).



**Figure 7: Performative Design: London Authority (GLA) Headquarters in London  
by Foster & Partners**

Performative design is therefore, a design approach that relies on shifting the performance-related information into the early design stages. Therefore, it represents a paradigm shift in the design process as the performative feedback of the building is shifted into the conceptual design stage. Thus, Oxman (2006) argument concerning the capability of ‘digital tools’ to support this kind of design method identifies a question concerning the specific software applications or modelling techniques that best enable performative design. Moreover, it is necessary to establish whether performative criteria can either be embedded within generative systems, or whether specific applications are required that are dedicated to performative design.

### **3.6 BIM (Building Information Modelling)**

The tendency to increase the level of complexity in design forms, and the growing need to enhance the environmental performance of these forms, are resulting in the emergence of a wide range of supporting digital technologies and software applications (Michalatos, 2016). This is, in turn, resulting in increasing complexity within the design process (Oxman, 2006; Thomsen et al., 2015), and is prompting the need to enhance collaboration (Kocaturk & Codinhoto, 2009). BIM is emerging from this need as a state-of-the-art technology to help practitioners collaborate effectively in the management of building projects throughout their lifecycle. It addresses this by automating the flow of information across a project’s platforms, disciplines and stages (Eastman et al., 2011; Eynon, 2016; McPartland, 2017). This section

defines BIM, its dimensions and maturity levels, alongside its benefits and problems in relation to previous methods.

### **3.6.1 BIM Definition**

BIM is an acronym that stands for Building Information Modelling. In any conventional, or CAD-based process, designs are developed by creating a ‘drawing’ or a ‘building model’; however, ‘information modelling’ involves embedding information into this building model. Thus, Holzer (2015, p. 67) states that BIM is “the concept of relating data to geometrical objects that form a digital representation of building component assemblies”, while Eastman et al. (2011) simply describe BIM as ‘an intelligent simulation of architecture’. For their part, Sacks, Koskela, Dave, and Owen (2010) define BIM as “a verb or adjective phrase to describe tools, processes, and technologies that are facilitated by digital machine-readable documentation about a building, its performance, its planning, its construction, and later its operation”.

When using BIM technology in the design process, an accurate digital model is created that contains both geometric and non-geometric information. This model enables automated and direct extractions of various sorts of information, including plans and sections (2-D drawings), quantities and costs, time schedules, and the structural and environmental performance-related information about a building (Eastman et al., 2011; Eynon, 2016; R. Liu & Issa, 2013; Luthra, 2010; McPartland, 2017). These definitions and discussions address most of the questions raised by Lawson’s definition of design (section 2.3), as they show how information is blended, including the variety of information, and automated manner in which blending can occur. In addition, the previous discussion reveals how the design can be presented in the form of integrated models, rather than drawings, as Lawson argues.

### **3.6.2 Dimensions in BIM**

In CAD-based design processes, an accurate 3-D model is normally created that represents a virtual version of building form or building geometry. When relying on BIM applications, different types of information can be embedded into the 3D model to give a richer understanding of building projects and how it will be delivered (McPartland, 2017). Therefore, each type of information is considered a new dimension in design modelling. In this regard, Thomsen et al. (2015) state that BIM is shifting the focus in design modelling from 3-dimensional geometric modelling to an n-dimensional field of divergent,

heterogeneous and conflicting information. While there is consensus about what 4D and 5D BIM entail, the definitions of 6D and 7D BIM are still debatable. In addition, the term nD BIM is widely used to describe its potential to embed any further sort of information into models.

- **4D BIM (time, sequencing):** A building model extends beyond 3D to 4D when adding the time aspect to form schedules (Luthra, 2010). BIM applications make it possible to assign time attributes to different parts in the model (Eynon, 2016), whereby, accurate programme information and visualisations can be obtained to show how the building will be sequentially constructed and delivered (McPartland, 2017).
- **5D BIM (cost, quantity take-offs):** A building model extends to 5D when information about the cost of different components are embedded into the model to enable automated quantity take-off, where the output takes a form compatible with cost planning or estimating software (Eynon, 2016). This information includes capital costs, associated running costs, and renewal and replacement costs (McPartland, 2017).
- **6D/7D BIM (Sustainability, Facility Management and Project Life Cycle Information):** A building model extends to 6D when information about facilities management and operations are embedded into the model (Eynon, 2016; Luthra, 2010; McPartland, 2017). This might include information on the manufacturer of a component, its installation date, and other information about the required maintenance and details of how the item should be configured and operated for optimal performance (McPartland, 2017). In many sources, 6D BIM is referred to as the model that includes information about sustainability, while embedding facility management information is referred to as 7D modelling.
- **nD BIM:** the term nD BIM was coined by the University of Salford. It is used to keep the concept open for further development, so that any sort of information can be embedded into a model to enhance collaboration, coordination, and integration among the different disciplines operating in projects. While the previous sections discuss how the applications that support performative design embed information about building performance into design model, this section explains how BIM applications embed a wider range of information that includes performance-related information.

### 3.6.3 Benefits of BIM

The multi-dimensionality in BIM explained in the previous section allows for the digital representation of both the physical and functional characteristics of a built environment asset. It serves as a shared knowledge resource for information about a facility and forms a reliable basis for decisions during a project's lifecycle, from conception to demolition (buildingSMART, 2014). More specifically, the benefits of BIM can be seen from both the design and managerial perspectives. They are prompted by the limitations of drawings as the dominant method to communicate the architect's design intentions (Jones, 1992; Lawson, 2006), and the practical and managerial difficulties in coordinating work in design projects (Emmitt, 2014). From a design perspective, BIM enables the accurate visualisation of a building. Rather than manually providing drawings, a central model is developed from which a wide range of 2D drawings can be automatically extracted at any time (Eastman et al., 2011). In such a context, BIM responds to Lawson's (2006) urgent call for new forms of modelling that can help to reduce the separation between design and making, and to mollify the resulting combative relationship between project stakeholders that is influenced by the full reliance on drawings. In addition, drawings in design are 'too simple for the growing complexity of the man-made world' (Jones, 1992, p. 27) as they can only show the form of a future building and not its performance. In contrast, a wide range of interdisciplinary information can be obtained with BIM (BuildingSMART, 2014), where the seamless and automated flow of such information (Eynon, 2016) allows for automatic corrections when a part is modified (MacPortland, 2014). This automation facilitates the development and evaluation of energy analysis where the environmental impact of any change can be traced in the real time (Eastman et al., 2011). This can reduce complexity and uncertainty in the design process where impacts caused by the continuous modification and re-modification (Lawson, 2006) can be crystallised earlier, giving designers and other participants the capacity to make better informed decisions. This capability can be enhanced by the singularity of information sources in BIM and the way in which information can be classified, developed, validated and transferred across disciplines and project stages (Eynon, 2016), allowing designers to access valuable information beyond their knowledge and areas of expertise (Jones, 1963). The reliance on BIM can therefore be an efficient alternative to the full reliance on scale drawings that can only be modified by one person, which results in isolating designers from valuable external criteria in the critical early stages of the design process (Jones, 1992).



The difficulties encountered by management when conducting design projects were discussed in the previous chapter. This difficulty stems from the contradiction between the iterative nature of architectural programs and the sequential nature of construction programs (Emmitt, 2014). This is accompanied by another difficulty that stems from the contradiction in priorities amongst different project participants; for example, a design manager prioritises design quality whilst also having to coordinate a range of contractors who are mainly concerned with the commercial and financial impact of the project (Emmitt, 2014). These contradictions also highlight the potential for BIM to reduce omissions and conflicts (Eastman et al., 2011) by offering an integrated platform for different project stakeholders to share diverse, heterogeneous and conflicting information (Thomsen et al., 2015). This can be accessed at any time to facilitate coordination and enable the synchronisation of design and construction information (Eastman et al., 2011). In addition, the critical balance between time, cost and quality is required in order to avoid sacrificing one or more in favour of the other/s (Emmitt, 2014). This balance echoes the dilemma associated with the criticality of decisions taken by design team. Such teams are expected to maintain design quality while also controlling the cost and time, despite their lack of qualifications in cost and time management (Emmitt, 2014). In this regard, BIM's automated approach to creating and exchanging information (Eynon, 2016) enables the extraction of time schedules with the ability to request notifications when changes are made (McPartland, 2017). This function is added to the ability to obtain an automatic count of components and the extraction of cost estimates at any time with acceptable accuracy (MacPortland, 2014). Moreover, this is also coupled with an earlier determination of potential errors (Eastman et al., 2011). All of these capabilities offered by BIM enable project stakeholders to deal with problems, contradictions and conflicts at earlier stages, allowing for the early involvement in design decisions. From Emmitt's (2014) perspective, this would provide all actors with the opportunity to contribute to the different design, detailing and planning stages, in order to achieve high quality design and the elimination of waste at later stages of the project (Emmitt, 2014).

The previous benefits are related to all stages of a building project; however, only some of these benefits are linked to the design process. In fact, the capability of obtaining automatic corrections when a part is modified shows the unlimited modifiability with BIM in comparison to CAD. In BIM, modifying part of the central model results in an automated update of the associated drawings, tables or schedules. In comparison, in CAD designers need to investigate the associated parts that require the relevant manual modification in order

to maintain consistency amongst all elements in the model. This is an important aspect that requires a search for similar capabilities in other computational design methods. Furthermore, a paradigm shift in the design presentation can be identified in BIM; it enables a shift from the creation of drawings for representation, to the extraction of drawings. This means that a set of activities in the design process are automated by a machine, rather than created manually by humans as in conventional and CAD systems. This discussion also shows a potential paradigm shift prompted by BIM, where some activities in the late design, or even construction stages, migrate to earlier stages of the design process. In addition, BIM's design process includes a wide range of non-architectural activities, such as structural and environmental information, time scheduling, and tables for quantities and costs.

### **3.6.4 BIM Mandate**

The previously discussed benefits of BIM led the central government in the UK to mandate the adoption of BIM on all public sector, centrally-procured construction projects by 2016 (MacLeamy, 2012; Tuckwood, 2016). This was followed by a similar mandate for the adoption of BIM in all transportation projects in Germany by the end of 2020 (BIMcrunch, 2015). This situation imposes a need for architectural practices to update their traditional methods in design projects, to explore appropriate strategies for the implementation of new methods.

### **3.6.5 BIM Maturity Levels**

The concept of 'BIM maturity levels' was proposed to provide a concise description and taxonomy of the steps, tools, and techniques required for the process of BIM adoption (Eynon, 2016), and to determine the criteria required for the recognition of practice as BIM-compliant (McPartland, 2014). The following provides a description of each of these levels (Figure 8):

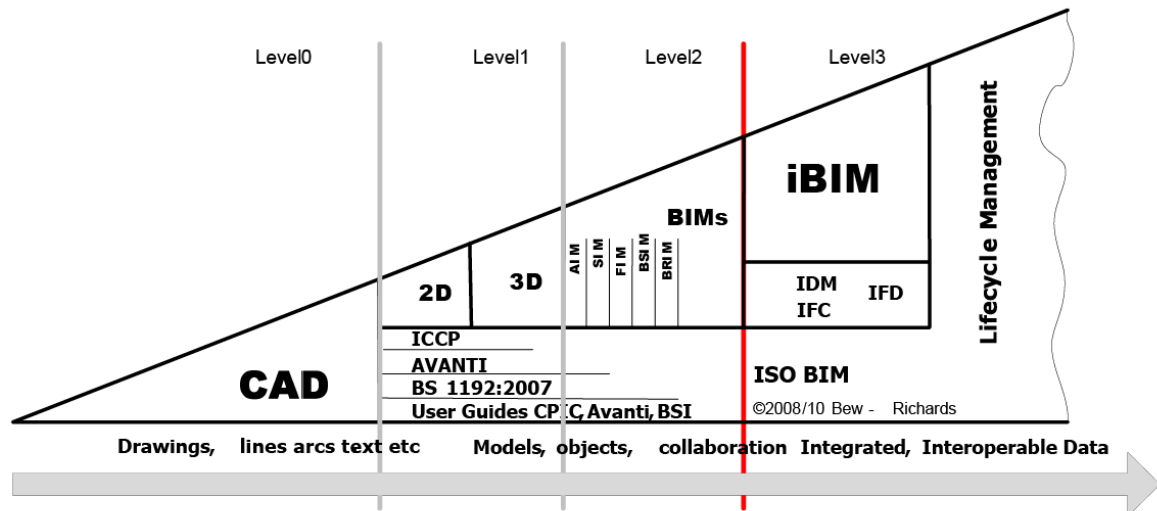


Figure 8: BIM Wedge illustrating the Levels of Maturity in BIM adoption (Bew & Richards, n.d)

- **BIM Level 0:** When unmanaged, CAD (mainly 2-D) is the most likely mechanism for data exchange (bsi., 2013; Eynon, 2016);
- **BIM Level 1:** When 2D and 3D CAD work is managed in order to comply with BS 1192:2007 (BSI, 2007), and where some data is shared for collaboration in a common data environment (CDE). This is often managed by a contractor, but without integration; i.e. without sharing models between project team members (bsi., 2013; Eynon, 2016; McPartland, 2014);
- **BIM Level 2:** This level is distinguished by collaborative working, where each team uses their own model, and the design information is shared through a common file format so that any team can embed these data into their own to form a federated BIM model. The software application used by all teams should be compatible with the common file formats, such as IFC (Industry Foundation Class) (McPartland, 2014);
- **BIM Level 3:** There is still no clear concept of what BIM Level 3 will look like (Eynon, 2016); however, it can be described as the level, where one single, shared project model is developed to enable full collaboration between all project stakeholders. The model is held in a centralised repository giving all parties the authority to access and modify the model (McPartland, 2014).

These levels of maturity reveal the evolution path of BIM, and how this evolution is gradually increasing the level of integration between the architectural design platform and other platforms. It also instigates further discussion about integration and the need to rearticulate this phenomenon in the theoretical context of this research.

### **3.6.6 The Impact of BIM**

In addition to the plethora of benefits that BIM offers for architectural practice and the AEC (Architecture, Engineering and Construction) industry in general, implementing BIM in practice requires various and systematic change in the way building projects are approached, communicated and represented. In this regard, Thomsen et al. (2015) state that the way that BIM allows a wide range of information from different types to flow within an n-dimensional field, triggers deep changes in the way architects work, particularly where the parsing, analysis and calculation of information becomes an integral part of the design representation. Therefore, the role of drawing (Jones, 1992; Lawson, 2006), which dominated design representation for a long time, is being marginalised in favour of the provision of 'Building Information Models', and the management of their associated information. Shifting from vernacular/crafts-based design to 'drawing-based' design offers the capability to split work into standardised components that can be simultaneously crafted by repetitive hand labour. However, BIM promotes a higher level of labour division, where the creation of a central model splits the work into smaller standardised drawings, schedules, tables and information that can be manipulated by different specialists, while maintaining synchronicity with the central model. This division requires the rethink of roles and responsibilities within practice, and demands the establishment of new roles to lead the implementation of BIM in practice (Holzer, 2015). From a different perspective, Thomsen et al. (2015) state that the potential of BIM to focus on component-based delivery and coordination across disciplines, is transforming the whole AEC industry to adopt more lifecycle thinking. This potential can be traced to performative design, where the focus shifts significantly to the performance of a building at the post-construction stage, and this underpins the entire design process from the outset.

These discussions prompt a wide range of investigations into the specification of these deep changes facing architectural practice and successful BIM implementation. It also raises more specific questions about how the roles and responsibilities shift when BIM is implemented, and whether it requires a team of BIM specialists or for design team members to be trained to deal with BIM tools and methods. Furthermore, it is important to identify the strategies that are being developed in practice to enable BIM implementation, and the specific technologies and tools needed.

### 3.6.7 Barriers for BIM Implementation

The documented benefits of BIM and the subsequent mandating of its adoption in several countries has led to an increasing uptake of BIM by multiple professions across the AEC industry, and this is where the disruptive nature of BIM implementations start to crystallise (Holzer, 2015). Implementing BIM is a highly-challenging task, that requires stakeholders to collaborate and interact effectively within an open environment of trusting relationships (Emmitt, 2014). In fact, up until 2011, no documented implementation had fulfilled the BIM criteria (Eastman et al., 2011). This indicates that BIM technology is still in its initial stages, and realising its promising potential should be accompanied with sophisticated strategies to enable successful, efficient and feasible implementations. The first step towards achieving this goal is to investigate the obstacles that might restrict the adoption of BIM in practice.

In this regard, Holzer (2015) reports a variety of such problems based on responses from a wide range of interviewees who have experienced BIM in practice; he states that project leaders avoid engaging with the BIM model development, and hence leave some of the decision-making to less experienced, technical staff. This situation can be viewed from different perspectives; on the one hand, it can be traced back to the power in architectural practice, which may stem from ‘esoteric experiences’ (Blau, 1984, cited in Cuff, 1992) or the ‘persuasive ability’ of an individual conducting a specific type of task (Cuff, 1992). In this case, the ability and experience of the BIM technician offers additional power. This power gives this technician the illegibility to take decision on behalf of the project leader. On the other hand, this situation can result in immature design decisions caused by a BIM technician’s lack of professional and managerial experience. This situation reflects the mixed levels and types of experience outlined in the previous chapter. In this case, the project leader’s level of experience should be used to inform better design decisions, while the BIM technician’s different types of experience should be used to support these decisions. Holzer (2015) raised another related issue concerning the architect’s knowledge; some architects may become involved in BIM-based, integrated design processes without understanding the associated construction needs, and without having a tectonic understanding of how a building is put together. While having some constructional, mechanical and other types of knowledge was highlighted as essential for architects in practice (Cuff, 1992), this can be inflated when BIM is implemented, where more in-depth knowledge in construction and other disciplines appears to be important for the successful coordination. Holzer (2015) highlighted a further problematic situation where some qualified designers may not reveal their technological

skills in order to avoid being recognised as merely technologists who lack creative skills. This recalls Cuff's (1992) observation of the behaviour of architects in practice, where one architect may spend all of their time only in model-making, and this focus impacts on their identity. Thus, hiding their technical abilities can be seen as a way for architects to protect their identity, and maintain their experience and creative skills.

Furthermore, a key obstacle encountered within architectural practices when implementing BIM is the cost of purchasing the software licenses, and the substantial costs required to upgrade computer hardware and network capabilities. This is in addition to the considerable expenditure involved with staff training (Holzer, 2011). This latter expenditure results from the lag in professional and tertiary education in adopting and addressing BIM practice (Macdonald, 2012). While BIM is meant to automate changes and omit conflicts to improve efficiency and save costs, this appears to be accompanied by different costs that contradict one of the essential purposes of BIM. Therefore, it could be argued that BIM is only affordable by large practices or by practices with high budgets. Moreover, its financial efficiency can only be gained by implementing BIM in multiple projects. Moreover, when considering full BIM implementation, where all project participants are given the authority to access and modify models, a new sort of problem arises, as this method of working incites nervousness in the industry around issues such as copyright and liability (McPartland, 2014). This is a critical point that requires further information as it may restrict collaborative work. Therefore, an investigation into the different technologies, methods and ideas that can help to protect copyright in collaborative and integrated work is necessary.

### **3.6.8 Parametric Principles in BIM applications**

In order to understand the true potential of BIM, it is essential to understand the logic of BIM applications, and how they operate. More precisely, it is important to fully understand the mathematical rationale behind the automation of the information flow in BIM software applications.

A wide range of BIM applications are currently available, such as Autodesk Revit, Graphisoft ArchiCAD, and Bentley Microstation (Oynen, 2016). All of these applications operate based on parametric principles by nature (Holzer, 2015), which allows for automation in the information flow, and hence enables a whole project update whenever an item is modified. According to AUTODESK.Help (2014), the parametric relationships in Revit can be established, either automatically by the software or by the user in order to enable

coordination and change management in Revit models. These parametric relationships enable a door that is located at a fixed dimension hinge side from a perpendicular partition to retain this relationship when the partition is moved. Moreover, they enable a floor's edge that is connected to an exterior wall to maintain this connection even when this exterior wall moves, and enable windows that are spaced equally across a given elevation to maintain these equal spaces when the length of elevation changes (AUTODESK.Help, 2014). These examples show the significant power of the parametric principles of BIM applications, which offer exceptional modifiability that is very limited in CAD systems.

The power of the parametric principles in BIM applications are important and may have a ground-breaking impact on the design process, due to their ability to automate different aspects of design. This function includes the provision of performative feedback, the extraction of time schedules and tables, and the ability to automate changes within the geometrical space. This can have a revolutionary impact on the design process and affect a significant change to the structure of its stages and activities. Consequently, it is essential to explore the computational design method that relies entirely on parametric principles. Thus, the following section discusses parametric design.

### **3.7 Parametric Design**

While the new technologies of computational design are the central keystone of the production of new methods and theories (Oxman, 2006; Tamke & Thomsen, 2018), the theoretical basis of parametric design is becoming the nexus of theoretical production of computational design (Oxman, 2017a, p. 1). This section will critically and thoroughly explore the different features of parametric design and its related tools. This focus is motivated by the unique features of parametric design (Oxman, 2017b) that differentiate it from all other computational design methods. In this regard, Schumacher (2009) coins the term 'parametricism' to refer to the inflation of the concept of parametric design, while the crucial 'ism' in parametricism takes on all the stylistic and social intentionality of a movement (Castle, 2016, p. 5). According to Schumacher (2016, p. 10), parametricism is the only architectural style that can take full advantage of the computational revolution that now drives all domains of society. While both Oxman (2017b) and Picon (2016) emphasise the essentiality of investigating historical precedents to understand current transformations, most of the parametric design features are investigated here in comparison to traditional CAD methods.

### 3.7.1 Parametric Design and its Tools

In an attempt to respond to the problem of misunderstanding parametric design (Jabi et al., 2017), a variety of definitions have been provided in the literature. As most of these definitions are short and poor in information, the best way to build a comprehensive understanding of parametric design is to start by understanding what ‘parameter’ means. In this regard, the Oxford Dictionaries (n.d) provides two definitions for a ‘parameter’; in technical terms, “a parameter is a numerical or other measurable factor forming one of a set that defines a system or sets the conditions of its operation”. In mathematical terms, “a parameter is a quantity whose value is selected for the particular circumstances and in relation to which other variable quantities may be expressed” (Oxford Dictionaries, n.d) . Therefore, a parameter is a number that is systematically variable, where the difference is determined by the variability of other parameters within the specific context.

According to Barrios (2005, p. 394), ‘parametric design is the process of designing in parametric modelling settings’. Parametric modelling, in turn, involves the representation of geometric entities along with their relationships through associated components and attributes within a hierarchical chain of dependencies. Based on this hierarchy, each of the geometric attributes is expressed through a parameter. The parameters are then split into independent and dependent parameters, where the independent parameters act as inputs to feed data to the dependent parameters that receive data and apply changes based on this data (Turrin et al., 2011). More precisely, the process enables the dependent parameters to change automatically when the independent parameters change manually, allowing an automated generation of several instances of a basic design form (Turrin et al., 2011). In this light, parametrisation is the process of defining the relations between parameters. This includes which parameters in the parametric model will be fixed, which parameters will vary, which of the variable parameters are independently variable (manually changeable), and which parameters are dependently variable (automatically changeable), together with how the variation occurs, and the range of each variation (Barrios, 2005).

From a more practical, contextualised view, Hudson (2010, p. 22) defines parametric design as the process of developing a computer model or description of a design problem. This representation is based on the relationships between objects and controlled by variables. Making changes to the variables results in alternative models. The selection of a solution is then based on some criteria, which may be related to performance, the ease of construction,



budget requirements, user needs, aesthetics, or a combination of these. In comparison to Barrios, Hudson's definition appears to be brief and less informative; however, it is more practically contextualised as it considers the potential use of parametric design in coordinating work with participants from other disciplines.

Parametric design can be approached through different tools, including object-oriented programming, functional programming, and visual programming (Wortmann & Tunçer, 2017). The latest is currently gaining a wider recognition in parametric design as it makes scripting more accessible for users with limited or no programming skills (Tedeschi & Andreani, 2014) by offering a user-friendly interface (Ercan & Elias-Ozkan, 2015), where designers can manipulate graphical elements to create computer programmes (Janssen & Wee, 2011). This can eliminate the necessity to write computer codes or text-based scripts, which is a substantial cognitive barrier for architects (Oxman, 2017b; Wortmann & Tunçer, 2017). Moreover, it reveals the criticality of recognising the difference between the impact of parametric design as a design methodology, and the impact of graph-based programming that is used as a tool within parametric design. This is addressed in the following sections that split the study into two parts.

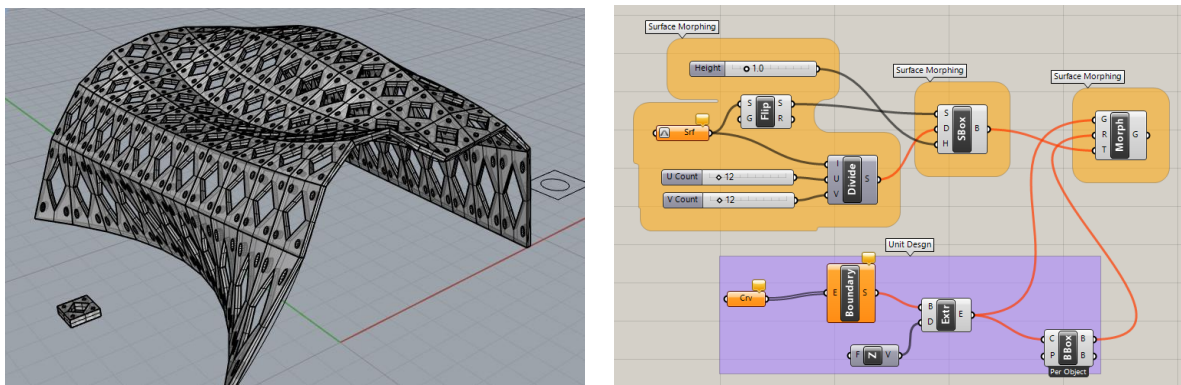
### **3.7.2 Parametric Design Tools and the Modality of the Design Process**

#### ***3.7.2.1 Parametric design tools***

The most popular parametric modelling software applications that rely on visual programming are Bentley's GenerativeComponents™(GC), McNeel's Grasshopper™, and AutodeskDynamo™ (Anton & Tănase, 2016; J. Harding et al., 2012). The proliferation of such tools was mainly facilitated by their affordability, and compatibility with CAAD (Computer-Aided Architectural Design) systems (Holzer, 2015).

In a typical parametric design application, such as Rhino-Grasshopper, the parametric design process relies on a simultaneous and interactive display of the visual image of the design object represented in the Rhino window, and a parametric definition in the form of a visual graph in the Grasshopper window (Oxman, 2017b) (Figure 9). Within this multiple representation, the building geometry is generated automatically while authoring the graph (Harding et al., 2012), i.e. authoring a 'parametric definition' within the graph. This definition consists of associated components (or nodes). Each of these components represent a block of scripting that receives input data from the left-side parameters, and changes it into

output data on the right-side parameters (Khabazi, 2012; ModeLab, 2014; Reilly, 2014). Based on a set of logical algorithmic rules, the parametric definition is built by linking the output parameters of a component to the input parameters of another component (Janssen & Wee, 2011). The result is a single directed acyclic graph (DAG) made up of components and parameters (Harding et al., 2012), that allows a ‘mono-directional and a real-time flow of data’ (Turrin et al., 2011). This process enables automated and direct changes in the design object as some of these components added to Grasshopper can be linked to specific geometrical items in Rhino, where designers can place/remove, associate, and manipulate components and parameters in Grasshopper, and directly observe the results in Rhino (Jabi et al., 2017).



**Figure 9: Simultaneous and interactive display of the graph and the design object**

The previous descriptions of how parametric design tools work reveal a close resemblance between parametric design and generative design, as they both rely on setting rules and developing algorithms to generate forms; however, the difference lies in allowing the automated generation of different options from one single algorithm which is enabled solely with parametric design.

### ***3.7.2.2 Visualising the design process in parametric design tools***

In addition to the previous limitations of drawing discussed earlier in this chapter, Lawson (2011) highlights two design-related issues in the architectural design process caused by the full reliance on drawing and other digital technologies; firstly, architects communicate their design intentions through providing drawings that cannot encapsulate all the design information. Secondly, the symbolic representations used by digital systems cannot properly map the designers’ mental symbolic representations. In this regard, Harding and Shepherd

(2017) convincingly argue that the graph in parametric modelling acts as a cognitive artefact explicitly describing the history of the design development. More precisely, parametric design tools allow for the development of geometric relationships that are visualised in a hierarchical binary tree structure (the parametric graph), which represents a record of the internal logic of the design development process, where external representations act as auxiliaries to the internal representation in the mind (Bernal et al., 2015). This appears to be responding to Lawson's concerns by bridging the gap between the designer's internal visualisation and the digital systems, and allowing designers to explicitly represent their logical formation process (Harding & Shepherd, 2017; Jabi et al., 2017; Oxman, 2017b), rather than relying entirely on drawings (Lawson, 2011). This feature of parametric design applications appears to respond to the need to externalise the internal design thinking within conventional design, where the most valuable and creative activities occur within the designer's mind and outside the control of their nervous system (Jones, 1992). This makes it difficult for designers to explain their mental process (Jones, 1992). Therefore, rather than relying only on a designer's memory to drive design, the graph in parametric design applications represents an illustrated version of this mental process. Thus, the designer can view their formation process history, understand the logic behind their design decisions, and subsequently make better informed decisions.

### ***3.7.2.3 Interaction with the design processes in parametric design tools***

The development of the parametric graph is a new skill in design thinking (Oxman, 2017b), that is becoming an integral part of the design process (Harding et al., 2012). In such a process, designers work at two levels: 1. designing the parametric graph, and 2. interacting with the graph by modifying parameters to generate options and search for meaningful instances (Aish & Woodbury, 2005; Oxman, 2017b). This feature in parametric design tools shows how, within such a design process, designers can interact with the very process, as building the graph is an essential part of the design process, where the components and associations in the graph represent the algorithmic logic of the design process that can be designed, modified and graphically illustrated. This can shift the interest from form making to form finding, where design can be transformed from a predefined fixed design to a process design (Anton & Tănase, 2016, p. 11). While scripting allows designers to interact with and design the tool, which is a new level in design (Mueller, 2011), parametric design allows designer to interact with and design the process itself, which is another level.

Parametric design tools, therefore, appear to be changing the modality of the design process, as the process of structuring the graph is an integrated part of the design process (Harding et al., 2012) that can be visualised and interacted with. It could be argued that the new parametric design tools allow designers to objectify the process. In this case, the reusability of the parametric graph in other contexts (Aish & Woodbury, 2005) enables this graph, and therefore a piece of the design process, to be recycled in another design project, which in turn, can shift the focus from recyclable buildings to recyclable processes. Furthermore, the ability to record history of form generation within a graph (Harding & Shepherd, 2017), together with the reusability of graphs across different projects (Aish & Woodbury, 2005) can lead to the assumption that parametric design applications are the ideal tools to empower the building seed concept (Carlile, 2014). This assumption, emphasises the need to explore this capability within real projects in architectural practice, where parametric definitions can be reused in different design scenarios to grow different shapes across diverse project contexts.

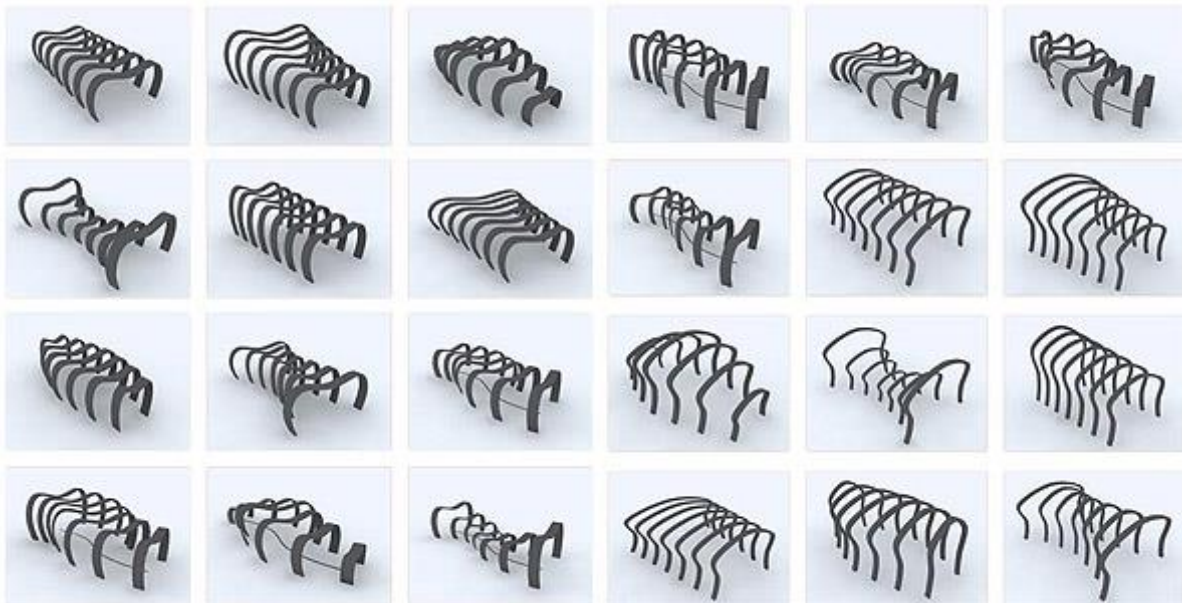
### **3.7.3 Parametric Design and the Flow of the Design Process**

While the previous section focused on the impact of parametric design tools on the design process, this section focuses on the impact of parametric design (as a design methodology supported by the tools) on the flow of the design process. This includes the capacity of the design space achievable, the flexibility and modifiability in the parametrically-driven processes and their impact on the pace of the design process, and the role of parametric design in collaborative environments and in supporting sustainability.

#### **3.7.3.1 Capacity of the Design Space**

According to Bernal et al. (2015), one of the challenges of computational design approaches lies in supporting a divergent early design process. This has to respond to the limitations of tractable geometrical forms, and the limited number of variations achievable using conventional methods (Chaszar & Joyce, 2016a). Dealing with such a problem is one of the main features of parametric design in which a wide range of design instances and variations can be explored (Figure 10), generated and tested simply by manipulating parameters (Barrios, 2005; Bernal et al., 2015; Chaszar & Joyce, 2016a; Hudson, 2010; Mueller, 2011; Turrin et al., 2011). This can give designers access to a much wider (or even infinite) design space (Aish & Woodbury, 2005; Anton & Tănase, 2016; Wortmann & Tunçer, 2017). The seamlessness and immediacy in generating and testing design possibilities in parametric design often leads designers to unexpected routes, unconceived geometrical configurations,

and unexplored design solutions (Jabi et al., 2017; Turrin et al., 2011). Chaszar and Joyce (2016a) refer to this phenomenon as ‘happy incidents’, whereby favoured design decisions are taken based on unintended results. This point was highlighted in the previous chapter, where Cuff (1992) explains the difficulty of undertaking a design process in practice and the complexity of the different activities that often result in ‘surprising endings’. The previous discussion shows how parametric design can transform those ‘surprising endings’ (Cuff, 1992) into ‘happy incidents’ (Chaszar & Joyce, 2016). Therefore, it could be argued that the significant explorative power of parametric design can lead to design solutions that are not only beyond the reach of other computational methods, but also beyond the designer’s perception.

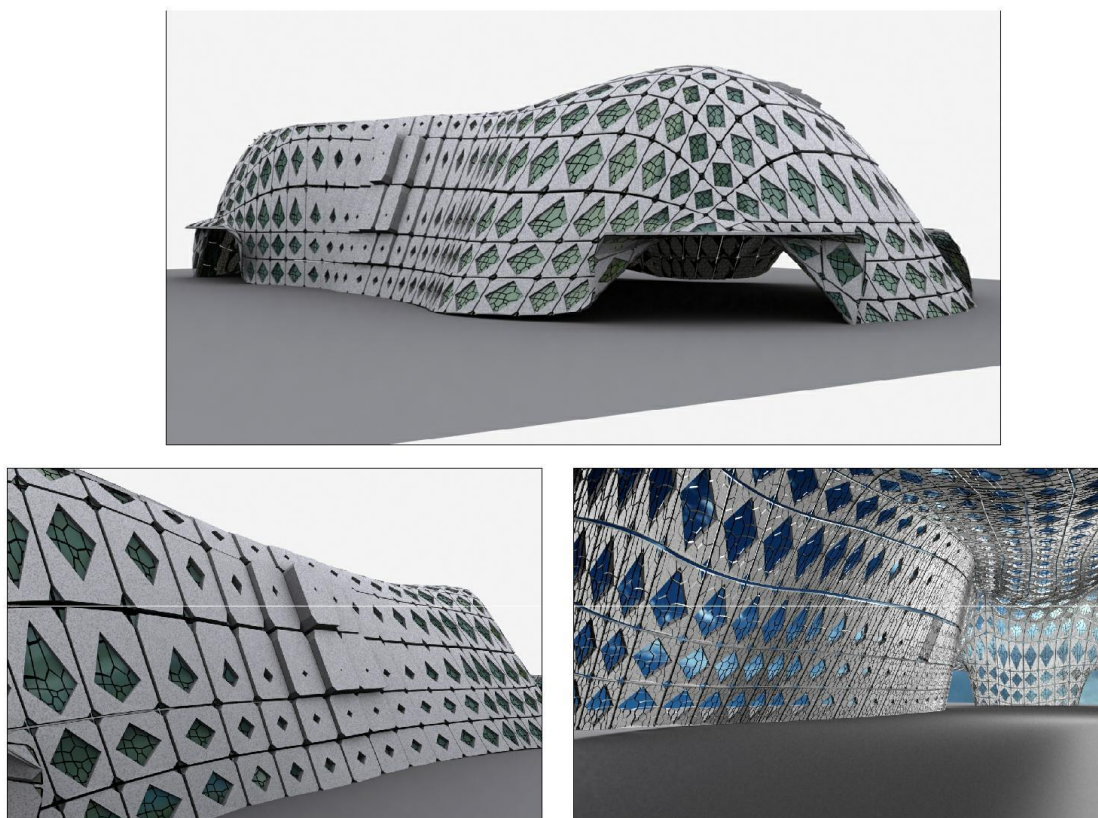


**Figure 10: Parametric design: the ability to explore several instances for the same basic design idea.**

Adapted from <http://www.designcoding.net>

Another challenge that new digital systems need to address is ‘the syndrome of repetition’ in conventional systems that contradicts ‘the dynamism, the constant change, and the minute incremental variations of the real world’ (Oxman, 2006, p. 37). To confront this challenge, parametric design systems enable new design strategies based on differentiation, which can be defined as ‘a type of topological parametric versioning schema that differentiates a formal topological pattern of the design in response to functional and contextual environmental goals and constraints’ (Oxman, 2017b, p. 28). Differentiation (Figure 11) offers designers richer architectural experiences by enabling the integration of environmental, structural and buildability concerns into the design process (Wortmann & Tunçer, 2017, pp. 173-174).

Kocaturk (2017) states that the new computational design technologies enable the exploration and rationalisation of ‘vastly complex building forms’, and the ability of parametric design in generating differentiated geometries can be a perfect example, where the level of complexity achievable is beyond the reach of any other CAD- or BIM-based methodology (J. Harding et al., 2012; Wortmann & Tunçer, 2017).



**Figure 11: A doubly-curved surface consisting of environmentally-informed differential panels: Concept Design by Adonis Haidar, University of Salford (2009)**

Parametric design can quantitatively and qualitatively expand the design space; in terms of the large number of variants that can be explored, while also providing the ability to explore complex forms which can later support the quality of the building performance. This results not only in a significant acceleration of the design process (Janssen & Wee, 2011), but also in improving the quality of buildings and their performance. This can be attributed to the ability in parametric design to pushing the generation, manipulation and evaluation of complex designs into the early stages of the design process, where the most impactful decisions are taken (Harding et al., 2012).

### **3.7.3.2 Flexibility and Modifiability**

The implicit methods in CAD have struggled with the interpretation of complex development processes, where a simple change in the initial stages often results in a complete re-run of the process (Harding & Shepherd, 2017). For their part, Jabi et al. (2017) attributes this limitation to the poor editing environments in CAD systems, while Aish and Hanna (2017) argue that these systems rely on direct manipulation, which offers flexibility in the initial sketching stage. However, changing and modifying shapes becomes cumbersome in the development stage, as it often requires the deletion and recreation of the design model. Thus, in CAD applications, only the final result of the design object is displayed and the history of the process is kept implicit. Harding & Shepherd (2017) refer to this issue as a fragile link between the ‘genotype and the phenotype’. This situation illuminates the potential of parametric design in addressing this fragile link, whereby parameters are associated to enable revisits and changes to previous modelling operations. From this, it is then possible to automatically and immediately update the final model (Aish & Hanna, 2017). In fact, parametric design tools, such as Grasshopper and Dynamo, keep a history of the design development process (the graph), where the design object is linked to its formation history through changeable parameters, allowing designers to access real-time feedback when exploring variations, rather than iterating the process manually (Chaszar & Joyce, 2016a).

These features in parametric design appear to be a paradigm shift in the design process, as it challenges the definition of the design stages, and changes their sequence by enabling a direct link between the conceptual design stage and the final stage, where any change in the initial steps of the design results in automated update to the final result. This seamlessness and flexibility in the design process offered by parametric design has the potential to significantly accelerate the design process, which reveals a different aspect of sustainability, since this acceleration can reduce working hours and energy consumption within the design process, resulting in sustainable ‘processes’.

### **3.7.3.3 Parametric Design and Collaboration**

When considering innovation in architecture, Kocatürk and Medjdoub (2011) argue that innovative architectural practices should not focus merely on adopting technology, but on harnessing digital technologies to structure and coordinate collaborative and multi-disciplinary design intelligence. In this regard, the explicit nature of modelling with parametric design provides the opportunity for different participants to engage more in the

process, which is not the case when relying on ‘black box tools’ (Harding & Shepherd, 2017), such as CAD tools. Indeed, Jabi et al. (2017) attribute this capability in parametric design to the explicit, repeatable and communicable relationship between the design intent and design response offered by parametric modelling tools.

Within the same context, Bhooshan (2017) attributes the difficulty of supporting collaborative and interdisciplinary working in AEC practice to the difficulty in exchanging geometry between the edit-friendly CAD applications and the numerically-biased CAE (Computer-Aided Engineering) applications. To address such a problem, parametric design methods enable designers to test the constructability of architectural geometric building components (Holzer, 2015). More precisely, parametric design allows for the testing of design variants against specialist criteria, where the design form can be translated into buildable components and the construction documents can be extracted automatically from parametric models (Hudson, 2010). Furthermore, the new advances in fabrication technology alongside the seamlessness and rationality of information flow in parametric applications result in an enhanced tectonic relationship between design and fabrication (Oxman, 2017b). In such a situation, the fabrication processes are integrated into parametric systems, where the manufacturing data can be obtained directly from parametric models (Oxman, 2017b). In general, parametric modelling applications enhance the integration between architectural design and engineers in collaborative environments, where different processes, such as materiality, fabrication, structural engineering, and environmental design, represent integral parts of the architectural design process (Bhooshan, 2017). This represents a substantial paradigm shift in the design process and challenges its definition. In parametric design, activities from other disciplines are incorporated into the core of the design process and shifted into earlier stages. From Kolarevic’s (2004) and Oxman’s (2017b) perspectives, this integration results in digital continuity in the design process, from design to production. This indicates another potential paradigm shift in the design process, where the design stages in parametric design could be integrated into one single continuous stage.

#### ***3.7.3.4 Parametric design and sustainability***

The irresponsible energy consumption, and the resulting climate change and natural disasters (Snell, 2018) are pushing architectural practice towards an emphasis on the environment, energy efficiency and minimal waste (Bashir, Ahmad, Sale, Abdullahi, & Aminu, 2016). Hence, sustainable design is being more and more associated with design innovation



(Kocaturk, 2017). In this regard, one of the main concerns is to find methods to shift the provision of the environmental performance of buildings into the early stages of the design process (Mueller, 2011; Thomsen et al., 2015). This is where the value of parametric design arises, as it allows variations, iterations and feedback loops to be automated from the early design stages (Bernal et al., 2015; Hudson, 2010). This potential in parametric design can be enhanced either by connecting parametric design tools into simulation software, or by adding built-in components inside parametric design applications (Ercan & Elias-Ozkan, 2015). A variety of analysis software, such as Ecotect, EnergyPlus, Radianc, Daysim and OpenStudio, are available that can be used in combination with parametric modelling in order to influence design form, as opposed to its environmental performance (Anton & Tănase, 2016). Furthermore, new plug-ins dedicated to environmental performance have been developed recently, such as Ladybug, Honeybee, Diva and Geco. These applications can be integrated into the parametric definition in Grasshopper, so that the environmental performance can be analysed and evaluated directly in the parametric model (Ercan & Elias-Ozkan, 2015; May, 2018).

All the previously discussed aspects show the different ways in which parametric design can significantly accelerate the design process by offering flexibility, automation and synchronicity in generating and evaluating a wide range of design alternatives and by integrating architectural and engineering platform to enable digital continuity and hence, to avoid interruptions of the workflow within the design process.

#### **3.7.4 Parametric design and BIM**

The previous sections describe parametric design's capability of incorporating structural, constructional, fabrication and performative information into parametric definitions, where different sorts of information can be exchanged and obtained from parametric models. This resembles the purpose of BIM applications, which support the same tendency and suggests that parametric design applications can be seen as BIM tools that support the integration of multidisciplinary information within one platform. The resemblance can be attributed to the common features between parametric design applications and BIM applications in terms of their reliance on parametric principles. This shows how BIM, as a concept, is rooted in parametric modelling, which raises a spectrum of critical questions about the relationship between parametric design and BIM. More precisely, it questions the similarities and differences between modelling with parametric applications and modelling with BIM

applications. It also queries the relevance of parametric design and BIM in the process of developing innovative strategies in architectural practice, and whether parametric models can be used to augment the function of BIM applications or considered as BIM tools in their own right. Moreover, it is also important to establish whether it is theoretically and practically possible to use parametric applications for BIM-related purposes, and whether there are examples of this. If there are examples, it is useful to determine the added-value of using parametric modelling applications, rather than the actual BIM applications. This study explores the possible responses from practice in Chapter 6.

### **3.7.5 Centrality of Parametric Design**

Among the uncertainty and complexity of design problems in paper-based design, the limitations of CAD applications in supporting divergent design stages, the cognitive barriers of scripting, the singularity of design solutions in generative design, the shift towards performative modelling and the parametric principles of BIM applications, parametric design is emerging as a unique design methodology in order to implement the other computational design methods, push some of their limitations, and eliminate some of the difficulties and barriers.

Parametric design can respond to the need to externalise a designer's internal thinking process (Jones, 1992) by enabling its illustration and visualisation (Harding & Shepherd, 2017; Jabi et al., 2017) in the form of a graph (Harding et al., 2012), with which the designer can interact (Oxman, 2017b) to enable more informed and explicit design decisions. Parametric design applications can also be added as plug-ins to some existing CAD applications with a high level of compatibility (Holzer, 2015) in order to augment their functionality and push their limitations into much more complex and associative geometries that are beyond the reach of any CAD method (Harding et al., 2012). In terms of scripting, parametric design tools offer designers visual platforms (Wortmann & Tunçer, 2017) to build scripts based on dragging and placing nodes (Aish & Woodbury, 2005) without the need for programming experience (Tedeschi & Andreani, 2014), which can eliminate some of the cognitive loads of text-based scripting (Oxman, 2017b). With regard to algorithmic design, parametric design can replace the singularity of design solutions in algorithmic design with a multiplicity of a wide range of automated and contextualised design instances for a much wider design space (Chaszar & Joyce, 2016; Hudson, 2010). Parametric design is becoming

the cornerstone in performative modelling (Oxman, 2006), and hence it has proven a high level of efficiency in supporting sustainability (Eltaweel & Yuehong, 2017; Imbert et al., 2012). Furthermore, parametric design offers designers the capability of integrating construction, fabrication and performative information into its models (Bhooshan, 2017; Ercan & Elias-Ozkan, 2015; May, 2018; Oxman, 2017), which is the same capability that BIM applications offer. This similarity can be attributed to the same parametric principles contained within both types of application.

The previous discussions about the benefits and potential of parametric design have highlighted the centrality of parametric design in developing innovative strategies, and raised the necessity of exploring these facets within real practice. More precisely, they have raised questions as to which of these benefits are achievable in the real-practice, rather than just theoretically possible. Furthermore, they have also questioned the real design situations in which parametric design makes sense through producing positive results, and how possible/impossible, effective/ineffective is it to achieve the same results using traditional CAD methods. Finally, the previous discussions raise questions about the problems or ‘side effects’ of parametric design, and the factors that may restrict its effective use in practice.

### **3.7.6 Problems and Limitations of Parametric Design**

Despite the potential of parametric design to offer solutions to problems experienced by previous methods, it also brings problems, restrictions, and negative impacts. This section considers these problems from different perspectives, where the problems are classified into design-related, parametric graph-related, and abstraction barrier problems

- ***Design-related Problems***

According to Turrin et al. (2011), the main challenges that designers encounter when working with parametric design are:

- The difficulty and time-consumption of providing performance-based optimisation, due to the breadth of design space;
- The lack of completeness in parametric models, which can be attributed to the high level of computation needed to generate alternatives when trying to completely represent the design in parametric development;

- The limitations that might be provoked by the mono-directional flow of information in parametric systems (Turrin et al., 2011).

To address the problem provoked by the ‘myriad of generated alternatives’ in the parametric design process, Turrin et al. (2011) provide a method to effectively explore the expansive design space. This relies on a combination of parametric modelling and genetic algorithms to enable automated performance-based optimisation.

- ***Graph-related Problems***

Nevertheless, the potential within the explicit nature of parametric modelling to support collaborative processes can be threatened as the parametric graph quickly becomes extremely complicated and incomprehensible, which significantly reduces the chance of external involvement (Davis, Burry, & Burry, 2011). To address this problem, Harding and Shepherd (2017) propose the ‘Meta-Parametric Design’ approach which combines parametric modelling and genetic algorithms using a plug-in, called ‘Embryo’. The plug-in automatically generates graphs that are connected to the manually-generated ones, in order to simplify the structure, and hence, give an overall feel of the design space.

The power of parametric design to quickly generate differentiated panels and seamlessly explore variations through the creation of logical algorithmic reasoning is confronted with obstacles in practice. According to Harding and Shepherd (2017), the time needed to develop such a process is the reason why conventional methods are still popular. Moreover, another problem associated with parametric modelling tools is the lack of integration with the host application, where the geometry generated in the parametric application can only be located on the host application through ‘baking’ (changing the parametric model into a CAD model). In such cases, the model loses its connectivity with the parametric model, as the baking operation cannot be reversed (Aish & Hanna, 2017).

- ***Abstraction Barriers-related Problems***

In an attempt to understand the reason for the misunderstanding and marginalisation of parametric design in practice, Aish and Hanna (2017) complain that the terminology and metaphors used in describing components and functions in parametric modelling applications (such as, trees, branching, and grafting) often replace underlying concepts, such as arrays and collections. This results in additional cognitive loads that are needed to enable users to translate terms and metaphors between the logical and geometrical spaces (Aish & Hanna,

2017). Furthermore, this feature in parametric design applications appears to exacerbate the difficulty in listing, classifying and measuring these types of knowledge (Lawson, 2011) triggered by designers' reliance on tacit knowledge (Plowright, 2014). This contradicts the assumption that graph-based parametric design applications can eliminate the cognitive barriers in scripting (Ercan & Elias-Ozkan, 2015; Tedeschi & Andreani, 2014) as it is accompanied by other types of cognitive loads for designers.

This section responds to Jabi et al.'s (2017) inquiry about the misunderstanding of parametric design, and Schumacher's (2009) concern regarding the marginalisation of 'parametricism'. Therefore, this study investigates how these problems are tackled and addressed in practice, while exploring further issues by classifying them into user-related and tool-related problems.

### **3.8 Chapter Summary and the Theoretical Framework**

Within this chapter, a narrative is created that shows how architectural design methods have been evolving in parallel to the rapid evolution of digital technologies. This is achieved by defining a variety of representational, generative, performative, BIM and parametric-based methods, and by investigating and comparing the benefits, potential and limitations of each of these methods.

Within this chapter, the theoretical framework started to crystallise, in that the emergent concepts from the previous chapter were used to analyse the impact of new computational design methods in this chapter. For instance, this chapter emphasised the need to recognise the different context in which the term design complexity is used as it can refer to form, and process complexity. In terms of form complexity, this chapter has explained how the advanced tools in CAD enable ease and seamlessness in creating and modifying complex forms, and hence offer designers more time to explore a wider design space. In addition, the chapter discusses how generative design enables the exploration of an unprecedented level of form complexity through the development of simple algorithms. This was discussed further in the parametric design section where the associated parameters enable the automated generation, alternation and evaluation of even higher levels of complexity. This shows the increasing process complexity in performative design caused by the incorporation of a wide range of structural and environmental performative information within the conceptual design process.

The previously established link between process complexity and coordination in collaborative work was further emphasised within BIM. This was investigated by exploring the demand for increased coordination required when BIM is implemented in design within practices where designers need to manage and coordinate different types of conflicting, heterogeneous and interdisciplinary information within integrated platforms. This was linked to collaboration and the social aspect of architectural practice that is discussed in the previous chapter. The link shows the potential for BIM technologies to support collaboration by offering an integrated platform and an automated and seamless way in which to transfer, exchange and synchronise information across different disciplines and project stages. Moreover, parametric design applications have the potential to support collaboration, due to its documented ability to integrate structural, constructional, environmental, performative and fabrication information into design models.

Furthermore, this chapter established a relationship between the digital technologies and methods and the designer's knowledge and experience. More specifically, 'scripting' and 'algorithmic design' highlights the necessity of programming knowledge that enables designers to adapt tools to match design intentions, while 'BIM' shows a designer's need for more in-depth knowledge on building structures and how the structural components can be assembled. The chapter explained that this would allow designers to achieve more effective coordination with engineers and other project stakeholders. In addition, the chapter discussed the new sorts of knowledge needed to enable designers to deal with parametric definitions that use a completely different language from traditional CAD applications.

The concept of knowledge acquisition was further developed from the previous chapter, to also consider the re-usability of parametric definitions across different projects. Furthermore, different concepts that emerged from the previous chapter were discussed in more depth in this chapter, such as; design alternatives, design, space, and future expectation. These aspects were discussed across different sections within this chapter, and were discussed at length in the context of 'parametric design'. The chapter explained the ability of parametric design to automate the generation of a large number of design alternatives and consequently, to explore a significantly wider design space alongside the associative parameters that enable automated and real-time updates in the final results when any change is made to previous steps. This, in turn, enables better expectations of the resultant future form.

In addition, the chapter identified the different paradigm shifts in the design process caused by the use of the different computational design methods and their associated software applications. The chapter showed how scripting enables a shift from using design tools to adapting the tools to match design intentions, thus representing a paradigm shift in architectural design. The chapter also explained that algorithmic design enables a remote control over the design product through the manipulation of algorithms, rather than the direct manipulation of the design form. Moreover, the chapter showed how the performative evaluation stage shifts to the early design stages and how different non-architectural activities can be undertaken within the conceptual stage of the architectural design process.

It was also explained that BIM represents another paradigm shift where coordination and feedback from other disciplines integrate within the early design stages, and the production of drawings in conventional and CAD-based design can be replaced by the automated extraction of machine-produced drawings from a central BIM model. This paradigm shift was further discussed by showing how the loop of ‘generation, synthesis and evaluation’ in conventional design can be totally automated in parametric design through the associated parameters that enable the automated generation, modification and evaluation of different design alternatives. Moreover, the chapter explained that parametric design applications enable the design process to be objectified, visualised and interacted with through parametric graphs.

These paradigm shifts add an essential concept to the theoretical framework, namely, ‘the design process’ and support a more in-depth investigation of the impact of digital technologies and computational design methods on the architectural design process. Moreover, the assumption regarding the relevance of digital technologies and computational design methods, which forms one of the aspects of the initial framework, was challenged in this chapter. The term ‘parametric design’ contains a fundamental difference between parametric design as a design methodology, and the node-based applications that are used within parametric design.

The value of this chapter lies in the specificity of investigating the real impact of digital technologies on architectural practice. In fact, many articles and academic papers involved in such an investigation focus on the impact of ‘digital technologies’ in general without specifying which digital technologies result in such an impact, and this can undermine the comprehensibility of the whole work. digital technologies are vast and various, and have different and sometimes contradictive impacts when it comes to architectural practice.

Therefore, this chapter has explored the digitally-based design approaches applied in architectural design in order for the impact of those approaches to be specifically and accurately investigated in the next chapter.



# CHAPTER FOUR

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## 4 Recent Phenomena in Computational Design

### 4.1 Introduction

Having clarified the historical evolution of ‘computational design’, and investigated the potential and the limitations of emerging computational design methods, this chapter looks at present phenomena in this area. Phenomena is plural for phenomenon. According to ‘Oxford Dictionary’, a phenomenon is ‘a fact or situation that is observed to exist or happen, especially one whose cause or explanation is in question’ (Oxford, n.d). Based on this definition, this chapter explores the ‘situations’ that are emerging from the adoption of digital technologies and computational design methods in design processes within the architectural practice. This is motivated by the fact that ‘the cause or explanation’ of those situations is still ‘in question’ due to the novelty and the rapid growth of the digital technologies in addition to the minimal reliance on those technologies in the majority of architectural practices, despite the sensational results that a minority of practices can achieve based on those technologies. According to ‘Cambridge Dictionary’, a phenomenon is ‘something that exists and can be seen, felt, tasted, etc., especially something unusual or interesting’ (Cambridge, n.d). In the context of this chapter, this ‘thing’ refers to radical and transformation changes and shifts in the way a design project is approached in practice caused by the rapid evolution of digital technologies. These new design approaches represent ‘something unusual or interesting’ as they are resulting in a series of paradigm shifts in the architectural design process as discussed in the previous chapter.

Therefore, this chapter critically investigates the impact of digital technologies and computational design methods applied in practice on the architectural design process and its related theory. To achieve this, a taxonomy is created to investigate which design aspects, activities, and stages are affected, changed, or shifted. Through this taxonomy, it is intended that recent phenomena in digitally-driven design processes are classified with more accuracy and specificity within the investigation. In this regard, it is important to note that the changes and shifts in the design process investigated here do not apply for the whole architectural practice, due to the fact that the majority of the architectural practices around the world are still following a traditional path. The outcome of the previous chapter will help to identify the

potential of digital tools for the architectural design process. This will be achieved by referring to some of the discussions on the specific computational design methods explored in Chapter 2. Similarly, the outcome of Chapter 1 will also be used to further explain the changes and shifts in the architectural design process. Thus, some discussions will refer to the specific design stage, design activity, method or practice, or managerial aspects explored in Chapter 1. In addition, this chapter identifies the problems that practitioners may encounter when applying the different digital technologies; thus, the ‘dark side’ of digital technologies is investigated to help in developing a fuller picture regarding the potential and limitations of computational design. The outcome of this chapter will represent the initial version of the theoretical framework that will inform areas of investigation in the subsequent chapters.

## **4.2 Recent Phenomena in Computational Design**

Within the rapid evolution of digital technologies, new computational design methods are emerging that are resulting in unprecedented and rapid transitional changes and shifts in architectural practice (De Rycke et al., 2018; Haidar, Underwood, & Coates, 2017; Kocaturk, 2017). In this context, Fürnkranz J and Hüllermeier E. (2010) in Holzer (2015) argue that these computational methods are not only optional approaches awaiting effective inclusion within the design process, but are silently becoming the norm within practice.

### **4.2.1 Complexity**

Digitally-driven design processes are characterised mainly by a high level of complexity (Mitchell, 2005 in Oxman, 2006). In fact, even in conventional design theory, design is described as a complex process that is “full of ‘messy activities’ and requires, “iterative attempts to solve ‘wicked’ ill-defined problems using incomplete knowledge and imperfect methods” (Chaszar & Joyce, 2016a, p. 167). However, the literature shows that the complexity and multiplicity of the new digital tools, software, and methods applied in computational design are making these processes even more complex. This view can be traced to Oxman (2006, p. 240), who states that an intensive nomenclature is emerging to help in identifying names for the ‘sub-tasks’ and ‘sub-phases’ within a design process, which in turn, help in crystallising the increasingly complex processes of design. Thus, the traditional representation of design as a “staged, linear/cyclical process is being replaced by another, which is more particularised taxonomically” (Oxman, 2006, p. 240). This shows how complexity in computational design results in changes to the structure and hierarchy of the design process through changing the sequence of its stages, and by adding more sub-

stages. To address this increasing complexity, Mueller (2011) argues that these new situations in computational design have an indispensable need for standardisation to reduce the complexity, and this results in a shifting the focus towards the management of complexity (Whitehead et al., 2011).

These previous arguments lack specificity in describing complexity. In Chapter 1, complexity in the design process (Cross, 2011) is regarded to the ambiguity, ‘wickedness’ and uncertainty of design problems (Chaszar & Joyce, 2016; Rittel & Webber, 1973 in Hudson, 2010), the obscurity, subjectivity and indeterminacy of the type of experiences and knowledge needed to solve design problems (Lawson & Dorst, 2009; Lawson, 2011; Plowright, 2014), and the need to provide reliable future expectation using insufficient information at the early stages of design (Jones, 1992). In response, Chapter 2 reveals the potential of the different computational design methods in accelerating the design process, automating the flow of information and automating the generation and evaluation of design alternatives in order to reduce uncertainty of design problems, obscurity of information and provide better future expectation for the design product. From this basis, the computational design methods can be seen as methods to facilitate and simplify the design process not to increase its complexity. However, the previous chapter shows some situations in which computational design that results in increasing complexity in the design process. While Cuff (1992) and Emmitt (2014) attributes complexity in the design process to the need to coordinate work with various participants in practice, the previous chapter shows how more intensive coordination is needed when using performative design, or when implementing BIM. This indicates that applying those methods can indeed increase complexity.

The purpose of complexity has started to crystallise in recent literature; for instance, Thomsen et al. (2015) attribute the growing complexity of design models to the need to embed the predicted behaviour of buildings into design models within nonlinear and multi-scalar relations. In this regard, Turrin et al. (2011) state that the tendency in computational design to embed different sorts of structural and environmental performance-related criteria into the conceptual design stage results in the stage becoming stuffed with heterogeneous information and processes from different disciplines. This therefore, results in a difficulty in driving this stage due to the increasing complexity. This argument identifies a purpose for increasing the complexity in the conceptual stage, it is self-evident that this complication in the early design stages is meant to facilitate and simplify later stages. Therefore, investigating complexity in computational design processes, should be accompanied with a critical

investigation of the aspects of simplicity that result in specific activities or stages within the design process.

#### **4.2.2 Emergence of New Roles**

The increasing complexity in some aspects of computational design processes is resulting in the emergence of new roles that are needed to manage this intricacy, such as, software developers, parametric designers, geometry specialists, sustainability specialists, BIM technicians, and 3D visualisers or scripters (Ceccato, 2010; De Kestelier, 2013; Hesselgren & Medjdoub, 2010; Katz, 2010; Whitehead et al., 2011). Architectural practice has already started to adopt BIM technology where the radical increase in the information content is challenging the capacity of a project architect who needs to deal with this substantial flow of information (Holzer, 2015). Such a situation has redefined the role of a project architect, and resulted in a growing need for specialists in information management, data integration, and multidisciplinary coordination in order to enhance efficiency in the information flow (Holzer, 2015). In some cases, this wide variety of roles and areas of specialisation within architectural practice exceeds the field of the built environment; for instance, most of the design teams at ZHA (Zaha Hadid Architects) are provided with software developers who work closely with designers to adapt the tools and make them more effective (Ceccato, 2010). Meanwhile, Foster + Partners and its in-house research groups have artists, mathematicians and an aerospace engineer who work within their teams to develop tools and solve complex geometry issues (De Kestelier, 2013; Foster+Partners, 2013a).

This section provides a response to the questions raised in the last chapter about the new roles needed to enable the adoption of BIM in the practice. However, this expeditious emergence of new roles incites the need to articulate the shifts in the skillsets needed for a designer to be effectively involved in projects within such digitally-enhanced environments and multiplicity of roles. They also raise questions about the power (Cuff, 1992) that can be gained relatively to those roles, in addition to the impact of those roles on the identity (Cuff, 1992) of practitioners that might change significantly when appointed to those new roles. Moreover, there is a need to investigate the temporality and the permanence of these new roles, or, in other words, whether these are permanent, or just temporal roles that are dedicated to lead a transitional period. Hence, it is necessary to establish how roles are changing over time.

### 4.2.3 Collaboration and Interdisciplinarity

The high level of complexity and the multiplicity of software applications and other digital tools alongside the emergence of many new roles in architectural practice are resulting in an increasing need for collaborative and interdisciplinary work environments, in which ideas are shared, information is transferred and experiences are coordinated.

#### 4.2.3.1 *The need for Collaboration*

Kock (2009) in Vannella (2017), defines collaborative design as ‘a design task performed in a dispersed group of workers with a joint collaboration objective’. Such group work is not a recent phenomenon in architectural design. In fact, many authors over time concentrate on the social aspect of architectural design and the need to work and think collectively to overcome challenges in design projects. This can be traced in the following quotation:

*“Expertise in design is not held only inside single heads, but collectively and socially in organisations”* (Lawson, 2006, p. 12)

Chapter 1 reveals the ‘social dimension of architectural practice’ that emerge from complex interactions among interested parties (Cuff, 1992). It requires management to deal with the complexity and ‘the chaotic nature of the design process’ (Emmitt, 2014). Thus, Lawson (2006) highlights the need to ‘externalise the internalised thinking of the designer’, while Jones (1992, p. 45) also emphasises the need to ‘externalise the design process’ and notes the ‘major advantage of bringing thinking into the open’. This enables other people to contribute information and insights from ‘outside the designer’s knowledge and experience’ (Jones, 1992, p.45). He argues that the ‘new’ complexities in design cannot be tackled with the mind of a single designer. Similarly in computational design, the previously discussed aspects of complexity demonstrate the necessity of collaborating in order to manage complexity and deal with the multiplicity of emerging roles and the vast array of digital technologies and methods applied that are beyond the capacity of any individual within practice. This necessity can be traced in Kocatürk and Medjdoub (2011), who argue that innovative approaches in architectural practices cannot emerge only by adopting technology, but by using this technology to develop coordinated and multidisciplinary design intelligence.

#### **4.2.3.2 *Results of Collaborative Design***

The results of this phenomenon is thoroughly discussed in the literature; for instance, Kocaturk (2013) describes these emerging collaborative environments as a “socio-technical transformation of architectural practice”. Meanwhile, Kolarevic (2004) claims that digital technologies are enabling ‘seamless collaborative processes’ by integrating design, constructional, analytical and other processes, which is resulting in a “a digital continuum in the design process from conception to production” (Kolarevic, 2004; Oxman, 2017b). Thomsen et al. (2015) argue that the collaborative and multidisciplinary environments help architects to learn from neighbouring fields, and to inspire new ideas and technologies rather than reinventing the wheel. Furthermore, Kocaturk (2013) considers that these new modes of collaboration, integration, and multidisciplinary in practice are becoming the main engine of innovation in architecture. For her part, Oxman (2006) states that the nature of digital tools applied in design practice has resulted in a shift “from implicit to explicit” in some aspects of the design process. All these arguments reveal the importance of collaboration in computational design and its potential in ‘transforming’, ‘integrating’, ‘innovating’ and ‘externalising’. This is enabled through the availability of the digital technologies that are opening up new horizons for collaboration in architecture by increasing the level of transparency in the design process. In fact, five decades ago, Jones (1969) was urging designers to augment the transparency of design process in order to allow contributions beyond the designer’s own expertise and knowledge; thus, recent digital technologies seem to be responding to this aspiration.

#### **4.2.3.3 *Collaborative Design in Practice***

Literature shows a wide range of examples of collaborative design within practice; for instance, PLP group has a collection of teams, such as; the computation geometry team, sustainability team, rendering team, physical workshop, and programming team. All these teams are integrated into the design team and they work together in a collaborative work environment to figure out the increasing complexity that accompanies the new technologies (Hesselgren & Medjdoub, 2010). Similarly, Foster + Partners rely heavily on highly-collaborative and interdisciplinary environments, where architects, engineers, industrial designers, model-makers, software developers, researchers and even mathematicians and anthropologists work together from the early stages of the design process to produce high quality designs (Foster+Partners, 2013b). Within the same context, Glymph (2003) presents a

detailed description of the design process of the Disney Concert Hall, designed by Gehry Technologies. In this project, a wide range of digital tools, such as 3D printers and 3D scanners were used to enable a highly collaborative work environment, where, for example, the nature of the project required the integration of an acoustician within the design team, and thus, influence the design form.

#### ***4.2.3.4 Mechanisms and Tools of Collaborative Design***

With regard to the mechanisms and tools that enable collaboration, Bhooshan (2016) argues that sharing digital tools, software and algorithms across participants and disciplines gives opportunities for collaboration and co-authorship within a design project. Meanwhile, from an educational perspective, Holzer (2015) emphasises the need to empower students with skills in orchestrating and managing the flow of information in order to streamline collaboration. This links back to the previous chapter and the discussion concerning the essentiality of BIM technology in enabling a seamless and automated flow of information to enhance collaboration and interdisciplinarity throughout the project life-cycle (Eynon, 2016). These mechanisms and tools can be added to parametric design, which is also discussed in the previous chapter, whereby the explicit nature of developing the parametric graph increases the transparency of the design process, and hence, offers further opportunities for different designers and other participants to work collaboratively from the early design stages (J. E. Harding & Shepherd, 2017; Jabi et al., 2017).

In considering hardware tools, Dorta, Kinayoglu, and Hoffmann (2016, p. 87) discuss the potential of the Hybrid Virtual Environment 3D (Hyve-3D), which is “a system that allows architectural ‘co-design’ inside Virtual Reality using ‘3D cursor’”. This system allows several participants from different places to connect to the same Virtual Reality environment, where they use interconnected and synchronised 3D cursors to view, edit and interact with the design object in real-time (Dorta et al., 2016). This system seems to have great potential in supporting collaborative work environments, and reveals the importance of the simultaneous evolution of both hardware and software tools in enabling more effective and informative design processes in practice.

Therefore, it is important to explore in greater depth the methods applied to support collaboration in practice, the technologies used to enhance the effectiveness of collaborative work, and the different types of problems that may arise when participants from diverse disciplines work together.

#### 4.2.4 Integration

The growing need for more collaborative and multidisciplinary work environments has prompted architects to address their remoteness from constructors (Lawson, 2006) and the limitation and ineffectiveness of design drawings (Jones, 1992) by searching for new technologies and methods. New digital technologies allow for unprecedented levels of collaboration across fields of expertise (Sprecher & Ahrens, 2016). This is enabled through the use of integrated platforms where ideas, tools, models, and algorithms are shared and exchanged throughout the different stages of the design process (Bhooshan, 2016; Fok & Picon, 2016). In this respect, the tendency to integrate performative criteria into the conceptual design stage (Mueller, 2011) has resulted in the development of novel modelling techniques to realise this tendency. This situation affects the boundaries of the architectural design discipline, and is expanding its breadth and concerns by shifting architectural practice into a shared interdisciplinary interface comprising architects, engineers, planners, and fabricators as well as material scientists, ecologists and physicists (Thomsen et al., 2015). Likewise, the simultaneous evolution of modelling techniques, materialisation, and fabrication technologies instigates the upgrade of different systems, such as parametric design, whereby the choice of materials, structures and fabrication technologies are integrated into the inception stage of the design process (Oxman, 2017b). In this regard, Bhooshan (2017) broadly discusses and exemplifies a wide range of methods, such as ‘iso-geometric methods of structural analysis’, ‘equilibrium modelling methods’, and ‘subdivision surfaces’, which aim to enhance integration between design and structural platforms by offering the capability to define and perform structural analysis directly on design geometries.

The previous discussion about the potential of integration in architectural practice highlights the substantial value of BIM technology, which is dedicated to offering an integrated platform for several project stakeholders from different disciplines to work, collaborate, and share information and knowledge throughout the whole project lifecycle. The effectiveness and fruitfulness of this integration lies in the parametric nature of BIM applications that gives the capability to leverage enormous amounts of information by automating the information flow throughout the different project discipline and project stages. Furthermore, the investigation of further aspects of integration can be essential when searching for radical changes in the design process that represent paradigm shifts. In fact, all these arguments represent paradigm shifts, which result from integrating interdisciplinary processes, and



hence the migration of non-architectural activities to the core of the architectural design process.

#### **4.2.5 Automation of Information and Data Flow**

This reliance on collaborative and interdisciplinary work environments and integrated platforms is facilitated through different digital technologies and software applications that allow automated and real-time transformations of information at any time across disciplines and stages throughout the design process (Eastman et al., 2011; Eynon, 2016; Kolarevic, 2004). In this sense, new technologies are responding to the difficulty in conducting a design project, which is caused by the reliance on poor and insufficient information when predicting the future state of a building (Jones, 1992). According to Kocaturk (2017, p. 167), one of the problems in conventional design systems is the difficulty and high cost of collecting data, where the data format and structure require manual transformation from paper into digital systems. This mechanism limits the use of data to specific technical functions instead of aiding high-level decision making (Construction Industry Knowledge, 2015 in Kocaturk, 2017, p. 167). In view of this limitation, new digital technologies are increasing the richness of information provided over the project lifecycle, which is substantially changing the entire work-context in current practice (Holzer, 2015). In fact, the reviewed literature shows that integrating platforms and disciplines is the main role for these novel methods of transferring information. For instance, Oxman (2017b, p. 10) states that the parametric and algorithmic systems promote a holistic process concerning a logical flow of information from concept to production. This, in turn, allows for the tectonic relationships to be informed, and hence the materials, and materialisation and fabrication techniques to be selected in the early design stages. Within the same context, Kolarevic (2004) states that the novel and high efficient way of constructing and describing designs is enabled mainly by the facility and speed of the extraction, exchange and utilisation of information. He considers that these enabling digital technologies have blurred the line between the design information and the construction information. For their part, Thomsen et al. (2015) argue that data generated from the model, should be understood as an integral, rather than predefined, part of the design project. They confirm that understanding this potential is central for both architects and engineers to enhance their co-evolution in investigating hybrid geometries and structures. Therefore, the new technologies, especially BIM, are not only increasing the intensity and extensity of data (Sprecher & Ahrens, 2016), but enabling integration and control over several levels of information (Anton & Tănase, 2016). In other words, new technologies are allowing data to

act as a new material for designers (Oxman, 2006), and to function as the ‘new oil’ of the digital age (The Economist, 2017). This is achieved by improving the capacity to share, capture, measure, and compile processes to translate data into meaningful and actionable information (Barista, 2014 in Kocaturk, 2017, p. 167).

The previous discussion highlights the potential of BIM technology including its multidimensionality and its parametric principles in automating the information flow. It also identifies an important area of investigation about the capability of parametric modelling applications in enabling information flow across different disciplines, rather than just associating parameters to explore design versions in the geometrical space.

#### **4.2.6 Copyright, Authorship and Ownership**

Using integrated platforms to share information and models in collaborative work environments often incites nervousness in the industry around issues such as copyright and liability (McPartland, 2014). The concepts of ownership, authorship and copyright in the architectural domain have, historically, been problematic (Colletti, 2016; Picon, 2016). Currently, with the emergence of digital and open source architectures (Garcia, 2016), this issue is becoming even more problematic and complicated (Ruy, 2016).

The extraordinary diversification of architects’ interventions and the increasingly complex modes of interaction in collaborative work are provoking difficulty in establishing the legal status of the various forms of involvement in the design process (Fok & Picon, 2016). This problem can be inflated when connecting design to fabrication systems, where the models rely on heavy, unexpurgated exchanges of raw digital information without regard for traditional definitions and divisions of labour and responsibility (Bernstein, 2016, p. 63). This situation provokes increasing necessity for architecture to resolve internal contradiction between ethics of its service and the requirements of its authorship (Ruy, 2016).

In an attempt to find solutions for this problem, Colletti (2016) states that in the film industry, a movie is understood as a collaborative effort, where a whole list is provided at the end of a movie to give credits for all contributors. He wonders why the same system is not applied in architecture, rather than presenting only architects, and sometimes engineers as the main and heroic creators of the whole building project. From this point, Michalatos (2016) introduces the notion of ‘granular ownership’ based on the use of ‘granular models’, that enable tracking the contribution of all participants in the design, where every single click is registered in a

database with a timestamp attached (Michalatos, 2016, p. 113). This system enables accessing digital models so that all sorts of contribution could be evaluated based on the granular data structure embedded in the model, which will allow credits to be given to all participants (Michalatos, 2016). Bernstein (2016) also wonders why architects do not sell the methodologies they develop, rather than just selling traditional services. In this sense, the ability of the granular data structures in recording and archiving every single detail could be the perfect tool to attribute credit.

The granular models concept are inspired from the software industry and video gaming, where similar methods of collective and concurrent authorship are applied (Michalatos, 2016). This tendency towards importing ideas from other industries appears to have precedents. In fact, the use of integrated models to drive design was essential in shipbuilding and aerospace engineering for a long time before similar methods were adopted in architecture (Kolarevic, 2004). Similarly, parametric modelling was the basis for most mechanical CAD systems before it started to be utilised in architectural projects (Aish & Woodbury, 2005). This opens new horizons for architects to go beyond the limits of the AEC industry when seeking innovation. Therefore, the following section discusses thoroughly the impact of other disciplines on computational design.

#### **4.2.7 Impact of disciplines beyond building industry**

In parallel to the rapidly evolving advances in computational design, new terminology from industrial design, informatics, topology, film-making, biology and art has started to invade the discourse of contemporary architecture. This includes algorithms, which is derived from computer science and used by Oxman (2017b) to refer to a set of rules that can be embedded within a design model. Additionally, NURBS, curvilinearity, hyper-surfaces, and kinematics, which are derived from topology and used by Kolarevic (2004) and Bhooshan (2017) to refer to shapes and techniques used in advanced CAD systems to deal with complex and doubly-curved geometries. Moreover, fractal geometry is derived from mathematics, and used by Dallas (2014) and Rian and Asayama (2016) to refer to simple smart shapes inspired by nature to generate complex architectural forms. Furthermore, bio-morphic genetics is derived from biology and used by Turrin et al. (2011) to refer to a programming methods used to automate the optimisation of parametrically generated forms. Finally, narrative and storytelling are derived from literature and used by Ampatzidou (2014) to refer to the design process. All these examples show the significant impact of other disciplines, and that new

technologies are enabling the transition of ideas and techniques across heterogeneous disciplines.

#### ***4.2.7.1 'Impact of Other Disciplines' in Practice***

Kolarevic (2004) broadly examines examples of how architectural design is affected by technologies applied in other disciplines, such as shipbuilding, aerospace engineering and industrial design. According to Kolarevic (2004), the design and production of curvilinear forms were broadly used in these industries long before they were imported into architectural practice. For instance, Frank Gehry utilised CATIA (Computer Aided Three-dimensional Interactive Application) that had been used in aeronautical design and industrial design for 20 years (Kolarevic, 2004; Lawson, 2011). Similarly, in shipbuilding and automotive design, the reliance on drawings was abandoned in favour of centralised 3D models long before similar methods were adopted in architecture (Kolarevic, 2004). For instance, “the manufacture of the NatWest Media Centre at the Lord’s Cricket Ground in London (1999) designed by Future Systems” was based on experiences from shipbuilders from Cornwall, England (Kolarevic, 2004). In addition, architects have started to involve CAD/CAM systems which were developed for the product industry, and some software applications from the film industry (Kolarevic, 2004). This is added to the fact that, as previously mentioned, parametric modelling was borrowed from mechanical CAD systems (Aish & Woodbury, 2005)

#### ***4.2.7.2 'Impact of Other Disciplines' in Theory***

With reference to the technological advances achieved in different works, Gehry, Eisenman, Hadid and Prix, Mario Capro in Schumacher (2016, p. 4) claims that “architects have been at the forefront of technological innovation as they have expressed the logic and opportunities of digital tools better than most other professions”. However, Carlile (2014) seems to disagree with this argument, as she complains about the slow motion of the process of adopting technology in the AEC industry in comparison with other rapidly evolving domains, such as the software industry. She urges architects and builders to learn from the software industry in inspiring new methods of innovation (Carlile, 2014). This complaint by Carlile cites an in-depth and critical exploration of the mechanisms applied in the software industry to result in such a rapid growth in order to investigate the ability to apply such mechanisms in architectural design. This is another level of the impact of other disciplines on architectural design, where the ideas and the spirit of innovation can be inspired from other disciplines, rather than just techniques and technologies.

In this regard, Bhooshan (2017, p. 119) states that the impact of digital technologies can go beyond giving the capability of developing more effective and smart design methods. They are actually enabling the assimilation of a wide range of techniques from different sciences into architectural design, such as mathematics, geometry, physics, and material chemistry. Similarly, Oxman (2017b) states that, within this rapidly evolving technology, new principles, methods and processes are being added to the architectural design domain which have their roots in philosophy, mathematics and computer science. From these two statements, the impact of other disciplines on architectural practice can again be exemplified by BIM and parametric design, which allow for the embedding of information and processes that are related to other disciplines and other fields of science into the architectural design process, such as materialisation, fabrication technologies, and mathematics.

#### **4.2.8 Topological, Non-Euclidean and Complex Geometries**

The extensive research for knowledge, technologies and techniques applied in other disciplines is the main factor resulting in the emergence of topological, non-Euclidean geometry, whereby architects tend to provide habitats similar to those of nature (Bhooshan, 2016). For this purpose, some architects have started to ‘manifest norms of beauty’ by migrating from Euclidean spaces and Cartesian grids towards double-curved, complex and interactive geometries (Kolarevic, 2004). Many historical attempts to embed such geometries into architectural forms failed due to the lack of representational and constructional technologies at the time (Moneo, 2001). In contrast, these attempts would now be more achievable due to the greater availability of affordable fabrication and construction technologies together with highly-advanced software applications (Oxman, 2006). Such a phenomenon brings the discussion back to parametric design, which is the most effective process for dealing with complex geometries, due to the smart ways it allows users to generate, edit, and automate design forms, as discussed in the previous chapter. This approach is again to enable specificity in discussing the enabling technology of this phenomenon.

The results of this phenomenon are vast; theoretically, Kolarevic (2004) argues that these ‘blobby’, ‘formless’ and ‘fluid’ shapes are shifting the focus from ‘spatial distinctions’ to ‘spatial relations’, while Oxman (2006, p. 252) claims that topological design is “characterising the first formal statement in new design philosophy” by providing a new kind of formal complexity, and departing from the “topological determinism” of traditional design.

Practically, despite Kolarevic's (2004) complaint of the lack of aesthetic theory to support curvilinearity in architecture, this phenomenon can be exemplified by some existing buildings such as 'Kustaus Graz' by Peter Cook (CRAB, 2003) (Figure 12), 'Web-of-North-Holland' by Sander Boer and Kas Oosterhuis (Kocatürk, 2006; Oosterhuis & Boer, 2004) (Figure 13), and 'BMW's exhibition pavilion at the IAA '99 by Bernhard Franken and ABB Architekten (Franken, 2003) (Figure 14). In addition, The Guggenheim Museum in Bilbao (figure 15), designed by Frank Gehry, is described in the literature as one of the foremost examples that reflect this paradigm shift in current design. According to Oxman (2006), the building was one of the main incentives for theorising new formal and methodological directions in contemporary architecture. Meanwhile Kolarevic (2004) calls this building "the new Eiffel Tower of the digital age" in reference to the similar ground-breaking influence of the Eiffel Tower in the 19<sup>th</sup> Century.



**Figure 12: 'Kunsthaus Graz' by Peter Cook**



**Figure 13: 'Web-of-North-Holland' by Sander Boer and Kas Oosterhuis**



**Figure 14: 'BMW's exhibition pavilion at the IAA '99 by Bernhard Franken and ABB Architekten**



**Figure 15: Guggenheim Museum by Frank Gehry, 1997**

#### **4.2.8.1 Topology and Parametric Design**

The ability of parametric design to differentiate geometries and automate the generation of design solutions, together with the mathematical and algorithmic logic of its applications, makes parametric design an ideal tool to realise topological, non-Euclidean, and complex geometries in architectural design. This connection can be traced in some recent studies that articulate the essentiality of embedding topological relations in generating curvilinear, cellular shapes, together with the potential of parametric design in providing the capability to deal effectively with such challenging geometries (Jabi et al., 2017; Oxman, 2017b). According to Jabi et al. (2017), smarter solutions can be obtained when considering topology in parametric design systems, due to the capability of those systems to accommodate the design context. Meanwhile, they ensure that, when the proper definition of topological relationships is overlooked in the early stages, there is a risk of brittleness and failure in later design stages. They enhance their arguments for experimental investigations that reveal the mechanisms for generating and manipulating ‘conformal cellular structures’ and ‘non-manifold topology’ in parametric systems (Jabi et al., 2017). Furthermore, Oxman (2017b, p. 33) argues that “leading concepts of topological design thinking offer unique design methodological approaches in parametric design thinking”. She enhances her argument through providing a series of case studies for existing design projects and buildings that show the capability of parametric design in generating topological patterns, and in differentiating these patterns in response to specific predefined functional and contextual goals and constraints (Oxman, 2017b).

In relation to the research topic, this phenomenon has a significant impact on the architectural design process, as designing such forms requires the incorporation of highly-advanced mathematics into the design process in order to analyse and generate highly-complex and doubly-curved surfaces and shapes. In other words, this kind of design requires a new sort of knowledge and experience that is not highly related to conventional design processes. This is reflected in the fact that currently, some practices have started to integrate aerospace engineers, mathematicians, and specialists from other disciplines within their design teams (Bhooshan, 2016; De Kestelier, 2013; Whitehead et al., 2011).

#### **4.2.9 Sustainability**

In searching for new values, efficiencies and environmental meanings for these emerging complex design forms, and more effectiveness for the new tools and approaches, architects

started to explore new ways to adopt available digital technologies and methods in order to respond efficiently to new environmental challenges. In fact, the rise of extreme weather events over the past 50 years (Snell, 2018) indicates that the rapid evolution of digital technologies is coinciding with a similar evolution of natural disasters. According to Snell (2018), humans are introducing materials into the air; mainly carbon dioxide that is resulting from the combustion of fossil fuel, contributing to ‘global warming’, which is, in turn, affecting a series of other catastrophic environmental variables. Originating from the fact that potential disasters are mainly human-induced (Snell, 2018), together with buildings consuming one third of global energy Wright (2018) and producing 30–40% of carbon emissions (Snell, 2018), Wright (2018) emphasises the major role of architects in dealing with the problem. He uses the term ‘unsustainability’ to refer to the evaluation of the current situation, and suggests improvement towards prioritising sustainable solutions, where concepts such as, energy efficiency, recyclability, low impact resources (Bashir et al., 2016), thermal comfort, and indoor daylighting (Levenson, 2018), are becoming the main factors that should drive the design process in any current building project.

These changes require new methods to eliminate the limitations of conventional design methods, whereby building performance feedback is provided at a late stage of the design process, as the building design is already developed and hence, changes could be expensive (Mueller, 2011). In this case, the performative feedback can rarely be used to change the design form (Anton & Tănase, 2016). Therefore, the singularity of traditional geometric representation is now being replaced by inherent plurality of network information models (Tamke & Thomsen, 2018), where the observation of structural and environmental building behaviours can be shifted into the early stages of the design process (Tamke & Thomsen, 2018), and feedback loops can be produced across the whole design process to inform and optimise decision-making processes (Tamke & Thomsen, 2018). This tendency is supported by a wide range of simulation techniques and analytical software that enable designers to model complex building behaviour, including environmental and structural performance, pedestrian flow, code compliance and other systems (Kocaturk, 2017, p. 166), and hence to engage more fully with the non-visual aspects of their buildings (May, 2018, p. 74).

As a result, the focus is shifting away from form-based modelling to performance-based modelling. On the one hand, this results in increased complexity at the conceptual design stage where designers need to deal with a large amount of conflicting and heterogeneous information (Turrin et al., 2011). However, on the other hand, it gives designers the



opportunity to embed intelligence into the conception and realisation of buildings (Kocaturk, 2017, p. 166), where the design process becomes more predictable and measurable (Bernstein, 2016), and the buildings become more comfortable, durable and energy efficient (May, 2018).

Supporting sustainability in building design and saving the environment is the main demand in the current time. Therefore, enhancing the efficiency of the digital technologies and computational design methods can mainly be achieved by dedicating these technologies and methods in supporting this major goal.

#### **4.2.10 Augmenting Functionality and Dimensionality of Design Models**

Supporting sustainability and energy-efficient design solutions combined with enhancing collaboration and integration in design have prompted the development of a wide range of modelling approaches, techniques and software applications. While Archer (1965) defines *design* as “the formulation of a prescription or model for a finished work in advanced of its embodiment”, a model is defined either as a method to communicate a designer’s ideas, as a simplified version of the real building, or as a version of a building with a specific level of abstraction. The next subsections show the different definitions of ‘model’ and investigate how the digital technologies are affecting the productivity of models, including their dimensionality and functions.

##### **4.2.10.1 Definition of Modelling**

According to Whitehead et al. (2011, p. 244), a model is “a representation of an idea that externalises a thought process”, while Klassen, 2002 in Veliz, Kocaturk, Medjdoub, and Balbo (2012, p. 272) defines a model as “a representation of a conscious simplification of reality filtered and determined by cultural and individual backgrounds which necessarily conceives a systematic understanding of the reality and a set of reductional constraints”. In comparing these two definitions, it is notable that the first focuses on the function of model within the design process, where the model acts as a medium that translates designers thoughts to other participants, while the second focuses on the entity of the model that acts as a simplified version of a real product. In fact, it could be worthwhile providing a double-layered definition to recognise a model from modelling, where in the first layer modelling can briefly be defined as the creation of models to externalise ideas, and in the second level, a model can be defined as a simplification of reality.

A variety of modelling techniques are enabled by different digital tools, which can be utilised to create different sorts of models, such as physical models, building information models, parametric models, script, and sketch (Kocatürk & Kiviniemi, 2013). While each of these models represents a specific degree of abstraction, each is produced for a specific purpose, such as analytical, geometrical, visual, contextual or environmental models (Whitehead et al., 2011).

#### ***4.2.10.2 Federated Models***

According to Hugh Whitehead (Head of the Specialist Modelling Group at Foster + Partners), the function of modelling is to manage ‘change propagation’ in the design process. This can be captured in a process by creating a “federation of models”, and then by exploring mechanisms to link these models allowing them to work together in a coordinated manner (Whitehead et al., 2011, p. 240). This multiplicity of models can result in more mature decisions as it facilitates referencing and data exchange between different modelling processes and provides feedback for designers (Whitehead et al., 2011, p. 240). In this light, Kocatürk and Kiviniemi (2013) argue that these various modelling techniques have the potential to shift the focus in the design process from providing drawings to providing ‘intelligent models’ from which different drawings can be extracted.

#### ***4.2.10.3 Interoperability***

The reliance on the multiplicity of technologies and software applications to provide federated models within a project raises the issue of interoperability where some information and geometries may be lost when exporting models and drawings from one application to another. In this regard, Ceccato (2010) clarifies some reasons behind the use of more than one application within one practice or even one project. He states that different teams within a practice or different individuals within a team may have different technological experiences. In addition, one application might be more effective than another in relation to the nature of the project in hand. In this regard, (Hesselgren & Medjdoub, 2010) ensure that, prior to using multi-software applications within one project, it is necessary to understand and experience the way these applications talk to each other.

#### ***4.2.10.4 Direct Connection between the ‘Digital’ and the ‘Physical’***

While a digital model created using software can easily be 3D-printed and a physical model can be 3D-scanned and translated into a digital model, Oxman (2006, p. 247) argues that new

technologies have enabled a “dual-directional process” of transferring information between digital and physical models. She describes such relationships as providing a “seamless integration of virtual and material”. Furthermore, Veliz et al. (2012) describe these techniques as a dialogue between physical and digital models that may occur at various stages throughout the design process. These kinds of techniques can be exemplified in the design process of Frank Gehry’s ‘Disney musical hall’ in which a physical model was first produced and manipulated. Later, in order to be modified in the computer, it was transferred into a digital model using a digitizer arm. Gehry also used a CAD/CAM machine to reproduce the physical model (Glymph, 2003).

#### ***4.2.10.5 New Dimensions in Design Modelling***

Thomsen et al. (2015) argue that current digital technologies have enabled the blending of different sorts of sciences to develop new modelling paradigms that not only allow the modelling of the building form, but also the modelling of the behaviour of a building. This enables a model to show how a building will look as well as how it will perform and behave. In BIM terms, this phenomenon is interpreted as new added dimensions to design modelling. In fact, as discussed in the previous chapter, BIM enables the embedding of information from different types within a design model, while each of these types of information represents a new dimension (Eynon, 2016; McPartland, 2017). This situation is shifting the focus in design modelling from a 3D geometrical representation to the representation of an nD space of heterogeneous and conflicted information (Holzer, 2015). This provides the capability for the development of highly-effective, collaborative and integrated work environments, as discussed earlier.

#### ***4.2.10.6 Inter-scalar Models***

According to Thomsen et al. (2015), the design process can be driven through design-based information modelling that is starting to focus on investigating inter-scalar interdependencies within the design process. More precisely, the new modelling methods are allowing for the integration of information from different scales and levels, from micro-level, to meso-level, and through to macro-level, into one single platform for representation in one single model (DeLanda, 2016). This is starting to challenge the traditional hierarchical organisation of design fields allowing for the creation of a congruous simulation of the potential relationship between architecture and its contexts (Thomsen et al., 2015).

The previous discussion about the role of different digital technologies in enhancing the functionality and dimensionality of design models demonstrates that modelling is shifting from a method to represent design ideas to a design method. Thus, modelling is becoming an integral part of the design process itself. This can be investigated as opposed to the levels of impact of digital technologies on design activities discussed in Bernal et al. (2015), where the potential of each modelling technique can be identified in aiding, automating or augmenting the design process. In this case, different modelling techniques can be used not only to aid the design process, or to automate some of the activities, but to augment the designer's mind by offering possibilities beyond human mental capacity. Furthermore, the levels of abstraction in design modelling, mentioned above, inspire a new area of investigation that focuses on the level of abstraction in relation to the design stages. Therefore, the development of the design process results in gradually reducing abstraction, and the sequence of abstraction reduction can be changed when relying on BIM and parametric design. Moreover, the discussion about the new dimensions in design modelling offered by BIM applications raises questions about the role of parametric modelling in enhancing this dimensionality. The previous chapter shows how parametric design can integrate other fields of research, such as materiality, fabrication technologies, and structural analysis, into the design process. This can be relied on in investigating the augmented dimensionality in parametric design, which enhances the assumptions raised in Chapter 2 concerning the usability of parametric modelling applications as highly-effective BIM tools.

#### **4.2.11 Adapting, Interacting with, and Designing Design Tools**

Within the availability of this wide range of modelling techniques and software applications, it is possible not only to use different applications as highly effective design tools to support high quality design, the new digital technologies, such as scripting, enable the tweaking of design tools to match a specific design intention or situation. From a practical point of view, Whitehead et al. (2011) emphasise the flexibility of technologies applied to the design process. They state that these technologies can be customisable based on the specific needs of each individual project. In other words, they can be developed by a design team in parallel to the development of the design itself. This new phenomenon is exemplified in ZHA (Zaha Hadid Architects), where a design team is provided with an in-house research team comprised of architects and designers with a high level of skills in formal software development. This team undertakes the responsibility for developing computational solutions independently or relatively to the project at hand (Ceccato, 2010). In other words, the team is

involved in building up and developing the design tools. From a theoretical perspective, Oxman (2006) states that the digital tools and techniques applied in current practice are resulting in “a paradigm shift in design process from form to formation” as they enable the designer to interact with the very process by providing the capability to adapt and reform the tools within the design process. Moreover, Mueller (2011) describes this phenomenon as a new level added to the design process, whereby a designer now not only needs to design a facility, but on a higher level, also needs to design the tools that will be utilised to design this facility. These arguments bring the discussion back to the previous chapter where scripting, as a tool to adapt software, was investigated, and parametric design tools were described as visual scripting tools. This understanding is essential to enable more specificity in describing the mechanisms behind this phenomenon, rather than just attributing its presence and application to the advances in digital technology in general.

#### **4.2.12 Adapting, Interacting with and Designing the Design Process**

The vast array of flexible and adaptable software applications that are currently available for architects are challenging what can be described and recorded, what can be observed and interacted with, and what can be represented (Michalatos, 2016). This leads to a more crucial question of what constitutes an architectural object (Michalatos, 2016). While this critical point was already exemplified in the previous section through the example of granular models and their ability in recording, tracking and tagging every single contribution in a collective creation process (Michalatos, 2016), the new ‘graph-based’ parametric design applications, discussed in the previous chapter, can be another valuable example to show how the design process can be recorded, visualised and hence objectified. In such a case, the ability to reuse this same process can lead to the definition of what in this research is termed ‘recyclable processes’.

The previous chapter explores different computational design methods and discusses the paradigm shift in the design process that can be provoked by each of these methods. This paradigm shift is thoroughly discussed in the literature. For instance, Oxman (2017b) argues that this impact of digital technologies on design manifests in the shift from hand drawing and sketching in conventional design, to code-based scripting and algorithmic reasoning in generative and parametric design systems. This further emphasises the aforementioned point that drawing is being replaced by coding and authoring algorithms. Considering the fact that drawing is the most essential activity in conventional design (Jones, 1992; Lawson, 2006),

this represents a significant paradigm shift in the design process. In addition, the ability of parametric design systems to integrate fabrication and material-related processes into the conceptual design process is expanding the scope of the decision making of designers, where they need to think about the material choices and fabrication technologies as an integrated part of their design decisions (Oxman, 2017b). This is another significant paradigm shift caused by the integration of non-architectural activities into the core of the architectural design process. From his perspective, Kolarevic (2004) argues that the new digital processes are ignoring traditional styles in design and concentrating more on processes driven by automated and responsive forms of generation. This responsive form generation is enabled through the power of associative parameters, where each parameter represents a geometric attribute within the form, and when this parameter changes, the associated parameters respond automatically based on the algorithmic logic of the whole parametric definition.

In general, the computational approaches applied in current architectural practice are re-addressing the entire cycle of the design process including the generation, evaluation and optimisation of design alternatives. This is stated by Bernal et al. (2015), who recognise the impact of computational methods on three levels of each design stage. These levels range from assisting, to automating or fully automating, to finally augmenting the actions undertaken within the design process. In reviewing the different CAD and computational design methods explored in the previous chapter, CAD can be seen as an assisting tool while BIM can be seen as an automating tool. In addition, parametric design appears to be both an automating and augmenting tool, as it can automate the generation and evaluation of design alternatives, which may augment the imagination of design with solutions beyond a designer's perception. This is what Chaszar and Joyce (2016a) call 'happy incidents'. However, one level is missing from the three impact levels outlined by Bernal et al. (2015). This is where a digital tool or method enables designers to interact with the process in order to adopt it and tweak its steps and activities to match specific situations, or to design the process itself. One aspect that exemplifies the significant impact of parametric design is the addition of a fourth level to Bernal et al.'s (2015) impact levels. This missing level can be traced to (Oxman, 2006) who attributes the significant impact of digital technologies to the centrality of digital tools, and the adaptability and "non-determinism" of the design process, in which designers can interact with the process. This argument can be exemplified by parametric design. For instance, the non-determinism in the design process can refer to the variety of approaches enabled in parametric design, where each design project can be

approached using a different algorithmic logic that is used to build a parametric definition. This definition can be considered a way to design or interact with the process. In parametric design, the model is based on parametric descriptions that algorithmically define a path to the end result; this differs from simply defining the end result of the design process, as was the case when relying on CAD (Thomsen et al., 2015). This new phenomenon provides an example of how the focus in the design process is shifting from form to formation (Oxman, 2006). It is also an example of how, in the recent digital age, the design process can be a creative piece of work in its own right (Spiller, 2009).

The ability to interact with and design the design process is an important potential of computational design methods that requires critical investigation within real architectural practice, where the potential of this phenomenon, its results and problems can be explored within a real practical context.

#### **4.2.13 Creativity**

Within this plethora of digital technologies and methods, that results in a series of paradigm shifts in the design process, a crucial question arises about the impact of these digitally immersed environments on design creativity. Chapter 1 discussed creativity, and how it can be challenged in practice with the availability of numerous voices involved in design decisions (Cuff, 1992; Emmitt, 2014). Chapter 2 discusses different ways in which computational design methods can accelerate the design process. A surprising result of this acceleration can be traced in Marion et al, 2012 in Kocaturk (2013, p. 24) who identify a paradoxical problem caused by the fluidity offered by digital design throughout all phases of the design process. They claim that, unless this fluidity is well-understood, managed and coordinated, the use of the digital tools may provide a ‘false sense of security’, which may result in a premature move to the next stage before sufficient maturity in the design solution is achieved. A lack of maturity in design solutions can refer to the different aspects of design, which may include creativity. Jones (1992) claimed that, within the ‘current’ diversity of technologies prompted by the industrial evolution, designers are shifting their focus to drawing capabilities and using visual forms to foresee future situations. Thus designers start to lose the special quality that distinguishes them from other participants, namely their reliance on creativity to produce designs (Cross, 2011; Jones, 1992; Lawson, 2006). Jones (1992, p. 5) also states that the most valuable part of the design takes place inside the designer’s mind. Therefore, the availability of a wide range of visualisation software helps to

immerse the designer in a vast number of images. However, instead of helping the designer to view the future image of the design product more clearly and accurately, Jones states that this limits the imagination and reduces the significance of the designer's mind in which the most valuable part of the design occurs. In other words, visualisation software is replacing the designer's imagination, which represents a serious threat to the creative aspect of design. Moreover, Jones (1992) argues that, within this industrial evolution, creativity can also be threatened as designers' activities are being planned on an industrial basis making use of man-machine systems. This is another powerful point that contradicts the potential for collaboration and integration.

Jones is not the only author who identifies the negative aspect of digital technologies. In fact, the literature presents a lot of criticism in relation to the impact of digital technologies on the creative aspect of design. This can be identified in Lawson's (2011) study in which he identifies the following problems in current software in terms of its capability of supporting architectural designers:

- 1- The vast majority of software applications currently used by architects are generic (non-architectural);
- 2- Most of software dedicated for architects is not written by architects;
- 3- Software driven by complex mathematics cannot hold proper dialogue with drawings;
- 4- No available software has the ability to record verbal words despite their essential role in the architectural design process.

Lawson (2011) argues that, in digitally-driven design processes, the symbolic representations used in digital systems cannot properly map onto the designer's mental symbolic representations. Similarly, Bernal et al. (2015) highlight the same difference between what is in the mind of the designer and what is represented on the computer. This contradiction seems to result in an unsophisticated method of design thinking that may threaten the creative characteristics of the design object. This can again be traced to Lawson (2011) study in which he astonishingly asks to not only "give up the idea of computers designing, but to give up the idea of computers even helping in design at least in some central roles" (Lawson, 2011, p. 11). His opinion is based on a series of experiments with students from various design fields. In all three experiments, the students were split into two groups; both groups were given the same or similar design projects. However, one group was provided with advanced digital tools and software while the other was only allowed to use conventional, paper-based



methods. Surprisingly, the results showed that using digital tools resulted in “ambiguous and less dense drawings, fewer lateral transformations, fewer ideas and consistently less creative solutions” (Goel, 1995; Kvan et al., 2003; Bilda & Demirkan, 2002 in Lawson, 2011, p. 9). For his part, Eastman, 2001 in Bernal et al. (2015) attributes this lack of creativity in digitally-driven processes to the significant cognitive cost of digital tools that may result in shifting the designer’s focus away from the creative aspects of the design product. Similarly, Thomsen et al. (2015) argue that the way in which performative and behaviour-based models are shifting the boundaries of the architectural profession into a vast shared multidisciplinary interface, is expanding the concerns of architectural design, and hence, infiltrating creative thinking with proprietary design methods and traditions for analysis and representation.

This discussion sheds light on the importance of investigating the impact of computational design methods on design creativity within real practice. It raises the need to focus on traditional design methods when developing innovative strategies in computational design. This will require more criticality in suggesting which specific digital tools and methods can be adopted for which specific tasks and situations, and which specific aspects of conventional design should be maintained.

#### **4.2.14 Research and Knowledge Transfer**

Relying on research in architectural practice seems inevitable. This is due to the rapid growth of increasingly complex tools and methods in computational design, and the resulting shifts in the sort of experiences and knowledge required to deal with such new technologies. Within this rapidly changing situation, the reliance on integrated platforms and the increasing deployment of information in collaborative work environments is increasing porosity among disciplines, and hence, resulting in ever-increasing convergence of knowledge, where researchers from multiple disciplines generate, share and recombine knowledge (Sprecher & Ahrens, 2016). This situation is not only replacing traditional geometric modelling by network information modelling (Tamke & Thomsen, 2018), but also challenging the infrastructure that underlies these models, leading to bigger, wider and deeper models (Tamke et al., 2018). The increasing need for such research was identified by Oxman and Gu (2015a), who urged designers to know more than merely basic architectural knowledge, and to focus on the cognitive base that underpins new design methods, such as the mathematical knowledge, the parametric schema, the parametric reasoning and the algorithmic thinking in parametric design environments. Therefore, new methods are necessary to enable information

transfer and knowledge, not only across disciplines within a project, but also across different projects. Such a situation is blurring lines between architectural practice and research, where the act of designing a building is becoming research in its own right (Till, 2007 in Bhooshan, 2017)

Many architectural practices are increasingly relying on research, in order to deal effectively with the rapidness in the evolution of technologies, and to keep up-to-date with state-of-the-art design methods and cutting-edge technologies. For instance, 'Foster & Partners' is provided with the 'Specialist Modelling Group (SMG)' that carries out project-driven research and development (Whitehead et al., 2011). According to Hugh Whitehead (the Head of SMG), the tools developed within the design process of a specific project are re-customised and re-used for other projects (Whitehead et al., 2011). Likewise, ZHA (Zaha Hadid Architects) have ZHCODE, which is a research group that carries out a wide range of collaborative research to capture knowledge from precedent work to inform future design (Bhooshan, 2017). According to Bhooshan (2017), the main objective of what he terms 'practice-embedded research' is to excavate from practice and explore a design thinking that is communicable, where the focus is on investigating the components of this design thinking, and on creating cognitive models, information processing models and design methods, in addition to analysing historical precedents and methods in order to develop prototypes, material and software to inform later work.

From another perspective, Lars Hesselgren, the Director of PLP Group, who also has a similar research group, argues that the role of such a group may differ based on the nature of each individual project and the stage at which the research group starts to engage. He also mentions some disadvantages of involving such a group as it may slow down the design process due to a difference in criteria in driving practice and research (Hesselgren & Medjdoub, 2010). This issue again highlights the impact of complexity, as research, according to Hesselgren and Medjdoub, may increase complexity in the design process due to the heterogeneous criteria needed for project and research. In general, such methods of working can enhance not only the porosity among disciplines, but also across different projects, allowing a shift in design thinking from the usability of digital tools and methods, to the reusability of those tools and methods, thereby allowing the knowledge, methods, and techniques that were generated in a design project, to be recycled in later projects.

#### **4.2.15 Digital Repositories**

Storing models, knowledge and methods for future reuse requires highly advanced data repositories and digital libraries. Ceccato (2010) states that the design teams at ZHA are provided with a variety of in-house online media and databases that contain a wide range of descriptive techniques, algorithms, and parametric scripts so that information and knowledge are recorded using different digital repositories to help in developing a sustainable and growing knowledge-base. This indicates that ZHA's teams can capture constructional and architectural knowledge and experiences from the different projects and transfer them from one project to another. This reliance on databases and repositories appears to be a highly effective way to respond to the increasing multiplicity and the novelty of the digital technologies and methods applied in architectural practice, where designers rely on previous experiences and knowledge, rather than reinventing the wheel in every single project. This can be even more effective if such kinds of database are available online for public use. Indeed, Tamke et al. (2018) mentions a wide range of digital libraries that are already available online, such as Tensor-Flow, Keras, CNTK, Accord.NET, Microsoft Azure, Amazon ML, and Google Cloud Platform. These libraries include a variety of algorithms, scripts, parametric models and many other content and services that support the creative production of knowledge and machine learning. This appears to be a further step towards more global level collaboration (Haidar et al., 2019), where the knowledge and experiences can be transferred across the globe rather than being limited to enterprise borders.

#### **4.2.16 Building Seeds**

Jen Carlile (currently co-founder of Outerlabs.io) spoke at length at KeenCon2014, in which she explained her views on how architects and engineers should think of smart ideas in order to radically speed up design and construction processes, and hence, respond to the significant population growth (Carlile, 2014). According to Carlile (2014), architects have the potential to inspire ideas from 'mother nature' such as the process of generating a tree from a seed, where this tree can take different shapes based on the location in which it is planted. She argues that the way buildings are being designed and constructed is not sustainable, as each building project is being approached from scratch following the same process over and over again. She suggests that it is time to think about designing 'building seeds', rather than single buildings; similar to the natural seeds in terms of the ability to generate buildings that can respond to the environmental context of the site they are 'planted' in. Similarly, within a scenario of a possible future of architectural design, Mueller (2011, p. 16) anticipates that

designers will be able to develop behaviour models with generative capabilities, which will be used to ‘seed’ sites, neighbourhoods or cities with ‘germs’. The germs will be able to automatically populate sites, neighbourhoods and cities to grow design solutions. Indeed, much criticism is placed on the ‘waste’ and the way the building industry operates (Kocaturk, 2017, p. 166). While Wright (2018) uses the term ‘unsustainability’ to refer to the current practice, where the principles of building sustainability are overlooked, Carlile (2014) in this context is criticising the processes in which buildings are designed and constructed, and hence shifting the focus from unsustainable buildings to unsustainable processes.

The building seed is a very important concept that inspires a wide area of investigation, which should focus on finding the appropriate tool and method that can enable the production of building seeds to accelerate processes in architectural design. This can be inspired from the second part of Carlile’s (2014) speech, where she suggests that architects and engineers should learn from other disciplines; such as the software industry, where different applications are built on top of each other so that software developers benefit from the products of other developers, rather than building their applications from scratch. She wonders why architects do not follow the same process, whereby they provide libraries, tools and open sources for other architects to utilise and develop in order to inform different design projects. This will allow architects to develop systems and design tools on top of others’ work, rather than repeating the same process again and again for every single building. She argues that this may help the slow moving AEC industry to achieve rapid growth similar to that of the software industry.

Similar tendencies can be seen in the web development industry, especially following the emergence of Web 2.0, the generation of websites that allow the users themselves to upload their material, their media and their information (Barnes & Tynan, 2007). The main feature of such a kind of interactive websites is that they give the website user the capability to upload their own material and information without the need to learn programming languages. This sort of interactivity with an extremely wide range of communities has resulted in a radical growth of different websites. For example, Wikipedia has developed an online encyclopaedia, where readers create and modify all of the articles. This policy has resulted in the emergence of an online encyclopaedia that contains millions of articles in many languages, which reveals the large benefit of such an interactive source of information, especially when it is compared to similar encyclopaedia such as Britannica, which is written by a handful of experts and

scientists. This is another powerful example that shows how architects may inspire innovative ideas from web 2.0 development industry to achieve similar sensational results.

### **4.3 Chapter Summary and the Theoretical Framework**

Having explained the mutual relationship among the ‘digital’, theory and the practice in the previous chapter, it was possible to begin to generate the theoretical framework in this chapter. For this reason, the new phenomena in computational design were identified through the exploration of the changes and shifts in architectural design caused by the utilisation of digital technologies and the implementation of computational design methods in architectural practice. In this case, each of the phenomena, alongside the relationship among these phenomena, represented the components of the theoretical framework and identified how the components were related.

The first phenomenon was increasing complexity in the design process, where arguments in the literature were challenged by recalling literature from conventional design, architectural practical and computational design. This demonstrated how the ‘digital’ could, in various situations, enhance simplicity in the design process rather than increase complexity. The section also emphasised the need to recognise form complexity from process complexity and to identify the relationship between them. The second phenomenon was the emergence of new roles in architectural practice, including unfamiliar and non-architectural roles within design teams. The chapter showed some samples of roles while questioning their permanence and temporality.

The complexity of the new technologies and the emergence of new roles raised a discussion about collaboration in computational design, and its need to address complex situations. The impact of collaboration was discussed and the potential for BIM and parametric design were highlighted. This was followed by a discussion about integration and its potential to blur the distinction among disciplines, and shift towards the digital continuum in the design process, from conception to production. This, again, resonated with BIM and parametric design applications due to their ability to automate the flow of information across disciplines to support collaboration and integration in architectural design. This showed the essential role of information and data in computational design, which was discussed by comparing the way in which data was shared and exchanged in traditional digital systems, and the way it could be automatically translated into meaningful and actionable information within new digital technologies.

The discussions about data exchange on integrated platforms raised issues of authorship, copyright and ownership, that resulted from the ease and seamlessness of sharing extensive amounts of data and the difficulty in identifying the legal status in the involvement in producing this data. Therefore, the ‘granular model’ concept was explained and its role in determining contributions. While this concept is already utilised in video gaming, this shifted the discussion to the impact of other disciplines on architectural design, such as, aerospace engineering, shipbuilding, topography, and biology. Therefore, some examples were explained to show how some architects were able to import technologies and techniques from other disciplines and employ them successfully in architectural projects. This phenomenon has resulted in the emergence of topological, non-Euclidean and complex forms in architecture, which are enabled through computational design methods, such as algorithms and parametric design.

In an attempt to find an environmental value for these fluid and complex forms, the chapter examined sustainability and a brief background was provided about global warming, climate change and population growth. In addition the considerable contribution of buildings to fossil fuel combustion and carbon emissions was considered. The importance of sustainability was highlighted and the different technologies that support it were explored. Therefore, the purpose behind the shift from form-based modelling to performative and data-based modelling was identified. Thus, different novel modelling techniques were explained, such as federated modelling, integrated and performative modelling, and inter-scalar modelling. Furthermore, some related discussions was provided on interoperability amongst modelling applications and its impact on the flow of the design process.

In addition to the benefits of the digital technologies in offering designers comprehensive and effective tools to facilitate design and automate tasks, the chapter showed how these technologies enable a designer to adapt the tool to match project’s needs, and how the design process itself can be objectified, adapted and interacted with in design projects. This multiplicity and range of techniques and choices, prompted a discussion about design creativity and how it can be challenged with such digitally-immersed environments. Thus, different arguments were reviewed to show: how creativity can be significantly affected by the contradiction between the ‘digital’ and designer’s mind; the plethora of digital visualisations; the limits on the designer’s imagination; and the false feeling of maturity in design solutions that can result from relying on these technologies.

The discussion about the multiplicity, variety and heterogeneity of digital technologies highlighted the need for practical research, and the importance of developing comprehensive and effective digital repositories to support knowledge acquisition and knowledge transfer across projects. In addition, the ‘building seed’ concept was discussed, which echoed the impact of other industries on architectural practice. However, the focus was on importing innovative strategies from other industries that had already achieved rapid growth, and to apply the same strategies to architectural design in order to achieve a similarly rapid evolution. Therefore, in general, the discussions enabled the exploration and the classification of a wide range of phenomena in computation design, and some of the relationships among these phenomena. These phenomena represent the components of the theoretical framework in order for those phenomena and the relation among them to be further explored within their practical context as shown in the following chapters.

# CHAPTER FIVE

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## 5 Research Methodology

### 5.1 Introduction

This chapter will identify how the research was undertaken, the steps taken to meet the research objectives and the methods applied to achieve the research aim. Therefore, the philosophical stance, research approach, and strategy, alongside the data collection and data analysis techniques will be explained. These are based on the nature of the research objectives, and the phenomena investigated.

### 5.2 Research and Methodology

Where the aim and the objectives represent the outcomes of the research, the methodology determines the research process undertaken to achieve the outcomes. In other words, the aim and objectives represent what will be achieved by conducting the research, while the methodology identifies how the aim and the objectives will be achieved.

The methodology is an essential part of any research, and many authors refer to the methodology in the definition of 'research'. For instance, M. Saunders et al. (2007, p. 5) define research as "something that people undertake in order to find out things in a systematic way, thereby increasing their knowledge". In this definition, the aim and objectives are represented by the phrase 'finding out things' while the methodology is represented to the 'systematic way'. Similarly, Groat and Wang (2002) define research as, "systematic inquiry directed towards the creation of knowledge". Thus, the methodology is referred to as 'systematic inquiry' in this study.

Introna and Whitley (1997, p. 32) define methodology as, "a structured set of techniques and tools that are used to tackle a particular problem". This definition emphasises the problem as the main focus of research, where research can be understood as a problem-solving process that aims to identify solutions for problems, that can often represent a gap in knowledge or a specific practical problem. According to Remenyi and Williams (1998, p. 35), research methodology refers to the procedural framework within which the research is conducted. In this research, the procedural framework will be extracted from the theoretical framework developed in the previous chapter. Therefore, the procedural framework that represents the



methodology will function as a tool to enable the development of the interim version of the theoretical framework through to its final version.

Understanding methodology as a ‘procedural framework’ requires a systematic approach to thinking about methodology in order to allow the classification of the different items that form the overall methodology, and the sequence in which these items will be addressed. Different ways of understanding and developing a research methodology were reviewed (Fellows & Liu, 2008; Gray, 2014; M. Saunders, Lewis, & Thornhill, 2015). As a result, this research will adopt the metaphor of the ‘research onion’ (Figure 15) created by M. Saunders et al. (2015), which offers a clear and highly organised way of thinking about the research process stages and the sequence of these stages. The ‘research onion’ consists of six different layers where the researcher starts from the outer layers, which represent the research philosophy and approaches, then moves into the inner layers, which represent the research design, until they reach the core of the onion, which represents the data collection techniques and data analysis procedures (Saunders et al., 2015).

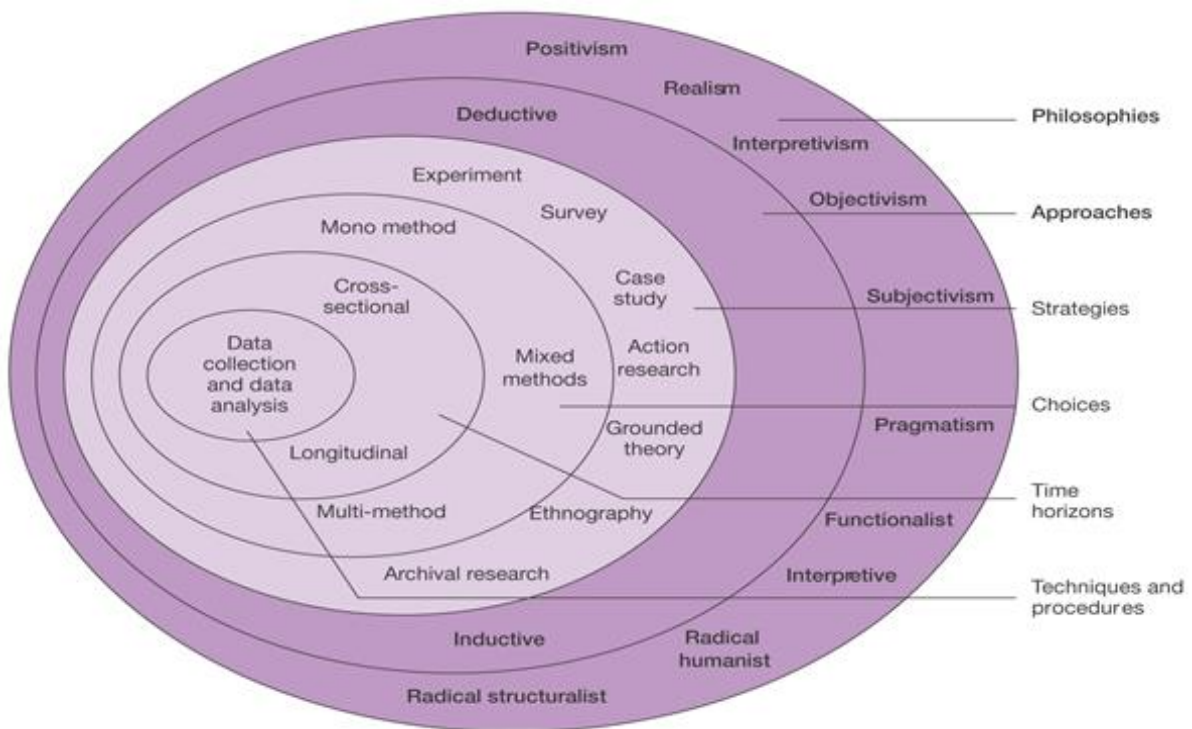


Figure 15 Research Onion (Saunders et al., 2015)

## 5.3 Research Philosophy

“Philosophy, (from Greek, by way of Latin, *philosophia*, “love of wisdom”) is the critical examination of the grounds for fundamental beliefs and an analysis of the basic concepts employed in the expression of such beliefs” (Britannica, n.d). In terms of research, the adopted philosophy contains the researcher’s assumptions and the way they view the world (Groat & Wang, 2002; M. Saunders et al., 2015). The research philosophy is represented by the outer layer of the ‘research onion’, which, according to Saunders et al. (2015), contains three ways of thinking about philosophy: ontology, epistemology and axiology. These ways determine how the research will be conducted and enhances the understanding of the approaches and activities of the research process.

### 5.3.1 Ontology

Although (Fellows & Liu, 2008, p. 68) state that, “Ontology concerns ... the assumptions in conceptual reality and the question of existence apart from specific objects and events”, Gray (2014, p. 69) defines it as “the study of being, that is, the nature of existence and what constitutes reality”. Moreover, M. Saunders et al. (2007) provide three aspects of ontology; objectivism, subjectivism and pragmatism. According to M. Saunders et al. (2007), objectivists assume that social phenomena exist external to their social context, while subjectivist assume that these social phenomena are created by the views and interactions of ‘social actors’ within a social context. Between these two extremes lies the pragmatist’s assumption, who claims that the research philosophy, in general, should be based on the nature of the research question, which may often mean working with more than one philosophy and with mixed methods (M. Saunders et al., 2007).

Based on the nature of the phenomena and research question explored in this study, the ontological position of this research leans mainly towards subjectivism. Achieving the aim of this research requires a thorough understanding of the actual potential of the ‘digital’ on architectural design. Hence, the research is not looking for a single reality, and in fact, this reality (the actual potential) is often subjective, differing from one design practice to another as each has its own methods, techniques and approaches in employing the ‘digital’. Furthermore, within the same practice, the potential for digital technology can be different from one architectural project to another. In fact, in the realm of architectural design, each project has its own nature (Rittel & Webber, 1973, cited in Hudson, 2010), and may require

different types of information and knowledge (Lawson & Dorst, 2009; Plowright, 2014), and unique methods and approaches (Cross, 2011; Lawson, 2006). Therefore, each project could require a different way of interacting with digital technologies. These aspects show that the ontological assumptions in this research rely heavily on subjectivism. Nonetheless, some few aspects of the research need to be investigated from an objectivist perspective. For instance, the research investigates whether parametric modelling applications can be used as BIM tools; therefore, the research investigates the existence of an underpinning common reality, that is not subject to different views. Therefore, a few examples from real projects will explore how parametric design tools were used for BIM purposes.

### **5.3.2 Epistemology**

“Epistemology is the branch of philosophy that concerns the origins, nature, methods and limits of human knowledge” (Fellows & Liu, 2008, p. 68). From a different perspective, Oxford Dictionaries (n.d) defines it as, “the theory of knowledge, especially with regard to its methods, validity, and scope, and the distinction between justified belief and opinion”, while M. Saunders et al. (2015, p. 135) similarly emphasised ‘validity’ by stating that “epistemology concerns what constitutes acceptable knowledge in a field of study”. It is important for a researcher to determine the epistemological position of their study in order to critically select the appropriate methodology in relation to the nature of the research. The following sections will explain these positions in order to determine the epistemological position of this research, which will be based on the aim and objectives, the nature of the phenomena being explored, and the type of data collected and analysed.

#### **5.3.2.1 Positivism**

The epistemological position of positivism is similar to that of a natural scientist. A positivist is mainly concerned with non-metaphysical facts, rather than impressions. These facts are normally observable and are measured by observer, who remains unaffected by the subject of the research; hence, the observer is less prone to bias (Saunders et al., 2007). Positivists believe that no credible data can be obtained from phenomena that are not observable. They also believe that the same outputs will result when replicating the same inputs under the same circumstances. This position is likely to require a highly-structured methodology; thus, positivists normally use a quantitative approach that lead to statistical analysis (Fellows & Liu, 2008; M. Saunders et al., 2007).

### 5.3.2.2 *Realism*

Similar to the positivist position, the realist uses a scientific approach to develop knowledge. However, realism is based on the assumption that the truth can only be grasped by human senses (Saunders et al., 2007). Nevertheless, it is important to differentiate ‘direct realism’ from ‘critical realism’. Thus, direct realists believe that the world can be accurately described by what humans experience through their senses, while critical realists believe that the senses allow us to experience sensations of things, but not the things directly, which, in some situations, may result in illusions (Saunders et al., 2007).

### 5.3.2.3 *Interpretivism*

M. Saunders et al. (2007, p. 106) define interpretivism as “an epistemology that advocates that it is necessary for the researcher to understand differences between humans in our role as social actors”. They state that interpretivists emphasise the conduct of “... research among people rather than objects”. According to Fellows and Liu (2008), interpretivists believe that reality is constructed by humans involved in social interaction. It can be interpreted through a variety of human perspectives; for example, reality is different from one person to another, and hence, interpretivists emphasise that researcher should have the ability to see this reality through the eyes of other people related to the research subject. As such, the interpretivist position appears to be the opposite of the positivist position.

Having reviewed different epistemological positions, and based on the nature of the phenomena explored, the epistemological position of this research leans mainly towards interpretivism. The research investigates the impact of the ‘digital’ on architectural design and the way in which the different digital tools and techniques applied in practice are reshaping the design process and influencing design activities and tasks. Thus, the research will gather knowledge that will be interpreted from people’s opinions (architectural design practitioners), and from people’s work (analysis of the design process of existing buildings). It will also consider the social context of these works within current architectural practice (collaborative and interdisciplinary work environments). All these aspects show the interpretivist nature of the phenomena explored. However, some few aspects of the study require investigation from a positivist perspective. For instance, the factors that restrict the effective use of technology in some architectural practices are facts that can only be determined through the observation of non-metaphysical phenomena. Thus, the observations of these phenomena will return the same output when reiterated.

### 5.3.3 Axiology

M. Saunders et al. (2007, p. 110) define axiology as, “a branch of philosophy that studies judgement about value”. It concerns the extent to which the researcher’s values influence the various stages of the research process. In this regard, the research axiology can lie somewhere between a value-laden research, and a value-free research. In value-laden research, the researcher can interact with other social actors involved in the subject, and can include their opinion, while in the value-free research, the researcher is external to the subject and works on the process and findings independently from their own views (M. Saunders et al., 2007).

The axiological position of this research is mainly ‘value-laden’. The research investigates the recent phenomena in computational design based on theoretical arguments made by different authors, and based on arguments and explanations provided by practitioners. However, the way in which the theoretical arguments are tested in practice, and the way in which the practical explanations are used to exemplify different theoretical aspects are mainly based on the author’s perception, and the logical analysis of the origin, impact and context of these phenomena. This logical analysis is based on the author’s knowledge and experience in the field, which is essential for the generation of the research outcome. However, some few aspects of the investigation rely on a value-free axiological position, such as the factors that restrict the effective use of technology in practice, and the use of parametric modelling applications as BIM tools. Having determined the philosophical stance of this research, this will be used to underpin later decisions concerning the research approaches, strategies, and data collection techniques and analysis procedures.

## 5.4 Research Approach

Having examined the first layer of the ‘research onion’, this section will address the second layer, which involves the research approach. According to M. Saunders et al. (2007), each study starts with a theory, and it is the clarity of the theory at the outset that most affects the choices concerning the research approach and design. The selection of the approach for this research is mainly affected by the lack of maturity of design theory, as explained in the introduction chapter. To address this, three research approaches are discussed, namely the deductive, inductive and abductive approaches (Saunders et al., 2015). These approaches are principally informed by the nature of the research objectives and the data collected and analysed, alongside the maturity of the theory.

Table 1 provides a comparative explanation of the deductive, inductive and abductive approaches.

**Table 1: Research Approaches**

<b>Deductive Approach</b>	<b>Inductive Approach</b>	<b>Abductive Approach</b>
Concerns theory testing (M. Saunders et al., 2007)	Concerns theory building (M. Saunders et al., 2007)	Concerns the modification of existing theory (M. Saunders et al., 2015)
Defined as: “a research approach in which a theory and a hypothesis is developed and a research strategy is designed to test the hypothesis” (M. Saunders et al., 2007, pp. 117-118)	Defined as: “a research approach in which data is collected and theory is developed as a result of data analysis” (M. Saunders et al., 2007, pp. 117-118)	Defined as: “a research approach, where data is collected to explore a phenomenon, identify themes and explain patterns, to generate a new or modify an existing theory which subsequently be tested through addition data collection” (M. Saunders et al., 2015, p. 145)
Appropriate when the research topic is supported by extensive literature (M. Saunders et al., 2007)	Appropriate when the research topic is new and there is insufficient supporting literature (M. Saunders et al., 2007)	Appropriate when the theory underpinning the phenomena is plausible (M. Saunders et al., 2015)
Deductive reasoning involves “moving from a general statement to specific statement” (Fellows & Liu, 2008, pp. 15-16)	Inductive reasoning involves “moving from specific statement to general statement” (Fellows & Liu, 2008, pp. 15-16)	Abductive reasoning involves “generalising from the interaction between the specific and the general” (M. Saunders et al., 2015, p. 145)
Deductive reasoning occurs within the boundaries of existing knowledge (Fellows & Liu, 2008)	Inductive reasoning extends the boundaries of current knowledge (Fellows & Liu, 2008)	The abductive approach aims to modify theory that is plausible (M. Saunders et al., 2015). Therefore, abductive reasoning interacts with the boundaries of current knowledge

An extensive body of computational design theory exists that lacks some maturity, as revealed in the previous chapters. To address this problem, this research, on one hand, explores different emerging novel design methods, in order for those phenomena to be tested and investigated in the real practice. On the other hand, the results of these tests, alongside the further investigations into more recent phenomena will help to deepen the understanding of the issue, and the practical context of those phenomena, in order to increase the maturity of theory. In other words, in order to increase the maturity of the theory that is currently plausible, the research establishes new links between theory and practice that requires a combination of theory testing in practice and theory building from practical phenomena. Therefore, the approach of this research is abductive.

## **5.5 Research Design**

According to Robson (2002), the research design helps to transform the research question into a research project, whereas Gray (2014, p. 128) defines research design as “the overarching plan for the collection, measurement and analysis of data”. Moreover, M. Saunders et al. (2007) state that well-specified research questions, together with a clear aim and objectives result in the determination of the research purpose, and convenient and appropriate methods for collecting and analysing data. The research design represents layers three, four, and five of the research onion, which refers to research choice and purpose, the research strategy, and research time horizon respectively (Saunders et al., 2015).

### **5.5.1 Research Choices**

This layer involves the choice between quantitative and qualitative methods, which may also involve “the way in which the researcher may choose to combine quantitative and qualitative techniques and procedures” (M. Saunders et al., 2007, p. 145). In quantitative methods, a research “seeks to collect factual data and relate it to theories and previous work”, while in qualitative approaches, a research “seeks to collect data concerning people’s beliefs, understandings, opinions or views in order to gain insight and understanding of people’s perceptions of the subject” (Fellows & Liu, 2008, p. 27). This comparison reveals the qualitative nature of this research, which investigates recent phenomena in computational design and the impact of ‘digital’ on architectural design practice. This investigation can only be conducted through exploring the beliefs, understandings, opinions and views of architects in practice. Moreover, the qualitative nature of this research is inherited from the qualitative

nature of the subject itself. Architectural design is a ‘messy’ activity (Chaszar & Joyce, 2016) that requires designers to rely on ‘tacit’ knowledge (Plowright, 2014), subjective cognitive support (Lawson, 2011), undefinable sorts of experience (Lawson & Dorst, 2009), and insufficient information (Jones, 1992) in order to solve ambiguous problems (Cross, 2011) that are unique in every situation (Rittel & Webber, 1973 in Hudson, 2010). This ambiguity, uncertainty, uniqueness and subjectivity highlights the difficulty in obtaining ‘factual’ data and hence, indicates the need to rely on qualitative data.

In quantitative approaches, the researcher uses scientific techniques to obtain measurements and depends only on theory and literature to evaluate the results and draw conclusions. In comparison, the techniques used to collect and analyse data in qualitative approaches are usually more complicated and impacted by external influences, including the researcher (Fellows & Liu, 2008, p. 27). This echoes the axiological position of this research which is mainly ‘value-laden’. In fact, the impact of ‘digital’ on design is subjective and may differ based on the practical context and project context. In addition, this impact is open to diverse perceptions and interpretations from different external individuals, including the author of this research, which re-emphasises the qualitative nature of this research.

The researcher in quantitative approaches uses data collection techniques and data analysis procedures to generate numerical data (Saunders et al., 2007, p. 145), while in qualitative approaches, the researcher uses data collection techniques and data analysis procedures that generate non-numerical data, such as words, narratives, pictures or video-clips (Saunders et al., 2007, p. 145). The research will not require nor generate any statistical or numerical data. The study investigates the phenomena in practice, and thus will be based on explanations, comments and feedback from practitioners about the methods applied and the way in which different problems are tackled. Therefore, the data required for this research will be collected from people’s opinions and perceptions (architectural design practitioners), and from the exploration of people’s work (the design processes of different projects). Furthermore, these opinions, perceptions and works will be compared to each other in light of the literature review outcomes and the author’s perception. Thus, the research only considers qualitative data, which will be analysed qualitatively.

### **5.5.2 Research Purpose**

M. Saunders et al. (2007) state that the way in which research questions are asked can determine the research purpose. They also argue that one study can have many purposes,



while Yin (2018) explains the significant impact of the research purpose on the data collection and analysis choices. Therefore, in the next three sections, different research purposes will be explored in order to specify the purpose that best reflects this study.

#### **5.5.2.1 Exploratory Research**

Exploratory research aims to explore aspects of theory in which the researcher usually develops a hypothesis in order to test it using convenient methods for collecting and analysing relevant data (Fellows & Liu, 2008). In this regard, M. Saunders et al. (2007) argue that the exploratory research can mainly be useful when the researcher needs to improve their understanding of the nature of a problem. They also argue that this kind of research is adaptable as the direction of the study can be changed during the research process. This change can be a result of new insights gained from the analysis of data. In this light, Adams and Schvaneveldt (1991) in M. Saunders et al. (2007) argue that the flexibility of exploratory research helps to narrow the focus of the study during the process, rather than a change in its direction.

#### **5.5.2.2 Descriptive Research**

In research that has a descriptive purpose, a researcher relies on their own perspective to systematically identify different elements of a phenomenon or a process (Fellows & Liu, 2008). M. Saunders et al. (2007) argue that this kind of research can be an extension of exploratory or explanatory research, and that collecting data in a descriptive study should be preceded by a thorough and clear understanding of the phenomena under study.

#### **5.5.2.3 Explanatory Research**

This kind of research studies a situation or a problem in order to establish causal relationship between different variables (M. Saunders et al., 2007). Explanatory research can be a continuity to an exploratory research (Fellows & Liu, 2008).

The previous discussions about the different research purposes, leads to the assertion that the purpose of this study is explanatory. The research process explores the relationship between three aspects; computational design theory, digital technologies and methods, and architectural practice. Moreover, this research investigates the dual-directional impact of each two aspects, namely how advances in digital technologies result in the emergence of novel design approaches and methods within current architectural practice, and how those novel approaches and methods are continuously developed, to hence, influence further development of technologies. Finally, this dual-directional impact between technologies and practice will

be considered in light of the need to reevaluate the computational design theory, and how theory is developed to enable a mature comprehension of the relationship between technologies and practice and thus increase the efficiency of digital technologies in architectural practice.

### **5.5.3 Research Time Horizon**

In order to specify the time horizon of a study, M. Saunders et al. (2007, p. 148) suggest thinking about the research as either “a ‘snapshot’ taken at a particular time” or as “a ‘diary’ and be representation of events over a given period”. ‘Snapshot’ research is referred to as ‘cross-sectional, while ‘diary’ research is referred to as ‘longitudinal’.

#### ***5.5.3.1 Cross-sectional Study***

According to M. Saunders et al. (2007, p. 148), the cross-sectional study is “the study of a phenomenon (or phenomena) at a particular time”. For instance, this kind of study is convenient when the research requires an explanation or description for the incidence of a phenomenon in a specific time.

#### ***5.5.3.2 Longitudinal Study***

In contrast, a longitudinal study investigates a phenomenon (or phenomena) over a period of time. Hence, it could be an appropriate choice if the researcher is interested in the changes and development of the subject over time (M. Saunders et al., 2007)

The time horizon of this research is cross-sectional in that it addresses a particular ‘snapshot’ in time of technological development and adoption by architectural practices, and the specific capabilities of exiting design technology. Although it considers both past and future in terms of the secondary and primary data collection, respectively (through the literature review and case study questions), both interpretations are grounded in a present-day reading of these data. It was not possible, and indeed beyond the scope of this study to trace the developing adoption and changes to design technology, thus a longitudinal timeframe was not adopted.

### **5.5.4 Research Strategies**

In order to choose a convenient strategy for a study, the main consideration should be “the logic that links the data collection and analysis to yield results” (Fellows & Liu, 2008, p. 20). According to M. Saunders et al. (2007, p. 135), the choice of a research strategy should be based only on “the ability of a strategy to answer the research question and meet objectives”.

Moreover, a variety of factors can guide the choice of a strategy, and these are (M. Saunders et al., 2007):

- The availability of knowledge and sources;
- The timescale of the research;
- The philosophical research stance.

From another perspective, the following conditions are essential in selecting a research strategy (Robert K Yin, 2014, p. 9):

- “the type of research question posed;
- The extent of control a researcher has over actual behavioural events;
- The degree of focus on contemporary as opposed to entirely historical events”

Influenced by the previous choices and discussion, the appropriate research strategies for this study are affected by the type of questions raised in the first chapter. These questions mainly focus on the way in which technologies effect design rather than the results of this effect. Furthermore, as discussed in the first chapter, the research principally focuses on how the situation is continuously changing, rather than what has been changed. In addition, the selection of the research strategies will be affected by the novelty of the digital technologies and design methods applied, which instigates the need to collect recent data to explore how state-of-the art technology is applied to practice.

#### **5.5.4.1 Survey**

The following features characterise this research strategy:

- Associated with deductive approach;
- Used to answer who, what, where, how much, and how many questions;
- Allows for the collection of a large amount of data at a low cost;
- Allows for sampling to generate findings;
- Data is obtained by using questionnaires, or structured interviews with standardised questions for all interviewees (M. Saunders et al., 2007).

The features of the survey strategy are not applicable for this research, as the research is not asking who, what, how much, and how many questions; instead, this study raises ‘how’ questions. More precisely, the research focuses on how digital technologies influence the emergence of novel design approaches, how these approaches affect architectural practice,

and how practitioners can enhance the efficiency of these approaches and technologies in practice.

#### **5.5.4.2 Grounded Theory**

Gloser and Strauss (1967) in Fellows and Liu (2008, p. 94) state that grounded theory involves “the discovery of theory from data”. More comprehensively, Strauss and Cobin (1998, p.23) in Gray (2014, p. 601) defines this as a theory that is “discovered, developed and provisionally verified through systematic data collection and analysis of data pertaining to the phenomenon”. Furthermore, Fellows and Liu (2008) state that the data in grounded theory is normally collected through observations, while, M. Saunders et al. (2007), state that forming an analytical theoretical framework prior to data collection is unnecessary. In general, grounded theory is described as the most convenient strategy for theory building (M. Saunders et al., 2007).

The previous definitions resonate with an inductive research approach which has not been adopted in this study. Thus, the grounded theory strategy is not applicable for this study, which is not building theory, but rearticulating parts of the theory to enhance its maturity. More precisely, the theoretical framework developed in this research is not generated from the practice, but extracted from existing theory, and further refined through examples from the practice.

#### **5.5.4.3 Experiment**

The research experiment strategy answers ‘how’ and ‘why’ questions (Fellows & Liu, 2008). They are mainly used in exploratory and explanatory research in order to study causal links between two or more variables (M. Saunders et al., 2007). More precisely, experiments can investigate how a change in one variable may result in a change in another dependant variable (Hakim, 2000 in M. Saunders et al., 2007). However, an experiment separates a phenomenon from its context (Robert K Yin, 2014). while the practical context is essential in this research, the experiment strategy does not seem to be applicable for this research.

#### **5.5.4.4 Case Study**

“A case study is an empirical inquiry that investigates a contemporary phenomenon (the case) in its real-world context, especially when the boundaries between phenomenon and context may not be clearly evident” (Robert K Yin, 2014, p. 16). Moreover, M. Saunders et

al. (2007) highlights several situations for which a case study strategy represents an appropriate strategy:

- When the study requires a rich understanding of the concept of the phenomena investigated (Morris and Wood, 1991 in M. Saunders et al., 2007)
- When a strategy is needed with the capacity to answer why, what and how questions
- When explanatory and exploratory research are adopted.

The ‘case study’ strategy is adopted in this research for several reasons. Firstly, this study explores phenomena that are ambiguous, as they result from recent and rapidly evolving technological advances (De Rycke et al., 2018; Haidar et al., 2017). Therefore, the theory that underpins these phenomena is not sufficiently mature. In other words, the boundaries between these phenomena and their theoretical context are not evident, and require a richer understanding of the concept of the phenomena and their practical context. In fact, the theoretical framework developed in the previous chapter requires inspiration from the methods and approaches applied within current practice. These approaches represent the practical context of the phenomena that are needed to enhance the maturity of the framework. Furthermore, the web is full of digitally-driven design experiments involved in parametric modelling and algorithmic and generative design. These experiments are disconnected from any context, while this research is focused on phenomena within their real context. Therefore, the contradiction between the multiplicity of parametric design experiments available on the web, and the rarity of its implementation in practice reveals a difficulty in implementing parametric design in real practice, which motivates the need to explore the factors that restrict its effective use in practice. Another important quality of a case study strategy is its role in compensating for missing information within the practical literature (Hudson, 2010), which for this study, currently lacks detail, depth, and an appropriate link to the design theory. In fact, it is highly likely that many practices may not publish in-depth information about their design strategies and approaches due to privacy issues. Furthermore, most of these practices lack the motivation to share information about their work (Hudson, 2010). This can be attributed to the privacy, confidentiality and limited time availability of architectural practices.

## **5.6 The Case Studies (Selection and Categorisation)**

Having specified the case study as the strategy for this research, this section discusses the application of this strategy. This is based on the nature of the research, its questions and

objectives, and helps to identify the data collection techniques and data analysis procedures in the following sections. Therefore, this section will identify the type of case study applied in this research, and the criteria applied to select cases. This includes the exploration of various sampling techniques and strategies to identify and categorise the research cases.

### **5.6.1 Single Case vs Multiple Cases**

Case study research may rely either on a single or multiple cases; the reliance on a single case normally occurs when the case is a critical, extreme or unique, while the reliance on multiple cases can be preferable when the rationale of the research focuses on whether the findings from one case occur in other cases. This allows the researcher to generalise findings from such multiple cases (Robert K.. Yin, 2003).

The strategy in this research is based on multiple cases rather than one single case. The main reason for this choice is because digital technologies and methods are vast; therefore, there is no one single architectural practice that has the capacity to effectively utilise all such technologies. Furthermore, the way in which digital technologies are utilised differs from one architectural practice to another as each has its own philosophy and approach, and diverse individual and collective experiences. In fact, Within one single architectural practice, the way that digital technologies are used in designing a specific building can be different to another building as each design project is unique (Rittel & Webber, 1973, cited in Hudson, 2010) and has its own nature and circumstances, and may require different approaches, tools, and potentially different experiences (Lawson & Dorst, 2009) and digital literacies. In addition, the impact of digital tools on architectural design can also be informed by the advancement of digital technologies utilised in the practice. In fact, the engagement of highly-advanced digital tools in design practices can be expensive, which results in different attitudes toward the feasibility and cost-benefit of such technologies. Consequently, the research needs to investigate the way that digital technologies and tools are utilised and developed from different perspectives.

### **5.6.2 Sampling**

According to Fellows and Liu (2008, p. 159), sampling provides the means to enable the collection of data collection and the processing of components. More comprehensively, M. Saunders et al. (2007, p. 204) differentiate a census from sampling, as census refers to “collecting and analysing data from all possible cases”, while, “sampling provides ways to reduce the amount of data needed to be collected by considering only data from some chosen

subgroups”. In this regard, they introduce the term ‘population’ which, in this context, refers to “the whole cases from which a sample is chosen” (M. Saunders et al., 2007, p. 205).

In this research, the ‘population’ signifies all architectural firms. As it is impossible and unnecessary to study all (census), the research selects some architectural firms for study (sampling). While a variety of sampling techniques is available, choosing the appropriate technique for this research is based on the ability of each firm to generate the data needed to answer the research questions and meet the objectives. In this light, M. Saunders et al. (2007) argue that in choosing fewer cases, greater accuracy and detail can be obtained. This accuracy and detail appears to be an essential necessity for this research; the wide range of phenomena explored in the previous chapter and the significant and multi-faceted changes in architectural design caused by those phenomena indicate that this research require exceptional level of breadth, richness and depth, which can be obtained from fewer cases.

#### ***5.6.2.1 Sampling Techniques***

M. Saunders et al. (2007) divide sampling techniques into two types; probability (or representative), and non-probability (judgemental) sampling. The representative samples have the same probability of answering the questions of the research and meeting the objectives; hence, they generate statistical data that are more suitable for survey research (M. Saunders et al., 2007). On the contrary, in judgemental sampling, each case has a different probability of answering the research questions and meeting the objectives. In this technique, no statistical data is generated, which makes it suitable for case study research (M. Saunders et al., 2007). Judgemental techniques are relevant to this research, as the case study strategy involves architectural firms with their own unique philosophies, strategies, and circumstances; hence, each practice will offer different valuable perspectives in response to the research questions and objectives.

#### ***5.6.2.2 Non-Probability (Judgemental) Sampling***

Having specified the sort of sampling technique required for the data collection and analysis, the exact sampling techniques used in this research can be identified. In this regard, Saunders et al. (2007) outlines five main judgemental sampling techniques, which are: quota, snowballing, self-selection, convenience and purposive sampling.

Quota sampling is normally used for interview surveys where the selection of samples relies on a non-randomised selection that tends to represent the whole population and with the same

variability (Saunders et al., 2007). The selection of cases are non-random in this research, and the study does not adopt a survey method. Moreover, the selected practices are not meant to represent all architectural practices. The level of reliance on ‘digital’ in architectural design and the purpose for which ‘digital’ is utilised is extremely varied and subject to the specific requirements and circumstances of each practice. Furthermore, each project is unique. Therefore, no architectural firm has the opportunity to represent all architectural practice, which indicates that relying on quota sampling is not applicable in this study.

Snowball sampling is used when there is difficulty in identifying sample members and hence cases are suggested by previous cases (Saunders et al., 2007). This sampling strategy appears to be useful; however, it has not been adopted as the main sampling strategy in this research as there is no difficulty in choosing practices as case studies due to the availability of information in the practical literature and in various design magazines and websites. Therefore the cases are mainly selected by the author based on the nature of the research objectives and the flow of information within the case study research.

Other techniques include self-selection and convenience sampling; in the former, cases volunteer their participation, while in the latter, the cases are selected according to opportuneness, for example accessibility (Saunders et al., 2007). Neither of these techniques corresponds are perceived as appropriate and therefore adoptable in this study. It is difficult to ensure participation through an open invitation, thus, self-selection is not chosen. Furthermore, it is important to consult firms sufficient practical experience and engagement with computational design phenomena, thus, the cases in this research cannot be selected through convenience. Indeed, the selection is critical and requires sufficient breadth and depth of data to answer the research questions and meet the objectives.

Purposive sampling is often used in a case study strategy where small samples are selected and the focus is on selecting the most informative cases. Therefore, the selection of each case depends on the outcome of the previous case (Saunders et al., 2007). This sampling technique enables the use of judgement to select cases based on the research questions and objectives. Considering the case study strategy that was adopted for this research, this sampling technique appears to be the most appropriate for this study. As discussed in the introduction chapter, advanced digital technologies and methods are only used in the minority of architectural practices. Therefore, the research will focus on this minority, which, in this case, represent the ‘most informative cases’. Furthermore, the focus is on the richness and depth of



information rather than the number of cases. In addition, the ability to use the outcome of the case to inform the selection of the next case appears to be a highly effective selection method, as it can accommodate a dynamic situation where a vast array of digital technologies are evolving within a short period of time. This results in the need to continuously revise the focus of the case study and the selection of the cases based on the novel design approaches and technologies that might emerge in the process of conducting the research.

### *5.6.2.3 Strategy for selecting cases in a purposive sampling technique*

Having specified the purposive sampling technique for the selection of cases, this sub-section focuses on the cases needed for this research, the level of variation required, and the nature of this variation. In this regard, Saunders et al. (2007) outline four strategies for selecting cases in a purposive sampling technique. The first is the ‘extreme or deviant cases’, where the focus is on ‘unusual cases that enables the generation of extreme outcomes which may have the potential to answer the research questions’. The second strategy is ‘heteroecious or maximum variation sample’ where ‘the sample is selected to ensure the maximum variation in the cases within the sample’. The third strategy is ‘homogeneous sampling’ where the sample is selected from similar cases that are related to the same ‘subgroup’ which may enable greater depth in studying the characteristics of this group. The fourth strategy is ‘critical sampling’ where the selection is based on the importance of each case and its potential to generate critical points that can influence the research. This can allow for logical generalisations based on the phenomena/problems explored by examining whether these phenomena/problems may arise in all cases.

Initially, the selection of cases for this research appears to suggest a combination of these strategies. For instance, both the ‘greater depth’ enabled through selecting ‘similar cases’, and the greater breadth enabled through ‘maximum variation’ are appropriate. However, the selection cases in this research lies somewhere between these homogeneous and heterogeneous strategies. The discussion in Chapter 4 explained the high cost associated with the adoption of ‘digital’ in practice. Therefore, the focus is placed on large practices that can afford those technologies in order to consider the development of more effective and efficient ways of utilising these technologies. Besides, the first objective of this research is to identify the true potential of ‘digital’ in architectural design by investigating the phenomena that result from the adoption of ‘digital’ in practice. This can be achieved by analysing the potential for ‘digital’ in architectural practices that have adopted highly advanced digital

technologies and utilised those technologies successfully in projects. In this sense, the strategy for selecting cases relies on homogeneous cases as the research questions and objectives require the collection of data from large architectural practices with highly advanced digital technologies. In this case, those practices will represent a ‘subgroup’ of architectural practice, and a focus on this group will enable ‘greater depth’ when studying the ‘characteristics’ of this group.

Nevertheless, as the research focuses on the ‘transitional’ changes caused by the rapid evolution of technology, this study also requires the selection of some cases that are transitioning towards a mature and efficient adoption of ‘digital’ in their practice. This enables the study of transitional changes in architectural practice. Furthermore, the obstacles that restrict the efficient use of digital technologies in practice cannot only be investigated in practices with highly advanced digital technologies. This investigation requires the selection of cases with various levels of engagement in digital technology, as this will enable the exploration of various problems and enrich the breadth of the investigation. This variety should also include cases where traditional methods are still applied; however, in selecting cases, it is important to explore those practices who demonstrate willingness adopt advanced technologies in projects. These types of practice will offer the opportunity to explore the problems that architects in practice may encounter when technology is adopted.

Moreover, a few practices have demonstrated a highly-efficient way to employ advanced technologies in projects, which would suggest they represent ‘extreme cases’ that enable the generation of ‘extreme outcomes’. Consulting such cases would offer the potential to answer the research questions and meet the study objectives. However, other ‘normal cases’ are also required to enable a broader investigation and identify the impact of ‘digital’ within a practical context.

Therefore, ‘critical sampling’ appears to be the most suitable for this research. This criticality stems from the need to select a range of cases that can demonstrate both a high level of commitment and use of technology in their practice, and those who are still developing this potential whilst also using traditional methods.

### **5.6.3 Selecting and Categorising the Cases**

Having selected the ‘purposive sampling technique’ and the ‘critical selection’ strategy, this technique and strategy informed the selection of cases in this research. The selection was

based on the potential for each case to support the research and achieving its objectives. This investigation explored a large number of architectural firms through their websites and projects. In addition, some architectural practices provided publications and research papers that discussed their work processes and the different technologies and computational design methods they utilised. Those publications were reviewed in order to inform the case study selection. In addition, the selection was highly affected by the work progress. For instance, the selection of cases developing their capacity for technology and who tended to rely on traditional methods was motivated by the insufficiency of the information regarding obstacles and problems that were generated from advanced practices. In addition, where the digital technologies are the main focus of this research, a software development firm was selected to show the potential of the unpopular software applications in enhancing efficiency of the other popular software applications in practice. This was incited from the literature that shows how software developers can integrate into design teams within architectural practices.

In general, the firms selected as cases for this research were categorised based on the level of technological and methodological advancement in their projects. The advanced technologies and methods in this context refer to the previously discussed digital technologies and computational design methods (outlined in Chapter 2) such as scripting, algorithmic design, performative design, BIM and parametric design. Therefore, the cases that were selected for this research can be categorised as follows:

- 1- **Advanced firms** (2 cases): these are large size architectural firms that have a large number of branches around the world. These practices have successfully utilised a wide range of highly-advanced digital technologies within real projects and based on a wide range of computational design specialists in these firms;
- 2- **Semi-advanced practices** (3 cases): these are large size architectural firms that have several branches in different countries. These practices have demonstrated an efficient use of advanced digital technologies in a limited number of projects and based on a handful of specialists in computational design;
- 3- **Developing architectural firms** (2 cases): these are architectural firms who are still using traditional methods to approach design projects; however, they have robust strategies to innovate and develop their tools and methods towards a greater adoption of digital technologies and greater efficiency in utilising these technologies;
- 4- **Software development firm** (1 case): This is a software development firm that provides an online platform. The platform contains a series of lightweight software

applications dedicated to support collaboration, integration and a seamless information flow in different building projects within the AEC industry.

## **5.7 Identification of the Themes of the Case Studies**

The previous section has explained the need to rely on multiple cases rather than one single case in order to explore the practical context of computational design phenomena. Several sampling techniques and strategies were explored, and the most appropriate technique and strategy were selected to inform the selection and the categorisation of the cases required for this research. This section dives deeply into the nature of each case by identifying the ‘unit of analysis’ and outlining the main themes of the individual cases.

### **5.7.1 Unit of Analysis**

According to Yin (2014), one of the main components of case study research is the definition of the ‘unit of analysis’, which is the ‘specific case(s)’ to be studied. He outlines two different steps that should be considered in the definition of specific cases, and these are defining the case, and bounding the case. He argues that the tentative definition of the case is related to the way the research questions are defined, where each question may point to a different unit of analysis or case. Moreover, the unit of analysis needs to be revisited during the process of the study following the emergence of new discoveries. After the case is defined, the researcher moves to the next step, which involves bounding the case in order to determine the scope of the study, and to distinguish the difference between the data related to the case, and the external data that represents the general context (Yin, 2014). Identifying the ‘unit of analysis’ can lead to more greater specificity in identifying ‘the case’ for study. The previous section shows the architectural firm as ‘the case’ or ‘unit of analysis’; moreover, the purpose of adopting the case study was identified as investigating the potential for digital technologies and methods within architectural practice. In this case, computational design in practice can be identified as the unit of analysis or the ‘case’ in this study, while the firm itself offers the practical context in which the investigation is conducted. Consequently, as the theoretical framework started to develop, the bounding of the cases started to crystallise, where the focus shifted to more specific aspects. This specificity was gained through the exploration of different phenomena in computational design (Chapter 4), where each phenomenon represents one aspect of the impact of ‘digital’ on architectural design. Moreover, the phenomena shaped the bounding of the case, and hence the scope of the case study.

### **5.7.2 Holistic Cases vs Embedded Cases**

Holistic and embedded cases refer to the unit of analysis in a case study. When using an holistic case, the research focuses on the case as a whole, while in an embedded case, the researcher divides the case into sub-cases and addresses each of these sub-cases as a specific level of focus that is based on the research context (Robert K.. Yin, 2003).

This research adopted an embedded case type, as the focus is not on computational design in architectural practice as whole, but on specific phenomena, where each phenomenon represents a sub-case, such as collaboration, adaptability of tools, and the reliance on project-embedded research. This focus can be attributed to the nature of this research, which develops a theoretical framework, where each of the phenomena explored in Chapter 4, represents a component of the theoretical framework. These need to be explored individually within a practical context in relation to the other phenomenon. In addition, some cases include discussions around specific design scenarios which focus on the way in which different digital technologies were used and developed within real projects. In such cases, each scenario is considered a sub-case.

### **5.7.3 Case Study Questions**

As the main purpose of a case study strategy is to answer ‘how’ and ‘why’ questions (M. Saunders et al., 2015), Yin (2014, p. 29) suggests three stages to establish the case study questions: Firstly, to use the literature to narrow the interest into key topic(s); secondly, to review similar case studies and examine whether they conclude with new questions for future research and thus articulating new questions, and finally, to repeat the same process by examining another set of studies. This research focuses on ‘how’ and ‘why’ questions; for instance, it asks how digital technologies are changing the structure of the architectural design process, why digital technologies are not effectively used in practice, how the efficiency of these technologies can be increased in practice. These questions were generated from a critical review of the literature, where similar cases were explored (Bhooshan, 2017; Hesselgren & Medjdoub, 2010; Turrin et al., 2011; Whitehead et al., 2011), and the questions and study outcomes were examined in order to inform the case study questions in this research.

#### 5.7.4 Themes

Having identified the ‘unit of analysis’ in this case study research, and adopted ‘embedded cases’, the core themes were identified. These themes were derived from the literature review (mainly from computational design phenomena classified in Chapter 4) and then reduced into main themes. The main themes will represent the frame of reference for the collection and analysis of data in the later stages, and are outlined below:

- 1- **Technologies and tools:** discusses the software applications, techniques and hardware technologies used, in addition to the purpose for using each technology and application, and the stages at which they are used in each case. This was identified as the first theme, as it will help in providing a description of the general ambience of the firm, that can be considered when investigating the other themes;
- 2- **Roles and areas of specialisation:** examines the different roles, responsibilities, teams and areas of specialisation for members in each practice. This theme is a continuity of the ‘emerging roles’ that was noted as a phenomenon in Chapter 4;
- 3- **Processes and workflows:** explains how the tools and technologies are used, and the different individuals and teams operate within current practice and design projects. This will continue the theme ‘adapting, interacting with and design processes’ which was discussed as a phenomenon in computational design in Chapter 4. Moreover, other phenomena explored in the literature can be explored within their context under this theme, such as complexity in computational design, and the impact of the ‘digital’ on design creativity. This theme includes project scenarios to enable the exploration of the practical context within the design process of projects;
- 4- **Collaboration:** discusses the methods of collaboration, and the context in which design teams collaborate with each other and other disciplines. It also outlines the technologies and tools used for collaboration. This includes, the different technologies used to create integrated platforms to support collaboration, and the way in which information is shared, exchanged and utilised. Therefore, different phenomena, such as ‘integration’ and ‘automation of data flow’, can be investigated within the practical context under this main theme. Furthermore, ‘complexity’ and ‘design creativity’, which are explored under the previous theme, can also be explored further by investigating the impact of collaborative and integrated work within a practical context;

- 5- **Adaptation of tools:** investigates the ability of a firm to develop tools, the background of the software developers, and the purposes for which tools are adapted. Furthermore, it examines how software applications are adapted within projects. Again, this main theme can be related to other phenomena explored in Chapter 4, such as ‘the impact of other industries’, ‘the emergence of complex forms’ and ‘interoperability’ among different modelling software applications.
- 6- **Problems:** identifies the problems that designers encounter when utilising highly-advanced digital technologies, and the way that designers address these problems. While this can be related to all phenomena, it was identified as a main theme due to the criticality of investigating the obstacles that restrict the effective use of ‘digital’. This aims to determine how the efficiency of ‘digital’ technologies can be enhanced which is linked directly to the aim of this research;
- 7- **Research and development:** explores the role of research in practice, the areas of interest in the research, and the context in which the research is conducted. In addition to the ‘increasing role of research in practice’ that was discussed as a main phenomenon in computational design in the previous chapter, other phenomena are highly relevant and can be explored within their practical context under this main theme, such as ‘knowledge transfer’ and ‘digital repositories’.
- 8- **Future expectations:** the future expectations of the participant are explored, where they forecast design practice in ten years’ time, including any challenges, and how these might be addressed. The inclusion of this theme was motivated by the rapid evolution of digital technologies together with the minimal use of these technologies that results in the difficulty in understanding their potential. This difficulty can be addressed through exploring the future expectations of architects in practice who are highly knowledgeable of computational design and able to provide plausible future expectations.

These core themes are iterated in each case study in order to establish validity and reliability in the outcome by investigating the same phenomena from different perspectives. However, the last case study has slightly different headings that relate to the same themes but from a different perspective, because it is based on a software development firm, rather than an architecture firm. Therefore, the focus is not on the way they operate, collaborate and adapt tools in their working processes, but rather on how the software applications that this firm develop aim to enable architectural practices to develop more seamless and feasible methods

of operating, collaborating, and adapting tools, and hence address the different problems that emerge when the ‘digital’ is adopted in practice.

## **5.8 Data Collection**

This section identifies the criteria for consideration when selecting the data sources. It also determines how the data was collected. It will also explain the ethical procedures undertaken while collecting the data, and how the quality of the collected data was assured.

### **5.8.1 Selecting the Data Collection Technique**

#### **5.8.1.1 Questionnaire**

Gray (2014, p. 352) states that, “questionnaires are research tools through which people are asked to respond to the same set of questions in a pre-determined order”. This makes the questionnaire an ideal data collection method for a survey strategy, while it can also be useful within experiments and case study strategies (M. Saunders et al., 2007). Fellows and Liu (2008) state that questionnaires can be based on two forms of questions; open and closed. Open questions give respondents the freedom to choose the form, content and extent for their answers; hence, the questions are easy to ask and difficult to answer and the non-standardised generated data is more challenging to analyse. In closed questions, the researcher provides a number of pre-determined answers for respondents to choose from. Respondents may still have the freedom to choose the form, extent or content of their answers when the researcher provides the ‘other’ response option, which enables further explanation. In both cases, all respondents are asked to answer the same questions in the same order, which allows data to be collected from a large number of respondents for quantitative analysis.

In this research, the same pre-prepared questions were applied to all cases; this enables the same phenomena to be investigated within various practical contexts in order to gain different perspectives and thus ensure greater reliability when investigating the potential impact of the ‘digital’. However these questions may vary due to the subjective nature of the phenomena and the uniqueness of each firm and project. In addition, only a few cases are selected in order to allow sufficient depth to the investigation. This indicates that a questionnaire is not a convenient data collection technique for this research as it is more appropriate for collecting data from a large number of cases. Furthermore, the study does not intent to gather quantitative data but rather focuses on qualitative data to enable greater depth and variety.



### **5.8.1.2 Observation**

According to M. Saunders et al. (2007, p. 282), “observation involves the systematic observation, recording, analysis and interpretation of people’s behaviour”; hence, it is an appropriate data collection method for research that requires an understanding of behaviours (M. Saunders et al., 2007). Observation also helps researchers in developing “a deep and long-term engagement in the field of study” (Gray, 2014, p. 412), and can be divided into two types; participant observation and structured observation (Gray, 2014; M. Saunders et al., 2007). In participant observation, the focus is on “the meaning that people attach to their actions”; thus, it tends to generate qualitative data, while in structured observations, the focus is more on the frequency of people’s actions; hence, it is likely to generate quantitative data (M. Saunders et al., 2007, p. 282).

Despite its potential in enabling a comprehensive understanding of the different phenomena in computational design in its social context, it is more appropriate for a single-case study research, while in this research, the various digital technologies and methods are investigated within multiple cases to capture the variety of approaches to technology in practice.

### **5.8.1.3 Interviews**

“An interview is a purposeful discussion between two or more people” (Kahn and Canne, 1957 in M. Saunders et al., 2007, p. 310). In a study, interviews can help researcher to gather reliable data that gathers views, beliefs and opinions that are relevant to both research questions and objectives (M. Saunders et al., 2007). Gray (2014) describes two main situations in which interviews can be an appropriate data collection technique:

- 1- Where explanatory research is undertaken, and the researcher needs to explore attitudes and feelings at depth;
- 2- Where detailed responses from interviewees enable opportunities for greater clarification and detail on a phenomenon Gray (2014).

The interview is suitable for this research, as it enables direct communication with the participant, and hence, a greater opportunity to investigate the practical context of the phenomena in more depth and breadth.

## 5.8.2 Types of Interviews

Interviews can be divided into three types, and each type has different nature. Meanwhile, the choice of interview type should be consistent with the research questions and objectives, and with the research strategy (M. Saunders et al., 2007) These types are:

### 5.8.2.1 *Structured Interviews*

The questionnaire is based on predetermined or standardised questions. These questions should be asked to all interviewees exactly as they are written and with the same tone in order to avoid bias, which may affect the reliability of data. This type of interview is normally used to collect quantitative, standardised data (M. Saunders et al., 2007).

### 5.8.2.2 *Unstructured Interviews*

This type of interviews has no predetermined list of questions but, instead, the interviewer relies on their clear idea about the subject in order to ask appropriate questions. The interviewee, in turn, is given freedom to talk and hence, to direct the discussion (M. Saunders et al., 2007).

### 5.8.2.3 *Semi-structured Interviews*

Researchers prepare a set of questions that can vary from one interviewee to another. They can also be changed or modified during the interview based on the context and the flow of information. For instance, the researcher can omit some questions, add other questions, or change the order of the questions (M. Saunders et al., 2007).

In this research, a standardised set of questions, derived from the literature review, are developed and used within the interviews in order to allow for comparison among the data collected from different cases. Thus, an unstructured interview is not suitable for this research as it relies on non-predetermined questions and thus produces less easily comparable responses. Furthermore, the structured interviews are not appropriate, as they do not enable flexibility in altering or tweaking questions to respond to the practice nature, specific adoption of technology and the participant background. As a result, the research adopts the semi-structured interview as the main data collection technique due to its flexibility in capturing the range of different perspectives on technology in practice. More precisely, the semi-structured interviews enable the author to obtain direct answers for the research particular questions from highly-expert practitioners. They also offer the freedom to ask for

more clarification or detail in order to respond to the uniqueness of each firm and the distinctiveness of each project scenario under study.

### **5.8.3 Managing Interviews**

#### ***5.8.3.1 Procedures for Selecting and Communicating with Participants***

Interviews were conducted with practitioners from various architectural firms, where the selection of participants was critical. For instance, the research needed to investigate the context of the phenomena within firms that are known to have achieved a degree of mastery in utilising and developing highly-advanced digital technologies and methods in their work. In addition, the research needed to gain insights from practices that continue to rely on traditional methods but indicate an appetite to innovate by developing strategies to enable more effective and efficient use of technology. A careful selection of participants therefore enabled a more in-depth investigation concerning the associated practical problems and the challenges. To achieve this, some practitioners were identified through a personal connection at conferences and events, whilst others were approached using social media, such as LinkedIn, after exploring their profiles. Furthermore, some participants were selected through snowballing, where the researcher was introduced to potential participants by other participants who had already been interviewed. The participants were contacted by email, telephone, or social networks, such as LinkedIn and Twitter, where they were asked about their interest in participating and their availability. The interview questions (Appendix C) were sent to the participant to give them time to consider their answers. Based on the availability of the participants, and their geographical locations, the interviews were conducted either face-to-face, on telephone, or via Skype. Furthermore, the interviews were, with interviewee permission, digitally recorded and transcribed verbatim.

#### ***5.8.3.2 Ethical Procedures***

The anonymity and confidentiality of the interviewees were protected within the study. Prior to an interview, a 'Participant Information Sheet' (Appendix A) was sent to each interviewee. This document contained details about the research to allow the participant to gain a general understanding, including why they were contacted, and other information about the participation, including: the purpose and duration of the study, how the research would be conducted, what was involved in participating, the terms for withdrawal, how the data generated from the interview would be used and stored, how the data would be destroyed in case of withdrawal, and who would be able to access the data. Thus, the sheet included

strategies to assure interviewees of the ethical use of their data. In addition, the interviewee was sent a consent form (Appendix B) to declare that they had read the information about the research, and had been given the opportunity to ask questions, and express their willingness in participating in the research. Furthermore, the participants were given the right to withdraw from participation at any stage without giving any justification, and it was clarified that, in such cases, all the protected data would be destroyed, and would not be shared or published. This was clearly explained before the interview and it was mentioned in the consent form.

The recording of the interviews was preceded by the participant's permission, which was expressed in the consent form. In addition, each participant was reminded that the interview was being recorded at the beginning of the interview. The recordings and the transcriptions were anonymous and coded. They were stored on a drive which required a password (known only by the author) for access. Furthermore, where some interview transcripts were printed, the documents were locked in a filing cabinet in the author's room, which could only be accessed by the author. Thus, data was only used in the thesis, where the identity of the participant was protected.

### ***5.8.3.3 Assuring the Quality of the Data Collection Strategy***

In order to assure the quality of the interviews and the reliability of the data generated from the interviews, a series of preparatory interviews were held with academics from different universities within the UK. In each of those interviews, the same questions were posed, and the academic staff members provided feedback about the appropriateness of each question in terms of its clarity, comprehensibility, and specificity. In addition, further discussions were held around each question. In most cases, the discussion focused either on the potential bias that could be caused by the way in which a particular question was asked, or the way in which the cultural differences could affect the interpretation of the answers. Furthermore, a couple of interviews held by other authors were also reviewed (Hesselgren & Medjdoub, 2010; Whitehead et al., 2011); these interviews were closely related to the subject of the research, as investigated the impact of digital technologies on two of the leading architectural practices in the UK. Based on these interviews, together with the feedback from the sampled academic staff, the interview questions were modified, reformatted, combined and made briefer to avoid repetition. Furthermore, the main focus was on tweaking the questions that could result in any bias.

#### 5.8.3.4 *The Participants*

All the participants who were interviewed for these case studies are architects by background, including the participant from the software development firm. In addition, all are highly knowledgeable in the different technologies available and the digital methods that can be developed from these technologies. These criteria were significant in enabling the collection of insights that are closely aligned to the research subject. However, the participants vary in several ways. Firstly, their backgrounds differ: some come from an academic background, while others come from a pure practical background, meanwhile, other participants are specialised in practice-based research, which blends the two fields. Secondly, each of the participants have different foci, in that some are specialised in BIM, others are members of design teams, whilst others are specialists in scripting and programming. Furthermore, while parametric design is central to this research, all the participants are knowledgeable in parametric design and have experienced its potential in different projects. Furthermore, the level of their experience and the sort of knowledge they have differ significantly; whilst some interviewees have practice-based knowledge, others have research-based knowledge. In general, the reliability gained from the selection of various cases is enhanced through a critical selection of a range of participants. The variety in both the cases and participants enables the same phenomena to be investigated from different perspectives.

In addition, the credibility of the data was secured by selecting participants who are representative of their firms. In fact, all the case studies rely on interviews with key persons within the firms who have a general view about the firm and know exactly which digital technologies and methods exist, the purposes for which those technologies are utilised, the range of experience available, how these technologies and experiences are employed in different projects, and the challenges encountered when these technologies are utilised. This is added to their direct involvement in different architectural projects so that they are able to narrate the stories of different processes and describe how the different technologies and methods have been utilised.

In Case 1, the first participant is an architectural assistant who is involved in several large projects at the firm including an international airport project, while the second participant is an associate at the research group. They have exceptional digital literacies and lead research projects that challenge the limits of the technologies. This is added to their major role in various design projects where they supervise the design team by offering their knowledge and

experience to help designers to get the most benefit out of the digital technologies available at the firm. In Case 2, the participant is a senior architect who has been involved in a large number of architectural projects around the world where highly advanced digital technologies and methods were used to enable the design and construction of highly complex and fluid shaped buildings. The participant selected for Case 3 is the only individual within the firm with parametric design experience and was brought to the firm because of this knowledge and experience. In Case 4, the participant is also the only expert in parametric design and one of few individuals with BIM knowledge and experience. Furthermore, they have a mathematical background that enables them to leverage different technologies and master different software applications. In Case 5, the participant is the head of the computational design group at the firm, and is able to apply different computational design methods in a wide range of projects at different locations around the world. In Case 6, the participant is the head of the research group that is leading the transition to full BIM implementation at the firm. In Case 7, the participant is also leading the research at their firm; they have 17 years of experience in architectural practice together with a wide and broad knowledge of computational design. This knowledge enables them to take major decisions on behalf of their firm in relation to the large budget allocated to the development of server and network systems. In addition, they have a role in supervising design teams and raise awareness of the potential of the different digital technologies at the firm. In Case 8, the participant is the head of the digital technology department, and leads the software developer team, who also consider the needs of practitioners in the AEC industry. A detailed list of the participants together with their position and codes can be shown in section 6.2.

## **5.9 Data Analysis**

Prior to analysing the data collected, a researcher needs to identify the logic of linking the data to the theoretical propositions developed in the literature review, and to set the criteria for interpreting findings (Yin, 2014). In this research the phenomena explored in Chapter 4 were further explored in the case studies within a practical context. Therefore, these phenomena represent the bridges or gates that will link the reviewed theory to the collected data. Furthermore, the criteria for interpreting the findings is derived from the variety that was critically established through selecting architectural firms from different level of digital advancement, and through selecting participants from different interests and focus, and from different experience level and knowledge nature in parametric design.

## **5.9.1 Data Analysis Techniques**

### **5.9.1.1 Content Analysis**

Content analysis is one of the most popular methods of text analysis that concentrates on the quantifiable aspects of this text, such as the relative frequencies of words per text or unit (Titscher et al., 2000 in Kohlbacher, 2006). It is ‘a research technique for the objective, systematic and quantitative description of the manifest content of communication.’ (Berelson, 1962, cited in Saunders et al., 2015, p. 18). According to Saunders et al. (2015), content analysis is an analytical technique that codes and categorises qualitative data in order to analyse them quantitatively. Therefore, the purpose of a content analysis is to quantify and describe aspects of textual or visual data, which enables researchers to identify ‘factual’ objects in the data and not rely on subjective judgement (Saunders et al., 2015).

Therefore, content analysis is more convenient for studies that are purely objective and do prioritise the ‘subjective judgement’ that is essential for this research. The impact of the ‘digital’ in design is subject to different interpretations, opinions and views that vary significantly based on the design context, which is unique in every situation. Furthermore, the nature of the data collected cannot be quantified and hence cannot be analysed ‘quantitatively’. Instead, the analysis should rely on detailed and critical explanations that respond to the complex nature of design, the wide variety of digital technologies, and the various impacts on the context in which this technology is utilised. As a result, a content analysis technique is not adopted in this research.

### **5.9.1.2 ‘Logical Models’ Analysis**

The ‘logic models’ analysis is increasingly applied to study theories of change. This type of analysis ‘stipulates and operationalises a complex chain of occurrences or events over an extended period of time, trying to show how a complexity activity takes place’ (Robert K Yin, 2018). This type of analysis could be applied to address changes and shifts in architectural design based on the rapid evolution of technology. However, a logic models analysis cannot be adopted in this research as it is more appropriate for longitudinal studies. Instead, the time horizon of this research is cross-sectional as it addresses a particular ‘snapshot’ in time of technological development and adoption by architectural practices, where the interpretations of the secondary and primary data collected are grounded in the present-day reading of these data.

### **5.9.1.3 Thematic Analysis**

In thematic analysis, qualitative data are coded to identify key themes or patterns for future analysis. The coding searches for similar themes and patterns that occur across a data set (interviews, observation, documents, etc.), which allows the researcher to comprehend large and disparate amounts of qualitative data, leading to rich descriptions and explanations of theories (Saunders et al., 2015). More precisely, this analytical technique integrates related data drawn from different transcripts and notes by linking units of data that refer to the same meaning. This facilitates comparison, contrast and relationships among multiple data sources. As a result, a comprehensive thematic description of data can be obtained by using these codes to rearrange original data into groupings for further analysis in order to draw and verify conclusions (Saunders et al., 2015).

This type of analysis appears to be suitable due the large amount of data that will be collected. The research divided the impact of digital into phenomena; this division also corresponds to the thematic analysis as each of these phenomenon represents one of the themes. Thematic analysis will enable the juxtaposition of different data sets based on each theme. Nonetheless, this type of analysis can fragment data and ruin the sequence of explanations. This may threaten the context of the collected data, which is essential in this case study. Despite this risk, thematic analysis can still be adopted, however, it requires another analytical technique in tandem in order to preserve the context.

Saunders et al. (2015) state that thematic analysis can be used for inductive studies and deductive approaches. They defines two types of thematic analysis; the first is deductive where the themes that need to be examined are linked to existing theories and hence the codes are extracted from the theory; the second is inductive where the themes emerge from the data and hence the codes are extracted from those data. However, Saunders et al. (2015) also state that both types can be used regardless of the research approach. Therefore, in this study, a combination of deductive and inductive thematic analysis are used, as justified in section 5.9.2.

### **5.9.1.4 Narrative Analysis**

Instead of using coding to fragment data within a thematic analysis, narrative analysis preserves the data within their narrated context to maintain the sequential and structural elements of each case. To achieve this, narrative data are analysed as a whole unit of



narrative sequence, where themes can still be identified and coded but from within a narrative (Saunders et al., 2015). This analytical approach is ideal for a case study research strategy where exploring the practical context of the phenomenon is the main purpose for adopting the strategy. It is also ideal for this study, as it considers the context of the data in each case study. In fact, Ampatzidou (2014) understands the design process as a narrative that tells a story about a future building. She urges the need to read ‘stories hidden in the process of giving shape to the space around us’ (Ampatzidou, 2014). Therefore, the phenomena in this research are investigated within the narrative of the design process provided by the participants. Thus, their narratives should be maintained and balanced with the extraction of examples and evidence.

Narrative analysis may be based either on constructing narratives from fragments of data collected from multiple sources, or on extracting related topics or incidents of interest from interview transcripts (Saunders et al., 2015). The latter appears to be more appropriate as it reflects the nature of the data collected from the interviews. In fact, the questions asked in the interviews were detailed and contained a series of sub-questions that encouraged the participants to give detailed answers in the form of stories. This is evidenced in their answers about the collaborative processes that they conduct within their practice. It resulted long and comprehensive narrative texts from which different topics and incidents were extracted in relation to the different phenomena.

Saunders et al. (2015) identifies two types of narrative analysis, which are: structural narrative and thematic narrative analysis; structural narrative analysis focuses on the way in which a narrative is constructed by examining the use of language to understand how it affects the listener or audience. In comparison, thematic narrative analysis focuses on the content of a narrative by identifying the analytical themes within the narrative. The latter is more suitable for this research as it allows for the adoption of case study themes to interpret the narrative data.

Nonetheless, the problem with this type of analysis is that it places additional emphasis on the context, which is extremely variable in architecture and subject to the unique situations and circumstances of each design project. Furthermore, preserving the context might restrict the analysis of different phenomena within the narrative data. For instance, the impact of ‘digital’ on design complexity and creativity can be investigated through analysing the narrative data

that correspond to design processes and collaborative processes. In this case, it is necessary to fragment the data in order to investigate each phenomenon.

Thus, this research requires a combination of thematic narrative analysis and thematic analysis. Thematic narrative analysis will first be used to analyse the data in accordance with the way it was collected and narrated by participants. After this, the thematic analysis will be used in order to interpret the narrative data against the phenomena classified in the literature. However, focusing on a specific phenomenon when analysing data will require the researcher to conduct a cross-case analysis to identify the practical context of this phenomena across different case studies. This requires the consideration of a cross-case synthesis, which is discussed in the following sub-section.

#### ***5.9.1.5 Cross-case Synthesis***

A cross-case analysis is applied when multiple case studies are conducted and where researcher can aggregate findings across a series of individual studies. This analytical approach enables the researcher to discuss the similarities and differences among the different individual cases in relation to specific topics (Yin, 2018). Achieving a comprehensible and coherent cross-case analysis requires a strong argumentative interpretation that addresses the similarities and contradictions that may arise amongst the individual cases. This enables the researcher to boost the quality of the entire study. (Yin, 2108). The cross-case analysis is therefore appropriate for this research as it enables each of the phenomena to be investigated within different contexts and compared across the different cases. This will enable a more in-depth understanding of the phenomena and will give the opportunity to identify how they relate to each other.

According to Yin (2018), a researcher can use a combination of other analytical techniques in a cross-case analysis. Therefore, the need to investigate the individual computational design phenomena in their practical context will require the adoption of a cross-case thematic analysis, which resonates the issue of the context reservation of the individual case. In fact, Yin (2018, p. 194) emphasised this issue, stating that ‘ignoring the holistic feature of cases by decomposing them into variables is precisely what is to be avoided’. In this respect, he suggested two approaches when conducting cross-case analysis; a case-based approach and a variable-based approach. In the case-based approach, the integrity of the entire case is retained and then compared to other cases, whilst in the variable-based approach, the focus is on the variables in each case where comparing those across the cases will enable the

aggregation of evidence in order to reach a conclusion about the variables but not necessarily about the cases.

Therefore, in order to combine the benefits of both approaches, this research will adopt a variable-based cross-case analysis in order to enable investigate phenomena across cases. This will be preceded as a thematic narrative analysis that will ‘maintain the integrity’ of each case. Therefore a dual-stage data analysis was conducted, and the stages are discussed in the following sub-section.

## **5.9.2 Dual-Stage Data Analysis**

To achieve the balance between the need to preserve the context of the narrative data and the need to fragment data in order to investigate the individual phenomena across the different cases, the analysis was conducted in two stages. The first stage applied a thematic narrative analysis, where the data was analysed on specific themes while preserving the context. To achieve this preservation, the same themes that were used when collecting data, writing the interview questions, and in the coding of the narrative data. Moreover, the narrative of the data analysis was structured and sequenced in correspondence with the structure and sequence of the narrative of the original data shown in the verbatim interview transcripts.

The second stage relied on a cross-case thematic analysis. This stage starts with the narrative of the case study analysis, where the phenomena developed in the literature review were used to code the narrative. This allowed the final cross-case narrative to be structured on the themes that corresponded to the phenomena identified in the literature review. The two-stage data analysis steps are described in the following two sub-sections.

### ***5.9.2.1 Stage 1: Thematic Narrative Analysis***

In this stage the thematic narrative analysis was applied to analyse each case individually based on the following steps.

#### **5.9.2.1.1 Preparing data for analysis**

Saunders et al. (2007) explain the steps that a researcher should take to prepare the qualitative data for analysis. Following this explanation, the following steps were conducted to prepare the data for analysis

- Based on the recording, the interviews were transcribed;

- Where there was some ambiguity in some information given by interviewee, or where there was an important point that required further clarification, the transcript was sent to the interviewee who provided comments. These comments were taken forward to confirm the accuracy of the information generated from the interview;
- The script format was prepared for use with NVivo.

Saunders et al. (2015) and Yin (2018) emphasise the need to become familiar with the collected data prior to starting the analysis. The manual manner in which the interviews were transcribed for this study enabled a high level of familiarity as the transcription required close and repeated listening to the interview recording. This enabled the author to consider the meanings and relationships in greater depth and in their connection to the theory.

#### **5.9.2.1.2 Categorisation of Data**

In this step, the data is classified into meaningful categories derived from the data and/or the theoretical literature; moreover, the identification of these categories is guided by the research questions and objectives. Each category is given a code or a label which results in an emergent structure that is relevant to the research purpose (Saunders et al., 2007). Moreover, different categories can be derived from the same data, which can be based on the nature of the research objectives (Saunders et al., 2007). According to Saunders et al. (2015), the codes can either be derived from the theory (deductive thematic analysis) or they can emerge from the data itself (inductive thematic analysis).

At this stage, the deductive thematic approach was applied as the codes were derived from the case study themes which in turn were originally extracted from the literature review and reduced into the main themes. Therefore, to start analysing the data, a set of ‘nodes’ were created in NVivo where each node corresponded to one of the themes of the case study. The transcript of each interview was exported into NVivo, and based on critical review for the transcript, each paragraph and part was assigned to the related node in NVivo; moreover, some paragraphs were assigned to more than one node. The tendency to preserve the narrative made the coding and categorising processes easier as many parts of the transcript were already categorised.

#### **5.9.2.1.3 ‘Unitising Data’**

This activity attaches each part of data to the appropriate category set in the ‘categorisation’ activity. This enables the formation of units of data. Consequently, the data will be reduced and rearranged into more a manageable and comprehensible form (Saunders et al., 2007).

Each paragraph was assigned to the corresponding node in NVivo, and hence, linked to its related category. In fact, the process of categorising data, giving each part a code and then unitising data is also applicable when using manual methods, like a Word file document. In such methods, each part is given a code, to then the data attached to each code is copied and pasted into the corresponding category in another Word document. However, using NVivo enabled the integration of these steps (coding and unitising), where the coding was automated and automatically added at the top of each paragraph within the nodes. In general, at this stage, the data was reduced, as irrelevant and repeated information were removed. As a result the analysed data were structured in the same way and sequence in which the data were structured in the interview transcript. This enabled preserving the context of the collected data. For instance, the stories told about the design processes and the project scenarios were maintained in the same way they were told in the interviews.

#### **5.9.2.1.4 Relationship finding and categories development**

Within this step, themes or relationships are searched in the rearranged data. This results in revising the categorisation of the data based on the research objectives and the meanings found in the data. Consequently, the categories may be sub-categorised, two or more categories may be integrated, and some new categories may emerge (Saunders et al., 2007). This stage will help in refining the focusing of the analysis (Dey, 1993 in Saunders et al., 2007).

Aside from to the addition of the nodes to NVivo, and the reduction and categorisation of the data by assigning each to the corresponding node, NVivo enabled the addition of notes for each part of the data. These notes explained how the part related to the theory, and to which part of the theory they were related. In other words, this feature in NVivo enabled the author to start establishing links between the theoretical literature and the information generated from case studies. This stage enabled the analysis of the narrative that was developed in the previous stage. In particular critical discussions were included to interpret each piece of data in relation the phenomena.

The previous steps were iterated across all the cases, where the different themes in each case were discussed in relation to the theory. At the same time, some comparisons were made to previous cases. This enabled the accumulation of evidence across the different cases. As a result, a narrative to explain each individual case was developed. Each narrative includes a critical discussion on each theme within the case while maintaining the integrity of each case.

These narratives are shown in Chapter 6, where each case represents a section within the chapter, and the themes are shown as sub-sections.

### ***5.9.2.2 Stage 2: Cross-case Thematic Analysis***

The steps in stage 2 are similar to those of stage 1 (coding and categorising data, utilising data and relationship findings) as they are both generally derived from the stages of a typical thematic analysis approach, with some differences. While the analysis in stage 1 started from the interview transcript, this stage started from the final narrative of the individual cases that were developed in stage 1. Moreover, while the codes used to categorise data in stage 1 were derived from the case study themes that were originally derived and reduced from the phenomena developed in the literature review, stage 2 returned to the original phenomena to derive the codes. This enabled a juxtaposition of the discussion and evidence concerning each phenomenon across the different cases, which resulted in a more in-depth investigation of each phenomenon in its different practical contexts. This depth enabled the emergence of sub-themes within each phenomenon that resulted from the comparison and accumulation of evidence across the cases.

Therefore, the analysis in this stage can be outlined in the following sub-stages:

- 1- The first was based on deductive coding, where the narrative of the individual cases developed in the previous stage were coded using codes derived from the computational design phenomena discussed in Chapter 4;
- 2- The second sub-stage was based on inductive codes where other codes or sub-codes emerged from the analysis of the practical context of each phenomenon across the different cases. In this case, the deductive codes acted as containers that hosted the inductive codes;
- 3- In the third sub-stage, the whole research outcome was discussed based on the evidence from all case studies as well as from the literature review. The discussion is shown in Chapter 7 and was structured based on the deductive and inductive coding used in the first 2 sub-stages. The deductive codes that were derived from the phenomena in the literature review were all maintained and represented in the main sections of Chapter 7, while the inductive codes which emerged from the data analysis are represented as sub-sections;
- 4- In the fourth sub-stage, the theoretical framework was developed and represented diagrammatically. Furthermore, the third and fourth sub-stages were undertaken

concurrently, where the process of the framework development was shown. This was achieved by providing a summary of how the discussion in each sections fed into the framework alongside a diagrammatic representation of each stage of the framework development.

## **5.10 Validity, Reliability and Rigour**

In qualitative research, validity refers to whether the findings of a study are accurate in reflecting the research context, and supported through the findings gathered (Guion, Diehl, & McDonald, 2011). Validation is important in this research, due to the subjective nature of most aspects of the study. In addition to the multiplicity, heterogeneity and novelty of the emerging technologies, the ambiguity and immaturity in design theory, and the difficulty in adopting these technologies in practice also influence the need for validity. Furthermore, architectural practice is in a transitional era, where the methods, tools, experiences and knowledge and rapidly changing.

### **5.10.1 Triangulation**

According to Guion et al. (2011) triangulation is a method used in qualitative research to check and establish validity in studies by analysing a research question from ‘multiple perspectives’. In this sense they present five types of triangulation:

- 1- Data triangulation: validity is enhanced by involving different sources of information, such as different participants or other researchers. This method enables a researcher to gain feedback from different perspectives for comparison, and the areas of agreement and divergence to be identified to enhance the reliability of the study;
- 2- Investigator triangulation: this is where different investigators use the same qualitative method and the same analysis process to investigate the same phenomenon in order for the findings from the different investigators to be compared, and hence, enable a deeper understanding of the phenomenon and more reliable results;
- 3- Theory triangulation: the different perspectives are gained by consulting professionals from different disciplines or from the same discipline but from different status positions to interpret a single set of data, and then compare the findings to ensure validity;
- 4- Methodological triangulation: different methods are used to study the same phenomenon, in order to test the correspondence or similarity in the resulting conclusion and thus secure the validity of the research;

- 5- Environmental triangulation: relies on using different environments (different locations, settings, time, etc.) to investigate the same phenomenon. This type enables an identification of the impact of environmental factors on the findings of the study in order to deepen the investigation, and establish its validity.

Based on the previous types of triangulation, the validity of this research is established on three levels:

#### ***5.10.1.1 Data Triangulation***

The data was collected from a wide range of heterogeneous sources, which include, theoretical literature, practical literature, technical literature, practitioners from different positions, and with differing experiences, and orientations. This was in addition to the variety in the practice disciplines selected for the case studies (architectural and software development practices). Furthermore, the architectural practices selected for the case studies varied in terms of size, budget, circumstances, geographical locations, and modernity of methods applied in practice. This was additional to a varied level of reliance on digital technologies. All these sources of information were relied on to investigate the same phenomena and thus gain feedback from different perspectives.

#### ***5.10.1.2 Environmental Triangulation***

The environmental triangulation was established due to the variety of the practices selected for the case studies. The practices were located in different countries, such as UK, Germany, Canada and USA. In addition, each practice has a different work environment. For instance, the advanced practices selected for this study rely on collaborative and interdisciplinary work environments, with a reliance on digital technologies, where the vast majority of the design team members have a high level of digital literacy. In the semi-advanced and developing practices, the reliance is mainly on traditional methods, and the willingness to innovate is lower amongst members in design teams, which results in a different work environment in comparison with the advanced practices. This variety, enabled the phenomena to be explored from different perspectives, and hence, to ensure criticality and reliability in reporting the findings.

#### ***5.10.1.3 Theory Triangulation***

Several professionals and academics from different backgrounds and areas of research were consulted in order to evaluate the quality of the research findings and the consistency



between those findings and the research contexts. These consultants provided feedback that, in most of the cases, focused on the richness of data and the need to reflect on this richness by providing a thorough, comprehensible and exhaustive discussion and conclusion.

### **5.10.2 Publication**

A brief version of the research was co-authored and published as paper with the research supervisors (Haidar et al., 2019). The paper is 30 pages long, and relied on the same literature review, the same data, the same analytical technique explained in stage 2, together with very similar discussion and conclusion with more focus on parametric design. After the first submission of the paper, a highly detailed and thorough feedback was provided by the reviewers of the journal. This feedback was fed into the paper for the final submission. It was also fed into the research.

### **5.10.3 Saturation**

Rich and thorough data was collected, which was derived from nine interviews, and the time of each interview was between 75-90 minutes. The rigour of the questions, interview approach and the time spent with the interviewees ensures that the data collected for this research was sufficient in terms of quantity. However, evaluating the sufficiency of the data requires further investigation to check their quality and adequacy in answering the research questions and exemplifying the phenomena explored in the literature review.

Saturation is the most frequently cited guarantee of qualitative rigor offered by authors (Morse, 2015, p. 587 in B. Saunders et al., 2018). In qualitative research, saturation is understood as a criterion for discontinuing the data collection and/or analysis, which means that no additional data are being found (B. Saunders et al., 2018). According to Urquhart (2013, cited in Saunders et al., 2018), saturation is the point in coding when research finds that additional data is resulting in mounting instances of the same codes rather than adding new codes. Similarly, Given (2016, cited in Saunders et al., 2018) considers saturation as the point at which ‘additional data do not lead to any new emergent themes’; saturation was similarly achieved in this study. In Chapter 7, the cross-case analysis resulted in the development of inductive codes that emerged from the analysis of the different cases. The codes were represented as sub-themes that were hosted by the main themes derived from the literature. During the analysis, all the sub-themes included evidence from most of the cases, which show that no particular case resulted in the emergence of a new unique theme and thus required further data collection to support this theme.

From a different perspective, Starks and Trinidad (2007, cited in Saunders et al., 2018) states that theoretical saturation occurs ‘when the complete range of constructs that make up the theory is fully represented by the data’. Despite the large number of phenomena explored in the literature review, all of these phenomena were exemplified in the case studies, such as complexity, process design, tool design, the building seeds and the impact of other industries.

Further evidence that can be considered when collecting data is when new data start to become redundant; for example within interviews, the researcher can begin to hear the same comments again and again. This indicates that saturation has been reached and that focus should be given to the analysis of the existing data (Grady, 1998, cited in Saunders et al., 2018). In this research, several aspects started to recur in the interviews. For instance, where the main focus in the data collection was to offer a narrative about the design processes, the same scenarios started to emerge in most of the cases such as the dual-model process and the use of BIM only in the development design stage rather than the conceptual stage. In addition, the methods used in collaboration and integration, and the heavy reliance on traditional methods also appeared in almost all cases. The same sort of problems that result in inefficient use of technology were reported and reoccurred in most of the cases, where the main problem is the lack of experiences and knowledge and the concern about confidentiality in integrated work.

#### **5.10.4 The CRAP Test**

In addition to using the triangulation method to establish the validity of the research, this validity was further enhanced by using the ‘CRAP Test’, which is a method for evaluating research based on the following four criteria: Currency, Reliability, Authority, and Purpose/Point of View (Orenic & Beestrup, 2008). The CRAP test was chosen as it contains important aspects for the validity of the research that are not covered in the triangulation method.

Based on the CRAP test, the sources of information that are relied on in this research, especially those related to computational design, are papers and articles published within the current decade, with a significant reliance on articles published in the latest three years. In addition, the participants in the case studies are all currently employed in their practices, and discuss different phenomena from their present perspectives. Moreover, the sources and manuals used to conduct the design experiments are websites and manuals related to the latest versions of the software applications used. Furthermore, the main reliance of this research

was on sources from journals that have a high impact factor, such as Design Studies, Architectural Design, and International Journals of Architectural Computing.

Apart from Case 1, the decision was made to rely on one participant for each case study. This decision was taken whilst conducting the case studies. In fact, the range of participants consulted suggested that the way digital technologies are used and the impact they impose differs significantly from one project to another, based on the size of the project, its complexity, nature and circumstances, and many other factors. Therefore, it was not possible to identify the general potential of the ‘digital’ within a specific firm as this potential is highly subjective and unique for every single project and every single situation within a project. Thus, in order to avoid the repetition of information caused by interviewing different participants from the same firm, priority was given to exploring the potential of the ‘digital’ from other architectural firms in order to enhance the reliability of the research by focusing on multiple perspectives in different contexts. In addition, to achieve greater reliability and credibility in exploring the practical context of the computational design phenomena, the author was careful to select key persons within the firms, as previously discussed.

### **5.11 Chapter Summary**

This chapter has adopted the research onion model to identify the research philosophical stance, approach, choice, purpose, time horizon, and the strategy needed to collect and analyse data. The nature of the phenomena investigated, and the knowledge required to understand these phenomena informed the ontological, epistemological and axiological assumptions. The ontological position of this research leans mainly towards subjectivism due to the nature of the impact of the ‘digital’ on architectural design that is subject to the uniqueness of every design project and every situation within the design process. The epistemological position leans mainly towards interpretivism as the impact of the digital on architectural design was interpreted from people’s opinions within various social contexts. The axiological position is mainly value-laden as the analysis of the origin, impact and context of the computational design phenomena was based on the author’s perception and his knowledge and experience in the field.

The tendency of this research in exploring the mutual relation between architectural practice and its related theory and its objective to establish new links between theory and practice has led to the adoption of abductive research approach. In addition, the subjective nature of phenomena under study and their reliance on social contexts and people’s opinions and

explanations showed that the research required qualitative data to be analysed qualitatively. Furthermore, the necessity to investigate the computational design phenomena within their practical contexts has led to the adoption of the 'case study' strategy. The 'multiple cases' type was chosen in order to allow in-depth investigation for the phenomena within different contexts. Based on this choice, the research adopted the persuasive sampling technique and the critical sampling strategy. This enlightened the criteria for selecting cases so that the firms selected varied in terms of their locations, disciplines and their advancement in terms of the digital technologies and methods applied. At the same time, the firms are similar in terms of the size and the capability and willingness of adopting technologies. Subsequently, the unit of analysis was identified and the 'embedded cases' type was selected. This selection enables the identification of the case study themes which were derived and reduced from the computational design phenomena classified in the literature. In addition, the semi-structured interview was adopted as the data collection technique in order to match the subjective nature of research and the necessity to amend the questions based on the context and the flow of information. The selection of the participants was very critical so that all the participants were architects with advanced experience and skills in computational design methods and are holding leading positions at their firms. At the same time, the participants vary in terms of their area of specialisation and their experience and knowledge in parametric design. The data was collected in two stages. In the first stage, thematic narrative analysis was utilised, where the codes needed for the analysis were derived from the case study themes in order to allow the same themes to be investigated for each individual case while maintaining the context of each case. In the second stage, cross-case thematic analysis technique was utilised where the codes needed for the analysis were derived from the phenomena classified in the literature review in order to allow the same phenomena to be investigated within multiple and various cases.

# CHAPTER SIX

## 6 Computational Design in Practice: Case Study Analysis and Findings

### 6.1 Introduction

The recent phenomena in computational design practice and the problems identified and classified within the literature review are considered in relation to real and recent practical contexts in this chapter. Furthermore, new phenomena and problems are explored in order to consider the literature review findings in light of practical issues, and design project scenarios. Each section represents a case study of an architectural or software development practice, and each case is divided into themes that are derived from the literature review.

### 6.2 Specification of Case Studies and Participants

The table below lists the case studies; their category, their location. It also identifies the participants; their position within the firm and their code. The number in the participant code refers to the case in which they participated and the letter refers to their experience and knowledge in parametric design that is explained in the table 2.

**Table 2: Specification of Case Studies and Participants**

<b>Firm</b>	<b>Category</b>	<b>Location (main headquarters)</b>	<b>Participant(s) Position</b>	<b>Participant Code</b>
<b>Case 1</b>	Advanced	London, UK	Architectural Assistant/Associate	C1
			Associate at the Research Group	R1
<b>Case 2</b>	Advanced	London, UK	Senior Architect	C2
<b>Case 3</b>	Semi-Advanced	Berlin, Germany	Senior Architect	E3
<b>Case 4</b>	Semi-Advanced	Manchester, UK	BIM Specialist	E4
<b>Case 5</b>	Semi-Advanced	New York, USA	Head of Computational Design Department	E5
<b>Case 6</b>	Developing	Montreal, Canada	Head of the Research Group	R6
<b>Case 7</b>	Developing	Montreal, Canada	Director of Integrated Practices	R7
<b>Case 8</b>	Software	New York, USA	Director of Design Technology	S8

The table below lists the participants in relation to their groups that correspond to their experience and knowledge in parametric design.

**Table 3: List of Participants in relation to their experience and knowledge in parametric design**

<b>Group</b>	<b>Description</b>	<b>Participant code</b>	<b>Parametric Design Experience (in years)</b>
<b>Experts</b>	Architects who have demonstrated efficiency and success in utilising parametric design in a wide range of architectural projects	E3	9
		E4	6
		E5	9
<b>Competent Users</b>	Architects who have utilised parametric design successfully in a limited number of projects	C1	2
		C2	2
<b>Researchers</b>	Architects with a robust research background who have a wide range of knowledge in parametric design, but their experience is based on limited practice. The main focus for the researchers is to push the use of parametric design in their firms and spread awareness of its potential	R1	-
		R2	-

## 6.3 Case Study 1

### 6.3.1 Introduction to the practice and the participants

Case 1 is a large architectural firm located in UK that consists of teams and individuals from a wide range of diverse and heterogeneous disciplines who work together within highly collaborative and multidisciplinary environments. Their work environment comprises architects, engineers, artists and other specialists from across the world. They deliver a variety of design and construction projects both nationally and internationally. The firm is categorised as an '*advanced firm*', due to the highly advanced digital technologies and methods they utilise.

In order to conduct this case study, two participants were interviewed. The first participant is an architectural assistant and associate at the firm, who has six-years of experience in architectural practice. The participant joined the firm two years before the date of this interview, and will be referred to as 'C1' in this study, as they are a competent user of parametric design. Thus, they have used parametric design effectively although in a limited number of projects. The second participant is an associate at a research group within the practice. They joined the firm four years before the date of this interview. They have interests in computational design and different tools and methods, including robotics, rationalisation, and different types of analysis. They work either on building projects, or research projects. They will be referred to as 'R1' in this study, as they have a research background coupled with a wide range of knowledge in parametric design.

### 6.3.2 Digital Technologies and Tools

According to C1, the firm has most software applications available so that employees are free to use the applications that they are most comfortable with; the main proviso is that the work is efficient and fast. Moreover, the firm provides its teams with an open resource for training and skill development. Within one single project, they rely on various software applications including, modelling, drafting, analysis, parametric, and BIM software. R1 attributes the multiplicity of software applications and modelling techniques to the firm's appetite to try and test everything that can benefit the design process. In the research group, they mainly rely on Rhino, as it gives them a greater capability to communicate design information with a wider range of architects; this is also influenced by its ease of use and popularity amongst recent graduates. They also widely use Grasshopper; according to R1 the most interesting

function within Grasshopper is its ‘amazing community’. R1 refers to the social networking enabled in Grasshopper’s official website, where users from around the world share their ideas, answer each other’s questions, and share their models to gather feedback.

The firm also uses Unity for AR (Augmented Reality) and VR (Virtual Reality). In addition, they build programs in Unity for use as analysis engines within the different projects at the firm. Furthermore, they also use a wide range of hardware technologies, such as SLS printing, robotic arms, robotic 3-D extrusion, and a number of super computers with potentially ten or twenty graphic cards that are used in complex projects. The 3D printer is essential and is used for several purposes at various stages of the design process.

According to C1, the main problem within previous work stems from limitations in the software applications available. This often results in too many constraints in the design choices, and additional time and effort spent in learning the software. On one hand, this demonstrates the need to be equipped with different sorts of software applications to match the diversity of experiences and cultures within an architectural practice (Ceccato, 2010), whilst, on the other hand, it requires a shift in skillset to deal with the range of complex technologies (Oxman, 2017), and an understanding of the additional cognitive loads for designers (Aish & Hanna, 2017). This issue is apparent in C1’s previous experience, which prior to the current firm, involved a limited range of software. Meanwhile, at the availability of all sorts of software at the current firm helps designers to use their previous experience, which is enhanced by the availability of open sources for training. Nevertheless, this issue raises questions concerning the interoperability issues provoked by the utilisation of a wide range of technologies (Ceccato, 2010; Hesselgren & Medjdoub, 2010). In addition, this issue resonates with Holzer’s (2011) concern about the affordability of new software applications, their related hardware technologies and training expenditure.

### **6.3.3 Roles and Areas of Specialisation**

While Cuff (1992) classifies and discusses various roles and areas of specialisation in architectural practice, an exploration of the roles in this firm reveals a variety of unfamiliar posts that were not discussed in Cuff’s book. According to C1 and R1, the firm has a variety of roles, specialists, and professionals from a wide range of diverse and heterogeneous areas of specialisation, such as architects, structural engineers, software developers and programmers, visualisers, model makers, product designers, mathematicians and geometry specialists, artists, and an aerospace engineer. The specialists are organised in teams and



groups, such as the environmental engineering team, structural engineering team, industrial design team, visualisation team, model-making team. In addition, they have two research groups that carry out independent and project-based research to develop innovative methods in approaching design projects. This shows the highly collaborative and interdisciplinary environment of the firm and their assertive tendency to involve research to transfer knowledge and experiences in order to achieve continuous development and innovation.

From the early stages of the architectural projects, the teams work together with a high level of coordination. The hierarchy is flexible, as individuals from different teams join for some projects, based on the specific requirements for each piece of work, which reflects the ‘temporary overlap of authority’ when those roles are involved in a real project context (Emmitt, 2014). In addition, C1 states that the firm has a team of BIM specialists, including BIM managers, BIM coordinators, and BIM technicians. During C1’s two-year experience at the firm, the BIM specialists have worked with the design team on most of the projects that C1 has been involved in. The importance of BIM is reflected in its increasing uptake on a global level (Eastman et al., 2011; Eynon, 2016) and a response to the BIM mandate in the UK (MacLeamy, 2012; Tuckwood, 2016) and Germany ((BIMcrunch, 2015).

While the majority of professional designers prefer to concentrate on design rather than business (Emmitt, 2014, p. 11), C1 emphasises the impact of the variety and diversity of technologies and specialities in the firm on their creative role as an architect. They state that the limitation in experiences and areas of specialisation in their previous job was one of their main concerns, where they were expected to adopt multi-tasking roles, during which they had to manage problems provoked by the different technologies used, and hence, had limited time to focus on their design projects. C1 states that this situation proved a distraction from their creative work. In contrast, the current firm has a wide range of specialists who respond quickly when any problem arises, giving designers the capability to focus on their creative work. Thus, C1 provides an example of the way in which complexity in digital technologies results in a shift away from creativity, and that this carries a significant cognitive cost. This is one of the main technology-related issues raised by Lawson (2011), and Bernal et al. (2015). C1 also identified a solution to this problem, namely the availability of various specialists to tackle complexity and reduce the additional cognitive loads.

Moreover, the firm broadly uses parametric design in various projects. In this context, R1 highlights an important aspect that was raised in Chapter 3 with regard to the permanence and

temporality of roles in practice. R1 joined the firm four years ago, and during this period, parametric design has been widely used in different projects. They explain how collaboration in parametric design has changed significantly since they joined. Four years ago, there used to be specialists in parametric design that joined the design team to support them in their work. Currently, there is no such specialist, as the designers themselves have this sort of experience and most of them can create parametric models whenever required. In fact, this situation could raise questions as to the future permanence or temporality of the research group. The Researcher in this case explained how the position of ‘parametric designer’ was gradually disappearing as the design team members themselves started to gain experience and become involved in parametric design processes, which thus reduced their reliance on specialists. As discussed in the literature review, this could be applied to all the new roles that are emerging. New technologies are evolving rapidly (De Rycke et al., 2018), therefore, new specialists are needed to join design teams to provide support in tackling the complexity in these new technologies. However, in time, the design team will be able to deal effectively with these technologies without the need for specialists.

### **6.3.4 Processes and Workflows**

#### ***6.3.4.1 BIM and Parametric Design in the Conceptual Design Stages***

The reliance on these technologies at the firm is not consistent throughout all design stages. For example, C1 states that, during the ideation and conceptualisation stages, they rarely use software to generate and communicate the first ideas for the project, but rather rely on freehand sketches and rough models. C1 believes that this is the only way to work when it comes to generating the first concept. They give an example from one of the recent projects they are currently working on, where the BIM specialists did not start to collaborate and coordinate with the design team until the concept design was achieved, which was three months after the project started. Moreover, they state that parametric modelling was not used in the early stages of the design process, although it became essential in the development and detailing stages, when the parametric modellers began to work closely to the rest of the design team, taking ideas, models, and descriptions to translate them into geometry. They argue that parametric design is too complicated for use at the conceptual design stage, but is more effective at the construction stage due to the accuracy it offers in detailing. With this argument, C1 contradicts R1, who states that parametric design is used to create design options at the conceptual stage, while in the development stage, the designer needs to focus

on one of those options, and then take it into further detailing. At this stage, developing algorithms becomes cumbersome and time wasting. In fact, R1's argument can be attributed to the 'lack of completeness in parametric models, which results from the high level of computation needed to generate alternatives' (Turrin et al., 2011). Therefore, a design form can be developed parametrically at the conceptual stage, where a low level of complexity exists. This emphasises the need to investigate the usability of parametric design in later stages within different case studies.

#### ***6.3.4.2 Early Design Stages***

In the early design stages, the design team rely on extensive discussions with different teams, managers and partners, where the discussions are the main method to communicate ideas and information. They also discuss their ideas with the founder of the firm, with whom they take notes to inform their conceptual design decisions. Moreover, they attend sessions in which they discuss their concepts with external and internal participants, clients and other stakeholders. After such meetings, they meet each other to discuss issues, and share ideas and inspiration. Despite the availability of a wide range of software and hardware technologies at the firm, the scenario described by C1 suggests that this does not affect the early design stages, when traditional free-hand sketching and rough models are employed alongside face-to-face meetings and discussions. Thus, C1 subconsciously encourages the use of various technologies to support their design, as shown in the previous section. At the same time they emphasise the need to avoid immersing the early stages in technologies. This resonates the 'creative' and 'rational' design activities (Jones, 1992) discussed in Chapter 1. From C1's perspective, technologies can be useful in the later stages where most activities are rational, while in the early stage, the intensive use of technologies may disturb the creative activities associated with these stages. However, this situation cannot be generalised. In fact, the design process discussed in section 6.3.6.2 demonstrates a different scenario, where scripting and algorithmic modelling was utilised from the first stage to generate a pavilion form. Indeed, C1 states that the approach used depends on the project. Therefore, the variety and uniqueness of design projects (Rittel and Webber, 1973 in Hudson, 2010), does not only affect the hierarchy of authorities within practice (Emmitt, 2014), but also affects the choice of technologies utilised, the design stage in which technology is involved, and the extent to which these technologies are relied upon across the different design stages.

#### **6.3.4.3 *The Role of BIM Specialists***

The BIM specialists integrate with the design team in order to guide the team through different design stages. The design team provides models, and after these are developed and approved, they pass them to the BIM specialists who develop their own BIM Revit model based on the conceptual model. C1 states that developing a BIM Revit model is essential as it is normally part of the agreement with the project clients who might rely on this for facility management during the operational phases of the building. This shows how the use of novel design methods can be motivated by the change in client demand (Whitehead et al., 2011). However, despite the potential for BIM to enhance coordination between different project stakeholders (Eastman et al., 2011; Enyon, 2016), this scenario appears to duplicate work, where the BIM model is created from scratch based on the conceptual design model, rather than imported as a conceptual design into the BIM application. This may reflect a limitation in the compatibility of BIM applications with other software, which results in a break in the continuity of the work. Therefore, digital continuity, from conception to production (Kolarevic, 2004; Oxman, 2017), is not accomplished.

#### **6.3.4.4 *Uniqueness of Processes***

The concept of the ‘building seed’ where architects think of designing a building ‘seed’ to grow different buildings (Carlile, 2014; Muller, 2011) does not seem to be accepted by either C1 nor many other architects and designers at the firm. In this regard, C1 states that the strategy at the firm is to be creative in every single project, and to rethink the design and solution for every problem, rather than adopting a template design ready to use. In fact, the firm appreciates the value and uniqueness of the design problem in every single project (Rittel and Webber, 1973 in Hudson, 2010), as each project has different requirements, a different nature, and different circumstances (Cuff, 1992; Emmitt, 2014). In this regard, C1 argues that it is just the experience and knowledge that an architect gains from projects that could be taken to ‘feed’ subsequent projects. This seems a complex issue, as the main role of the research groups at the firm is to conduct projects to gather experiences and knowledge from existing projects to inform innovative methods for later projects. This knowledge may include techniques and methods that exemplify the ‘building seed’ concept.

### **6.3.5 Collaboration and Interdisciplinarity**

#### ***6.3.5.1 Collaboration and Coordination at the Early Design Stages***

In addition to these scenarios concerning different aspects of collaboration, other scenarios reveal the importance of collaborative design within the general culture at the firm. According to C1, all design activities are based on teamwork; employees work as a team from the very initial stages of design projects, where ideas are shared and discussions and meetings take place. They send design models and information to managers whenever a new design task is achieved, and at the end of every day, send work-in-progress updates in order to elicit feedback from managers and clients. The feedback includes advice and guiding notes about the best way to develop the design. In a complex projects, such as the large-scale project at the time of C1's interview, the coordination can become harder where there is a very large team involved in the project. They also participate in large, online meetings where several aspects of the project are discussed with other participants and stakeholders.

This scenario suggests that the complexity and size of the project can result in complexity in the design process. This lies in the intensive coordination needed to deal with the large teams involved, which thus provides a response to the question in Chapter 4 regarding the purpose of complexity in the design process. This link between complexity and coordination becomes clearer when the design team start to coordinate work with participants from other disciplines. According to C1, the design team coordinates with both internal and external teams. This coordination starts at the very early stages of the project. For instance, the visualisation team becomes involved very early in the design process due to the need to share visuals with clients to secure the design approval. At the same time, the design team meets with the structural engineers and project managers who guide the overall process.

#### ***6.3.5.2 Sharing Information***

Furthermore, this is different from the scenario explained in the previous section as it shows how the design team relies heavily on models to communicate design ideas with other participants and clients. According to C1, the type of shared material in such a collaborative and multidisciplinary environment depends on the design stage, and the needs of different participants in the design project. These stages and needs also constitute the way that materials are shared. For instance, at the early stages, the reliance on collaboration is mainly

conducted through meetings and discussions, while at later stages, the design team also starts sharing drawings and models with other disciplines, such as the structural engineering team.

#### ***6.3.5.3 Collaboration with External Consultants***

Moreover, the design team has a high level of coordination with an external engineering company. This coordination operates as a loop where the model is shared with the engineers who provide feedback and sometimes develop the model based on their experience; they subsequently return it to the design team who also provide feedback, and again send the model back to the engineers, and thus, the loop continues until the final design is approved by all parties. This cyclical process is very similar to the conventional design process explained by Bernal et al. (2015), which relies on the iteration of three activities; generation (in this case the model generated by the design team), evaluation (which takes place through the feedback given by the engineers), and optimisation (which is the production of the final model that is approved by all parts, as explained in the previous scenario). In fact, this cyclical process can be broken down when relying on cloud-based systems that allow for a simultaneous viewing and modification of the model by different participants. This has the potential to facilitate coordination, and reduce the impact on storage resulting from saving different versions of the same file. In fact, the cloud-based systems can save the history of the evolution of the design within one single version of the model. This technology is not used in the scenario described by C1, which instead relies on the classical methods of file sharing despite the wide range of technologies available at the firm.

#### ***6.3.5.4 Collaboration with Research Group***

One of the main aspects that differentiates this firm from the majority of the architectural practices is their heavy reliance on research groups, especially with complex projects. In this regard, R1 states that the amount of intervention by the research group in design projects, and the stage at which they intervene are subject to different considerations, which include the nature of the project and the complexity of the design form. Therefore, the need to conduct research and transfer knowledge is instigated by the complexity of design projects, which is often associated with the unfamiliarity of the knowledge and experiences needed to address the unique problems of such innovative design forms. For instance, in one of their competition entries, they collaborated with the design team from the first day, due to the complexity of the project which required checks on how the different parts of the complex form would be assembled, and how the whole form would be rationalised to ensure it was

buildable. In other projects, they work as consultants supporting designers to solve problems that may emerge during the design process, especially with problems that require highly expert and highly digitally-literate architects. This highlights another problem when designing complex forms, namely the need to focus on the rationality and buildability of the design form, which in turn, enhances the importance of the rationalisation activity.

The role of the research group shows how the advanced emerging technologies in computational design require the effective use of specialists in these particular technologies in project contexts. This raises two issues; firstly, the affordability of such a research group for smaller practices, and secondly, the need for parallel technological developments and relevant experiences. Furthermore, this situation may offer a response to the question raised in Chapter 4 about the permanence of newly emerging roles in architectural practice. Over time, the experiences of highly-expert research group members could become incorporated into the role of designers, whereby design team will become experts, and gradually gain the capability to leverage different technologies to perform design roles unaided. This may gradually reduce the role of the research group in practice. In fact, R1 exemplified this situation, stating that the reliance on parametric design specialists was gradually abandoned in favour of developing parametric design experience within the design team itself.

### **6.3.6 Adaptation of Tools**

In Chapter 2, scripting was discussed as a method to adapt tools to match the specific needs of a project (Bury, 2013). This section discusses the purposes of scripting and the context in which this design method is utilised at this firm. Developing the tools and software applications is essential at the firm, especially for complex projects, which often require the continuous development of the software used in parallel with the development of the design form. For this purpose, in many projects, a team of individuals specialised in programming and scripting join the design team to help adapt the different software applications used. This adaptation makes these applications more efficient, simpler and ensure a better fit with the project needs. Therefore, C1 states that most software developers involved in their design projects are provided by the research group.

Moreover, R1 states that all of the members at the research group have programming and coding skills, regardless of their professional background, and adapting tools and software is one of their key roles at the firm. They build bits or plug-ins on top of existing software, and collaborate with other teams, including those external to the practice. Thus, all teams

continue to develop the software on top of each other's' work to avoid reinventing the wheel. This situation reflects the views of Carlile (2014), who urges architects to adopt inspiration from the software industry where people work on top of each other's work, rather than re-iterate the processes for every project. R1 explains that this is a smart collaborative method for development in the software industry; however, it is also applied within architectural practice and for architectural purposes.

#### ***6.3.6.1 Tool Adaptation: International Airport***

From the design team perspective, C1 states that software development and scripting were necessary to address a variety of geometrical problems within the design process of this project. This was due to the large size of the project and its highly-complex form. The project as a whole was challenging as members from the research group had to develop different software applications and scripts in order to meet all the requirements of the project. The main issue was to ensure the building geometry achieved a high environmental and structural performance. In order to realise this, the project required a team of five specialists in scripting and programming who worked all day throughout the 18-month design process period. The project also required support by external engineering consultants who participated in the development of the software and the rationalisation of the geometry. This situation shows how scripting specialists and software developers become integral parts of the design team. This was needed in order to deal with the complex form of the building and the need to adapt the tool to address its limitations.

In general, the tools are mainly developed within the context of a design project; in other words, the tools are developed in parallel to the design itself. Furthermore, many architects at the firm participate in the development of software applications; according to C1, about 20% of the architects in the design team have this level of digital literacy. This shows an important aspect of the shift in skillset required for an architect when working in such a firm, where programming and scripting knowledge become essential for some projects. This type of situation, counteracts Lawson's (2011) argument concerning architects' use of generic software that is not developed by architects; in the case of this firm, it is true that architects use generic software applications, however, those applications are developed and tweaked based on architects' desires within real architectural project situations.



### **6.3.6.2 Adaptation of Tools: Pavilion in International Exhibition**

From the software developer's perspective, R1 described the design process of a pavilion that would be constructed later within an international exhibition. Whilst this was a small-sized project, the form of the pavilion was extremely complex. In this project, the firm needed to develop a 'masterpiece' in order to respond to the client's need, the nature of the project, and its exceptional context as part of an international exhibition; therefore, research was undertaken alongside the development of several pieces of software, such as an algorithm that used reaction diffusion. This algorithm generated patterns that looked like sand; such patterns were populated around the core of the pavilion. The algorithm enabled a high level of control over the boundary of the main body of the pavilion in different conditions, where, in each condition, it produced patterns that were complex and random. Meanwhile, it simultaneously provided the capability to control how the patterns fitted together, and the ability to exchange the way they were located and connected. In general, the patterns looked quite random; however, they were based on rigorous algorithmic logic. Despite the project's complexity, the use of the algorithm enabled teams to complete the work successfully within a very limited amount of time.

This particular project provided an example of several aspects raised in the literature review, as it shows that the adaptation of tools for specific project requirements represents a new level in the design process, where designers design the tool itself (Mueller, 2011). In this project, the algorithm represented the tool that was utilised to generate the patterns. Furthermore, this example shows how new digital technologies allow the realisation of forms that are beyond the reach of traditional CAD tools (Harding & Shepherd, 2017).

### **6.3.7 Problems**

Despite the reliance on a wide range of diverse and heterogeneous digital technologies at the firm, C1 has not yet encountered problems with, or missing, data or damaged geometry when files are transferred across different applications. They state that they have highly qualified IT and support teams who have developed the strategies and standards required. Hence, whenever an individual identifies a problem, this simply needs communicating to the IT members who can resolve it. The IT team, according to C1 has succeeded in addressing a wide range of limitations by developing a highly-effective communication program between architects within the company.

Furthermore, C1 states that the complexity of working in a large firm with various multidisciplinary teams demonstrates benefits. Due to the lack of specialists in their previous position, they spent the majority of their time doing ‘boring stuff’, which included management and communication; this meant they rarely found time to focus on their creative work. At the current firm, a variety of specialists exist to provide the management and communication needed to allow architects to spend their time working on designs. Nevertheless, Ceccato (2010) states that interoperability problems emerge when people from different cultures and experiences work collaboratively, and hence, use different software applications. Meanwhile, Hesselgren & Medjdoub (2011) state that, prior to working on different software applications, architects need to understand how these applications talk to each other. Therefore, with the availability of a wide range of experience and two research groups, the dialogue between software applications appears to be well-managed at this firm.

R1 states that the main challenge they experience is the limited ability to quantify which links to general problem in architecture, caused by the nature of the profession, where the reliance is mainly on visual presentation and aesthetic perception. This problem appears clearly when several design options exist and a mechanism for optimisation needs to be developed. In this case, the research team can use different applications and develop scripts to enable automated structural and environmental optimisation. However, the visual and aesthetic optimisation remains unquantifiable, which supports the essential role of the human-designer who does not seem to be replaceable despite the availability of a wide range of technologies and experiences at the firm. In other words, the creative aspect of architectural design (Cross, 2011; Jones, 1992) is human-centric and cannot be replaced by machines.

In general, both participants struggled to identify an issue that reveals a technology-related problem. In fact, C1 instead reported problems from their previous work to explain how the problems are addressed at their current firm. Similarly, R1 also struggled to identify a problem, and the issue they explained about quantifying creativity was general, and appeared to be beyond the reach of any current digital technologies. This reveals the maturity in the way tools and applications are managed and experiences are organised. Therefore, in order to report technology-related problems, this research needs to elicit experiences from different case studies, and particularly practices using less advanced digital literacies.

### 6.3.8 Research and Development

The capability of the firm to leverage technology to develop smart processes in order to produce highly-complex and appealing buildings is the result of adopting expert research groups, which consists of members from a variety of disciplines and backgrounds, including structural engineers, BIM software developers, computer scientists, aerospace engineers and mathematicians. This reflects the increasing impact of different industries on the architectural profession (Kolarevik, 2004), and the tendency of this firm to import technologies and methods from other industries to inform their innovative practice.

Despite this wide variety of skills, experiences and backgrounds amongst the research group's workforce, all employees have programming skills in common. In fact, every employee has exceptional coding skills, which is the common language amongst the group. They also focus on computer science and artificial intelligence when looking for new members to join their team. Furthermore, they support any member at the firm who may have a 'gold personal research agenda' that needs to be developed into mature research. In addition to research, the group members directly participate in architectural projects within the main firm, 70% of their work is on architectural projects, and 30% on research projects. Where many architectural firms may explore new methods and technologies to support innovation, this firm dedicates a whole team for innovation, which in this case is the research group. This allows the firm to challenge the limitations of the tools and complex forms in every design project.

In terms of projects, the group works as a consultant inside the main firm in order to solve problems that cannot be addressed by their architects, and requires experts with a greater degree of programming skills. Therefore, their role becomes more significant in design projects that have complex geometry, where they start to connect the latest laboratory advances with architects and engineers. In some cases, they just provide the tool that is most appropriate for the problem, while in other cases they directly provide the solution. The latter was the case for the Pavilion project discussed above. Besides these contributions, they provide expertise in computational design, performance analysis, fabrication and interaction design, in addition to multi-objective analysis.

According to R1, the group started with a major project in London, where they were able to solve a highly-complex geometrical problem concerning the curved surface of the building. The problem was solved through panelisation, and since then, they have developed expertise

in this particular way of panelising curved and complex shapes in order to make them buildable. R1 ensures that they never contribute to buildings that are only pleasing aesthetically, but rather each building has a story about how it was designed, why it was designed this way, how the form was rationalised structurally and environmentally, and how it was managed on budget. These skills and activities show the power of scripting and programming in leveraging software applications by expanding their functionality and adding new features that can fit a specific project purpose. This provides the capability to solve a range of design complexities that concern several authors in the literature (Oxman, 2006; Thomsen et al., 2015).

With regard to research, they conduct independent research projects, where they explore new methods of collaboration, and undertake experiments to test the potential of robotics and different machines. When it comes to collaboration, the research group is not limited to the borders of the form, but can go beyond by collaborating with other enterprises, and participating in research conducted in different universities and laboratories around the world, in order to explore innovative technologies and design methods, and test their applicability for different projects, such as those at the firm. They also communicate with large software vendors, with whom they regularly meet; they provide feedback and report on issues within software applications and suggest additional features or functionality. They also access direct help from such software vendors for their projects. Furthermore, they are currently conducting a research project where they are looking at the practice in 10 or more years to explore what technology will look like; this helps when considering plans for continuous development. This relationship shows the dual-directional relationship between digital technologies and architectural practice. In comparison, the previous chapters explored the transitional impact of digital technologies and methods on architectural design (Kocaturk, 2017; De Rycke et al., 2018). This collaborative scenario reveals a contradictory direction where the new demands of some architectural practices and their desire to innovate prompts software developers to continuously update their applications to fulfil such requirements. Furthermore, the collaboration of the research group with many software vendors is not only beneficial for the firm and software vendors, but also beneficial for architectural practice as whole. This is because the feedback given by the research group helps software vendors to develop their applications and add features and functionality to make them more mature, where these same applications will be used by practices around the world. Kocaturk (2013, p.24) argues that innovation is hidden in the process of bridging the gap between the

possibilities and the constraints offered by technology, and this argument helps to define the global role of this research group, where the tendency to expand the scope of what is possible in design solutions result in pushing the limitations of technologies.

### **6.3.9 Future Expectations**

With regard to future expectations, R1 thinks that machine learning is going to be very influential from now on. This will mean identifying complex and efficient solutions for many problems, like structural and material efficiencies. Furthermore, R1 states that the convergence between these efficient software solutions and the fabrication technologies and robotics will enable the development of 'incredible solutions', which in turn, will result in the removal of the human builder from the equation.

## 6.4 Case Study 2

### 6.4.1 Introduction to the practice and the participant

The case is a large architectural firm with their main headquarters based in the UK. They rely on an open network of young professionals from various heterogeneous disciplines, who work together in a highly collaborative work environment. They believe in the built environment as a totality, and that is why they operate at all scales, from urban planning, architectural design, interior design, to furniture and product design. They lead a wide range of international projects where they rely heavily on an extensive variety of technologies. The main concern in using these technologies is to push the possible boundaries in every project. Therefore, the firm is classified as an '*advanced firm*'.

The participant interviewed for this study is a senior architect at the firm, with a 15-year experience in architectural practice, five of which is at the firm where they work in challenging projects, tackling geometrical complexity as a key focus. They are involved in various design aspects and coordination, which include working in design development packages, tender packages, site supervision, and site coordination. The participant will be referred to as C2, as they are classified in this study as a competent user of parametric design, and have used this design methodology successfully in a limited number of projects.

### 6.4.2 Digital Technologies and Tools

A large number of software applications, scripting platforms and hardware technologies of varying types are used at the firm. In terms of scripting, they rely heavily on Maya script, to solve the geometrical problems in the complex forms they generate within many of their projects. In fact, Autodesk Maya is very popular amongst the design team, as they find it friendly and intuitive. Using Maya scripts helps in rationalising complex forms in order to overcome arbitrary issues in such shapes. Furthermore, they widely use algorithmic scripting platforms, such as Generative Components, Grasshopper, and Python, which help them to develop parametric models where necessary.

In terms of other software applications, almost all popular software applications are available and widely used in order to meet the diversity in their work environments, and to give their teams freedom to select the applications that best meets their needs, their experience and their culture. In addition to Maya, which tends to be the most popular software at the firm, they use

Rhino, Digital Project, AutoCAD, 3DS Max. Furthermore, they use a variety of hardware technologies, such as CNC machines, laser cutters, and 3-D printers. This wide variety of rapid prototyping tools, software applications and scripting platforms show the robust technological infrastructure that underpins the, visually striking, fluid, and complex buildings that they produce.

Parametric design is widely used in the firm, and most of the design team members are relatively familiar with these novel design methodologies. C2 states that parametric design was used in their practice for the documentation of both design and construction processes. This is combined with the efficiency of parametric design in their form finding and rationalisation processes, which allows the design to be seamlessly optimised against the structural and environmental performance of building. Therefore, C2 agrees with C1 on the usability of parametric design in the late stages of the design. This is due to their practical experience in parametric design. Therefore, both disagree with R1, whose theoretical, research-based knowledge on parametric design focused on its potential impact for the conceptual design stage.

### **6.4.3 Roles and Areas of Specialisation**

The array of technologies utilised at the firm required specific experiences and skills to make effective use of them. According to the participant, in order to work effectively in such a technologically-enriched atmosphere, a member of the design team needs to have highly developed computer skills, as they heavily rely on a multiplicity of software applications, even in the very early stages of the design process. More importantly, a designer needs to be aware of the capability, and capacity of each technology or application utilised. The participant explained that having scripting and programming skills is also useful, or ‘a plus’. However, mastering scripting and algorithmic knowledge and the software applications that support this kind of method in design is essential for some projects. This depends on the nature of the design project, including its complexity, and size. While the literature shows how the reliance on computational design results in shifts in experiences and knowledge required for architects (Aish & Hanna, 2017; Oxman, 2017), this description shows the impact of the general atmosphere and work environment on the skills and experiences of an architect, as they need to continuously develop their digital experiences and programming skills to ‘survive’ despite the cognitive barriers associated with those technologies (Wortmann & Tunçer, 2017).

Most of the graduates that join the firm come from architectural schools that support this kind of tendency in architectural design. As such, most will already have a solid background in algorithmic and parametric design, and will have experienced these kinds of smart software, such as Rhino, Grasshopper, and Maya during their study. This situation provides an example of the shift in knowledge and skillsets for computational design (Oxman, 2017). In the case of this firm, programming, scripting and parametric design are the knowledge that are most welcome and sometimes essential, considering the fluidity and complexity of the buildings they produce. Therefore, the design team has many programmers who are specialised in Maya Scripting, Grasshopper, Python, and many other scripting platforms. Such skills give the designer a key role in a wide range of projects at the firm, especially in the conceptual design stages, and when working on schematic design. These situations resonate with the ‘power’ that some practitioners can gain through their ‘persuasive ability’ in conducting specific types of tasks (Cuff, 1992, p. 169) or through ‘esoteric experiences’ (Blau, 1984, cited in Cuff, 1992). In the context of this firm, the ‘persuasive ability’ or ‘esoteric experience’ of individuals in leveraging these technologies provide extra power and enable them to adopt key roles and participate in critical design decisions. In this context, C2 states that many designers have substantial experience in using Autodesk Maya. This experience enables those designers to have major roles in projects, where they focus on planning layouts, and on figuring out the project program. They fit this program within the complex form generated in the conceptual stage as an essential part of the rationalisation process.

Whilst initially, the work environment at the firm seems similar to the environments at Case 1 in terms of the availability of various technologies and applications, there are actually significant differences. Firstly, in this Case there is heavy reliance on technology from the initial stages of the design process, whereas at Case 1, different scenarios were explained that show classical ways of meeting, sketching and collaborating. Secondly, the individuals in firm’s design team have programming and scripting skills, which is not usually the case at Case 1, where advanced technology is handled by the research groups. This difference can be explained in two ways; firstly, that this firm is more advanced in their use of technology than the previous firm, where designers’ technology skills and experiences are already part of the design team and do not need interventions from a research group. In comparison, the second explanation is that the culture at this firm is notably different and relies on equality among individuals in the design team; this is, again, different to the previous case, where the



members of the research group have exceptional skills and experiences, which enables them to supervise the design team individuals, who have ‘normal skills’.

At the later stages, multidisciplinary starts to gradually appear, where participants with other sorts of skills engage in the project; these are mainly experts in providing tender and construction packages which involves a lot of detailing. Later on, different specialist consultants are engaged, such as façade consultants, or consultants involved with complex geometry and rationalisation, who are mainly structural engineers. These are in addition to other consultants specialised in landscaping, MEP, and quantity surveying.

#### **6.4.4 Processes and Workflows**

The design processes at the firm are various, as every design project is unique (Rittel & Webber, 1973, cited in Hudson, 2010) with its own nature, and is processed within a unique context and circumstances. To explain this issue, C2 narrated stories about processes they were involved in at different times, where they described various scenarios from a range of projects. These scenarios are classified by the design stage.

##### ***6.4.4.1 Early Design Stages***

In the early design stages, the design team relies on Autodesk Maya, and McNeel Rhino. According to the participant, both Maya and Rhino rely heavily on algorithms and mathematical formula. However, they find Maya more intuitive, and more user-friendly in terms of designing and forming, which is why they rely on it at the conceptual design stage. This situation resonates with the issue raised by Lawson (2011) who emphasises the need to develop software capable of mapping a designer’s mental symbolic representation in order to support the creative aspects of design. Therefore, Maya’s capability of creating and modifying freely could make it a preferable tool to Rhino, which is more mathematical. According to C2, Rhino is more rational in terms of the way the model can be built, as it requires a more mathematical way of thinking to execute forms, which is why the firm rely on Rhino for the rationalisation within the schematic design stage. In other words, the participant explains that the nature of the software application constitutes the stage at which it is used. Thus, the intuitive nature of Maya makes it more suitable for the conceptual stage, whereas the mathematical way of modelling with Rhino makes it more convenient for the later stages. Therefore, the design team usually starts the concept design using Maya software, where they work on generating the design form. They continue to develop this form

based on feedback given regularly by design managers, until the final form is approved. After that, they move to schematic design stage, where they start the rationalisation of the Maya model, which, in most of the cases, requires the model to be rebuilt using Rhino. This is similar to the previous case, as the model is rebuilt in Rhino rather than exported from Maya, which reveals interoperability issues. In addition, this process fails to exemplify digital continuity from conception to production (Oxman, 2017; Kolervik, 2004)

#### **6.4.4.2 ‘Rationalisation Stage’**

In the schematic design stage, the team starts to involve all of the other consultants, especially those concerning the façade. In some projects, they engage the façade consultants in the design process from the conceptual stage. The consultants are usually engineers with broad experience in rationalising complex geometries. The consultants start working closely with the design team to tackle the complex geometry problems and to rationalise the whole shape, and hence ensure it is buildable. Rationalisation is a complex and cumbersome process that includes surface facilitation and surface reformation, where the consultants start to reform and simplify doubly-curved surfaces into a series of single-curved surfaces. In fact, this scenario demonstrates that working with such a high level of form complexity results in a paradigm shift in the design process; while the previous case reveals how complex design form enhances the importance of rationalisation, this scenario shows that, when designing complex forms, rationalisation changes from an activity to a principal design stage that consists of sub-stages. Within this stage, the doubly-curved surface is divided into single-curved panels, so that each is fabricated individually to allow the surface to be constructed out of intersected panels during the construction stage. Meanwhile, the design team starts to work more intensively on producing plans and sections and on a range of architectural drawings, and in doing so, they first use Rhino, and then move to AutoCAD. More precisely, they normally extract sections out of the Rhino model, and then export these to AutoCAD, in which they continue to work on it. Thus, they develop sections and all other drawings in AutoCAD, and develop them through to construction or tender packages. This again shows the relationship between the software application and the design stage in which it is used, where the accuracy that AutoCAD offers makes it convenient for detailing. Furthermore, this scenario shows that working with complex forms results in key roles for engineers at the core of the design. In this scenario, engineers are integrated into the design team to rationalise the design form. However, the scenario shows no integration, as the design is approached using different platforms and different participants at each stage.

#### **6.4.4.3 Design Development Stage**

The participant was engaged in a project where the design form was too complex to construct in a rational or traditional way. More precisely, exchanging plans and sections in AutoCAD with a consultant was not efficient. This project required the use of Digital Project software, which was able to satisfy the needs of the consultants, who were able to take all the package in one single file. Within this scenario, the design team took the conceptual design model from Maya, and then rebuilt the model again in Digital Project. From this, all other consultants, or sub-consultants, working with the design team needed to work at a basic level in Digital Project. As a result, they had one big model which contained everything so that the design team and all consultants were able to extract sections, plans and 2-D drawings directly from the central Digital Project model. This demonstrates the potential for using Digital Project in integrating architectural and engineering platforms by providing a centralised platform that contains the model, and where different kinds of drawings can be extracted at any time for different purposes. In relation to the link between complexity and coordination raised in the previous case, in this scenario, the coordination was facilitated or automated, which gives designers a greater opportunity to focus on their creative tasks.

#### **6.4.4.4 Construction Stage**

In addition to the potential for Digital Project to act as a single platform for all designers and consultants at the design stage, it was also helpful at the construction stage. In this regard, the participant states that, within the same project, they continued working in Digital Project for the site coordination during the construction stage. At this stage, the design team used Digital Project to extract sections. This shows the potential for using Digital Project when dealing with complex forms at the construction stage. According to the participant, the traditional way of sectioning, used in previous projects, was not helpful, as it sometimes required the taking of 100 sections to know exactly what was happening on site. Therefore, the potential to rely on Digital Project lay in allowing the capability to produce a fully coordinated model, or at least a 90% coordinated model according to C2. This, in turn, allows for the automated extraction of sections that are used to enable the investigation of the different potential problems.

One of the problems, that the team encountered in this particular project was that some of the MEP ducting clashed with some of the structural elements, or with the proposed ceiling. The problem was visualised and then resolved on the same central model by shifting items, and

sometimes shifting ducts, or conducting slight modifications to the design shape. Subsequently, the problem and the modifications were reported with some recommendations.

In general, when Digital Project is utilised, all coordination supposedly occurs at the design stage; however, it is usual that working on site reveals problems that were unforeseen at the design stage. In addition, there are always unexpected discoveries related to the site conditions. In addition to the clashes between the different parts of the building, some of these problems require slight changes to the shape, as explained above, while other problems require significant changes, and this is where the rationalised or built shape starts to deviate from the design shape. In fact, some problems could not be resolved by local contractors in the project, thus, interventions were needed, where external specialists joined to interface with local contractors as well as the supervision team. They returned to the original Digital Project model to investigate the problem by comparing what was happening on site, to what had been designed; from this they were able to coordinating solutions between the two. This scenario resonates with the main dilemma in any architectural project that results from the ambiguity of the design problem at the outset of the design (Chaszar & Joyce, 2016), and the difficulty of using current information to predict future scenarios (Jones, 1992), which often results in ‘surprising ends’ (Cuff, 1992). Thus, the ‘surprising end’ at this scenario is the need to modify the design form at the construction stage, which means deviating from the original design. This shows the potential of BIM software, which allows for earlier information and hence, more accurate future expectations.

#### **6.4.5 Collaboration and Interdisciplinarity**

The way the members in the design team collaborate differs, based on the nature of the project and the different teams involved in the process. Therefore, there is no one scenario that describes the way in which firm members and teams collaborate; however there are, instead, different policies. Thus, the participant chose to narrate a collaborative scenario that is the most likely to be iterated within different projects.

##### ***6.4.5.1 Collaborative Scenario in the Conceptual Design Stage***

The members of the design team start working together from the initial stage of the design process, where they create a collaborative and competitive work environment. For instance, in some projects or competitions, a group is created within the design team, and a senior architect is appointed as the group director, who starts the process with a meeting involving

all the group members as well as the head of the design team, who is normally an associate at the firm. During the meeting, all members, the director and associate sit around a large meeting table, where the associate talks about the project, and explains the constraints and client's requirements. From this foundation, the associate starts raising ideas, and hence everyone-else in the room follows this lead, which appears to be a brainstorming session (Jones, 1992); thus, verbal words are the sole method for communicating ideas and thoughts amongst members within the room. At a later stage of the discussion, designers start to draw sketches and some simplified rough models and share these with the other designers as well as the group director and associate. Such a scenario reveals the importance of drawing in design (Jones, 1992; Lawson, 2011); therefore, despite the vast array of digital technologies and methods applied in this firm, it is still a key method to communicate design ideas.

The process of debating and drawing continues this way until they reach a point where the ideas start to crystallise, and a general concept about the design is formed. At that point, the associate asks everyone to return to their PCs and design certain forms or ideas, whilst some designers continue to develop the rough models. The process continues throughout several more meetings, so that, at the end, the team develop a large number of options in the form of 3D models, rough models, or simplified models. At this point, another meeting is being organised, where each of the options are analysed and discussed by everyone so that some of the options are filtered out, while others qualify to the next stage. At this phase of the process, a number of models are selected as the initial design options, which normally total ten. The options are sent to one of the managers or senior architects at the firm, who then chooses three, and gives feedback to the design team, who takes this on board to further develop the three selected options. The three options are sent to one of partners, who chooses one or two of the options, and provides comments and guiding notes to inform the development of the final conceptual design models. Therefore, the design team work on the remaining options for presentation to the client as semi-developed design solutions. The client selects one of the two options, and that is when the design team starts to communicate to different participants from different disciplines to develop the design. This scenario demonstrates the culture of firm, which focus on equalising members in the design team, where each designer, regardless of their experience, can participate in the process.

#### **6.4.5.2 Collaborative Scenario in Design Development Stage**

After the conceptual design model is completed, the team prepares the design development packages as well as the tender packages. This requires intensive coordination and communication with a wide range of disciplines and consultants. First of all, they start to organise regular meetings which can either be weekly or more frequent, depending on the size and complexity of the project. Furthermore, the project is divided into components, so that someone can, for example, start developing the external envelope, or external skin, and thus be in contact with the façade engineer, or the geometry engineer. Meanwhile, other designers, or groups of designers, can work on the plans (i.e. developing the plans, making the layout), and others can start to coordinate with the structural engineer or the group of structural engineers, depending on the size of the project. In the meantime, weekly meetings are organised with all consultants, while every two days, the design team meet to check the coordination.

When working on complex projects, the development of a design requires intensive interventions from other consultants who are specialised in complex geometry. Those consultants take the forms generated by the design team and rationalise them in order to make them buildable. This scenario responds to the issue raised in Chapter 2, where Lawson & Dorst (2009) state that the activities in the design process differentiate based on a designer's level of experience. In fact, within this equalised and collaborative work environment, the activities differ based on the type of experience of each participant.

The design team uses normally classical ways of sharing information and models with the consultants, where they send files by email, or use WeTransfer when sending large files. However, in some projects they use a simple cloud storage, such as Google Drive, where they create an interface to transfer and exchange information and models with other consultants. Therefore, a combination of highly-advanced and classical sharing methods are used, despite the existence of an extensive range of digital technologies at the firm.

#### **6.4.6 Adaptation of Tools**

Adapting tools and software applications within processes is popular at this firm, as they develop highly-complex forms that, in most of the cases, go beyond the capabilities of the software applications they use. According to the participant, the design team is provided with four Software Developers or Scripting Specialists; three are specialists in Maya script, while

the fourth is a specialist in Grasshopper. These specialists work together with the design team, especially in complex projects, where they develop patterns, and resolve issues in terms of the complex design form. Thus, whenever a designer has a form-related problem, these specialists will start to find solutions. This shows the essentiality of adapting software when designing complex forms. In fact, the members at this firm tend to test the limits of the designed form whilst also testing the limits of the tool.

When those scripters or parametric design specialists have extra time, they develop other sorts of patterns and solutions so that they have a solution ready to solve similar problems in subsequent projects. They sometimes work independently by designing different forms and conducting research to develop systems and algorithms that can be used in current or later projects. For instance, one of the scripting specialists used to develop parametric definitions and components that could act as ready-to-use algorithms intended to solve different sorts of problems; from this they then used to send the algorithms to specific members of the design team. This is a valuable example that resonates with the ‘strategic level’ and ‘operational level’ highlighted by Emmitt (2014). In this scenario, scripters and parametric design specialists give priority to the operational level and, when they have extra time, they shift to the strategic level where they start to develop scripts and Grasshopper definitions that can work on different projects. In other words, they generate seeds that can be planted in future projects to further generate contextualised design solutions. These seeds are created independently from scratch, rather than extracted from a project context.

#### **6.4.7 Problems**

Similarly to C1 and R1 from the previous case, C2 did not report any technical problems. However, they criticised the overall complex forms designed, and the material selected in relation to the software used. From their perspective, the participant states that dealing with such technologies and forms is challenging as they are not interested in technology. They prefer sketching shapes by hand, and therefore, are concerned about the heavy reliance on computers to generate and to resolve forms, where a designer can end up being dictated to by the software capability. The participant feels that this results in limitations on what a designer can do. For instance, the participant claims that all forms generated using Maya are somehow similar; this is so that they can recognise the form generated in Maya from those generated by other software. Therefore, the participant is not convinced of the way that forms are designed and presented or the way the different design components are put together into

the architectural fabric. This is another valuable argument that reveals a reasonable explanation for the heavy reliance on digital technologies, which results in harmful impacts on the creative aspect of design. In this regard, C2 agrees with C1, as they both emphasise the need to rely on free-hand sketching when developing creative design solutions. In comparison, according to C2, the use of advanced software results in limitations on the designer's capability due to the limited capability of the software.

Furthermore, the participant feels that the overall shapes produced are not that appealing to the non-architect, and that this is not only a result of the limitations in the form caused by the software capabilities, but also due to the limitations in the material used for the structure and the cladding of the complex and fluid forms. For instance, they state that it can be very difficult to design a brick building out of a Maya-generated form, because Maya does not have the capability to lay out the brick in a way that makes bricks responsive to the seamless and fluid shapes produced in the software. This means that using Maya dictates a certain kind of cladding material, which is going to be either metal or GRC; therefore, a designer is limited to certain materials, which in the end, results in limiting designers to a specific kind of final product in terms of the form and texture, where in the end, all forms appear similar. This argument challenges Bernal et al's (2015) definition of the levels of impact of digital technologies on design activities. With regard to parametric design applications, C2 states that the tool as a whole was disappointing, as they were looking for a more intuitive tool, where a designer could use touch screen techniques, to slide and explore variations, thus using the hand akin to paper-based sketching. Bernal et al. (2015) argue that the technologies can either aid, automate or augment the design activities, whereas the participant adds a fourth item to those levels by claiming that digital technologies may dictate the design solutions and materials used by a designer, and hence, limit a designer to certain forms and textures. Therefore, digital technologies can place limits on creativity.

#### **6.4.8 Research and Development**

The firm has an in-house computation design research group that carries out practical research, where they conduct research within the context of different projects in order to acquire knowledge, techniques and methods from a project to inform later projects. The research group also participates in several research projects alongside with other enterprises, organisations and institutions. Furthermore, they conduct independent research that focuses on identifying shapes and predicting their performance, and conduct design experiments



where they develop, for example, Grasshopper definitions and components and send them to the design team for use in projects. The knowledge, information and outcomes of the research form a library that is saved on the main server, and accessible and editable by all employees at the firm. This, again, reveals the insistence of the firm to continuously address both the limitations of digital technologies, and the limitations on the level of form complexity possible when using these technologies. Reflected in the previous project scenarios as well as in the research, this shows the intensive work that underpins the complex and fluid design forms which characterise this firm.

#### **6.4.9 Future Expectations**

The future expectations of the participant are derived from the problems they report. Therefore, they predict that new applications and technologies will be developed to enable an architect to ‘use their hands again’. More precisely, new applications will be based on touch-screen and sliding techniques to enable architects to retain the role of their hands, such as with sketching. Furthermore, the participant states that digital technologies are going to develop very fast, and might gradually start to take over the role of the architect at some point. Thus, the traditional role of an architect will change to focus more on how to control the technologies and methods used. More specifically, the role of the architect will focus on trying to fill the new parameters, as designs will be made from templates and ready-made designs, where a designer just needs to fill the templates with the criteria needed to produce the design object.

## **6.5 Case Study 3**

### **6.5.1 Introduction to the Practice and the Participant**

Case 3 is an architectural firm with their headquarters located in Germany. The practice has 170 members organised into project teams consisting of architects, interior designers, landscape designers, engineers and surveyors. The teams at the firm are involved in a wide range of architectural projects in Germany and worldwide, where they focus on the quality, efficiency and economy of their design projects. The firm is classified in this research as semi-advanced due to the limited reliance on advanced technologies in their projects. The firm is classified in this research as semi-advanced due to the limited reliance on advanced technologies in design projects.

The participant is a senior architect with 10-years of experience in architectural practice, who has worked for the firm since 2013. They have worked within a variety of projects inside the firm with the main focus on glazed façade design, including the creation of automated panel schedules, and the coordination of façade panelling systems with structural, MEP, fire safety and acoustical systems. They rely on a wide range of parametric modelling applications and plug-ins, together with 3D printing and rapid prototyping tools. Furthermore, they have worked on design competitions, where they have been involved in leading the final stages, coordinating with engineers and consultants, managing BIM models, and leading the coordination between the different design and engineering platforms. The participant will be referred to as E3, as they are classified as an ‘expert’ due to their in-depth and wide-ranging experience in using parametric design on various projects, both within their current firm as well as in previous companies.

### **6.5.2 Digital Technologies and Tools**

A wide range of software applications are used at the firm. For instance, they use Revit for project delivery, which helps them to coordinate work with contractors, sub-contractors, engineers and clients throughout the project stages. In addition, Revit is heavily relied on in the last stages of the design process where it is used to provide detailing and shop drawings. One more benefit of using Revit at the firm is, according to E3, the ease of extracting a full schedule of areas, and the project program and plan. This emphasis on using Revit reveals the firm’s main tendency, which is to facilitate coordination among different disciplines by using a relevant software application that acts as an integrated platform, from which different

disciplines can extract their information. Furthermore, they started using Grasshopper in the last few years, and within a short time it became an essential tool, due to its efficiency in dealing with large, complex projects in comparison to traditional CAD tools. E3 states that working in a parametric design context allows for flexibility in exploring different design options, where the designer can manipulate the parameters and the model recreates itself as a new version to display the results in real time. In addition to Grasshopper, E3 uses a wide range of plug-ins that can be added to Grasshopper to expand its functions beyond tracking complex geometry. For instance, they use Panelling Tools, Lunchbox, Honeybee, Ladybug and Kangaroo in order to automate the evaluation of the environmental and structural performance of their design within the same parametric design platform. This variety of parametric design applications helps the firm to enhance the interoperability between the heterogeneous set of applications utilised in design projects. For instance, to enhance the interoperability between parametric design applications and BIM applications, E3 uses a third plug-in between Grasshopper and Revit to transfer the information and geometry generated in Grasshopper to Revit, which generates native families and geometries out of this information. With regard to hardware technologies, a limited number of tools are used in comparison to Case 1 and Case 2; they use 3D printing in many projects in order to test shapes in the early design stages. The 3D printer is also used to build site models, and sometimes for the building itself. They also have a laser cutter that helps to add more detail to the 3-D printed model.

### **6.5.3 Roles and Areas of Specialisation**

The wide range of roles and areas of specialisation, such as geometry specialists and software developers, at Case 1 and Case 2 do not exist at this firm. The roles in this practice are similar to any traditional architectural practice, as most members are architects, who work collaboratively with engineers, quantity surveyors and project managers. E3 states that they do not have software developers as they are not software vendors. However, they confirm that they rely on Python programming language in developing scripting formulas to solve some geometrical problems in a number of projects. Furthermore, they have a handful of parametric design experts (which includes E3), who use Grasshopper and multiple plug-ins to deal with complex projects. Therefore, the reliance on developing software and parametric modelling is placed on specialists, although a minority of architects have these skills.

#### 6.5.4 Processes and Workflows

With regard to the design processes at the firm, E3 emphasises the uniqueness of the design situation for each project (Rittel & Webber, 1973, cited in Hudson, 2010). Moreover, they add another dimension as the unique design situation also results in a unique choice of software applications. In this regard, they state that the scenarios differ based on the nature of the project and its specific circumstances and context. However, such as in Case 1, they mostly use their hands to initiate the design process through drawings, sketches and rough models, and then move to Grasshopper if the ‘unique’ design problem requires parametric modelling. Therefore, despite the heavy reliance on parametric design, it is still essential to use sketching and drawing (Cross, 2011; Jones, 1992) to communicate a designer’s initial ideas.

According to E3, Grasshopper allows them to test issues and generate different geometries inside Grasshopper. If they find that using parametric modelling is unnecessary, they conduct the test and generation in Rhino. In both cases, they continue to use Grasshopper or Rhino until the design is approved; at this point they transfer their geometry into Revit, and start building their project with the accuracy and detail required for communication to the different project stakeholders. This scenario shows the appetite to develop and innovate, which is clear at the firm as they use parametric design in some projects when the design form is complex. In this case, the need for accuracy, and the lack of completion in parametrically-generated design models (Turrin et al., 2011) motivates the firm to re-create the model from scratch in Revit. Similar to the previous cases, this process does not seem to help in achieving the digital continuity that Kolarevik (2004), and Oxman (2017) discuss.

In general, E3 states that using parametric design in their design projects gives them flexibility in exploring different design options, where they can manipulate parameters and the model recreates itself as a new version to display the results in real time. This method of designing enables them to keep track of the design throughout the whole process, and to speed up the pace of the design process. Therefore, E3 emphasises the capability of parametric design in accelerating the design process, which is not the case in the reviewed literature (Chaszar & Joyce, 2016a; Holzer, 2015; Oxman, 2017b), where the focus is on automation (Turrin et al., 2011), flexibility (Aish & Hanna, 2017), modifiability (Jabi et al., 2017) and all of the other aspects that appear to be progressive results, which lead to process acceleration.

In addition to the different practically-informed arguments that E3 provided about the impact of parametric design on different aspects of the design process, they described different project scenarios that were driven by parametric design applications.

#### ***6.5.4.1 Project Scenario: Metro Station Front Façade***

The front façade of the metro station building was a doubly-curved surface that was made from quadrilateral glass panels. The irregular curvature of the façade made the panels different in size, orientation and curvature. Therefore, in order to prepare the panels for fabrication, the designer (E3) needed to identify the dimensions of each panel, the location of each panel within the façade, the coordinates of each of the four points of each panel's corners, the rotation angle of each panel, and the unique shape of each panel. This information was needed in order to prepare the table of panels with the accurate dimensions and sizes for sending to the manufacturer. To avoid the cumbersome process of dealing with each of the panels individually, the designer imported the curved surface of the front façade into Rhino, and introduced the surface from Rhino into Grasshopper. Subsequently, this surface needed to be divided into panels so that each panel would be manufactured individually for installing on site to form the façade. The division could be made using a simple algorithm on Grasshopper.

However, the rationalisation process made the algorithm more complicated, as there was a series of considerations and constraints related to the aesthetics, the cost, the performance, and the manufacturer's constraints. With regard to the cost, the division resulted in doubly-curved panels, which were extremely expensive to be manufactured. Therefore, the algorithm was modified in order to make the panels flat, so that the curvature of the façade could be obtained through the accumulation of flat panels. The aesthetic problem emerged at this point, as flattening the panels resulted in deviating the façade form from the original design of the surface. Increasing the number of panels reduced this visual effect of this deviation. In contrast, this increase resulted in a performance problem, as one of the main considerations was to get the maximum possible amount of natural light into the interior space of the station, which required the use of larger panels. However, the size of the panels was constrained by the maximum size allowed for the panel. The glass manufacturing company provided this maximum size.

To deal with these problems, the designer was able to embed these issues as rules into the algorithm created in Grasshopper. Moreover, an additional plug-in was installed and

integrated into the Grasshopper environment. This plug-in enabled a direct link between Grasshopper and Excel, where the table of the panels in Excel was generated automatically from the façade geometry in Grasshopper. The flexibility of Grasshopper and the direct link to the table in Excel enabled the designer to test a wide range of possibilities just by using number sliders to change numbers within Grasshopper. In each possibility, they were able to see the end result in the geometry presented in Rhino, as well as in the table presented in Excel. In the end, they were able to select the optimal solution that ensured a balance between all the criteria. In addition, the algorithm created in Grasshopper enabled tagging each panel with a number that showed its location within the whole façade. This number tagging significantly facilitated the installation of the panels during the construction of the metro station on site.

This scenario shows the flexibility and seamless modifiability offered by parametric design (Jabi et al., 2017) when tackling complex geometry (Oxman, 2017), as opposed to emphasising the limitations of CAD systems in achieving similar tasks (Aish & Hanna, 2017). It shows the potential of parametric design in establishing differentiation in design geometry, namely creating a large number of differential panels or parts by creating a set of rules and embedding them into an algorithm to force the panels to comply. When using any CAD or modelling software, the designer would have to create the panels one by one within an iterative and cumbersome process. Furthermore, using parametric design enabled a high level of modifiability, as any change in the overall surface or in the number of panels resulted in a real-time and automated change in the shape of the panels and in the table. This shows another aspect of the potential for parametric design, as, in most of the cases, such a modification in CAD would result in a repetition of the whole process, or what J. E. Harding and Shepherd (2017) terms ‘a complete re-run of the process’. In this regard, the designer states that using CAD could enable them to have a high level of control over each panel; however, they decided to sacrifice this level of control in favour of having differential panels and hence, generate a more creative solution. With regard to the conflict raised by two participants in Case 1 regarding the design stage at which parametric design can be used, this scenario supports the arguments of both C1 and C2 in showing an effective and efficient use of parametric design in automating repetitive tasks in the late stage of the design process. However, E3 appears to disagree with C2; while C2 criticises the impact of parametric design tools on the creative aspect of the design, E3 assures that, in this project, parametric design helped to augment their imagination when exploring alternative design solutions. This

enabled them to achieve a high aesthetic and environmental value through differentiation on the panels of a façade. The arguments corresponds to Chaszar and Joyce (2016a) ‘happy ends’, whereby favoured design decisions are made based on unintended results. This suggests the classification of parametric design as an augmenting tool and thus accords with Bernal et al.’s (2015) findings.

From a broader perspective, this scenario shows the potential for parametric design in generating highly detailed and accurate information, and to drive this information across multidisciplinary platforms, which in this case can be a design platform (design geometry in Grasshopper) and a quantity-surveying platform (table in Excel). Therefore, this scenario can be seen as an answer to the question raised in Chapter 2 regarding the ability of parametric design applications to function as BIM applications. According to Enyon (2016) and McPortland (2017), a 5D model is considered to contain information about the cost of different components. In this project scenario, the model generated from Grasshopper is considered a 5D model, as it contains information about the cost, where a table of quantities and costs can be extracted from the model at any time within the process.

#### ***6.5.4.2 Design Scenario: Football Stadium (Architectural Competition)***

In another project, the firm was involved in developing a design proposal of a football stadium project for an international architectural competition. One of the issues was the cumbersome and repetitive process needed to provide the layout of the seats within the stadium. Considering the limited time available to provide the design, E3 searched online to find anything that was available to use. Within a short time, a pre-built Grasshopper definition for a football stadium seats was found, which had the rules of a football stadium design. After checking the accuracy and reliability of the rules, this parametric definition was embedded into the stadium project that was under development. Thus, all the complicated equations were implemented to comply with the strict rules related to the height of the seats, the visual lines, and the curvature of the stadium shape. This process proved to be more timesaving than the process needed to build the algorithm for the stadium seating area from scratch.

This scenario resonates with the previous discussion in Chapter 2 regarding the reusability of parametric definitions (Aish & Woodbury, 2005) and the resulting recyclability of the design process. This project represents an example of how part of the design process can be recycled, for example, parametric definition of stadium seats found online. Furthermore, this

parametric model can be an example of a ‘building seed’. Just like in nature, and similar to Carlile’s (2014) scenario (discussed earlier), the parametric definition of the football stadium that E3 found online represents a building seed that was taken from a previous project and ‘planted’ inside the environment of the new stadium project. Therefore, the associative parameters embedded in this definition helped its contextualisation within the new project.

Furthermore, the successful attempt to embed a pre-made parametric model inside a stadium project has encouraged E3 to search in their own previous work to find other parametric definitions that could also be embedded into current projects to further accelerate the design process and save more time. In this regard, E3 states that within one of their previous projects, they developed a Grasshopper definition to generate a staircase. The definition enabled the staircase to automatically adapt its shape, height, depth and number of steps based on the levels and space available in the project. This same staircase was embedded into the stadium project, which adapted not only its dimensions, but also its total shape in order to ensure it could go around the curved skin of the stadium building. This is another example that shows how parametric definition can act as a building seed, and is a powerful example of Carlile’s (2014) scenario. However, an essential difference can be traced when comparing both scenarios. According to Carlile (2014), architects need to consider creating buildings seeds to generate buildings, rather than repeat the same process for every single building. This suggests the potential to generate a whole building from one seed; in this project scenario, a seed was used to generate the staircase, while another seed was used to generate the stadium seats. Therefore, by using parametric design applications, a building can be generated from a combination of different seeds, where the associative parameters enable the integration of those seeds within a single entity of a building model.

### **6.5.5 Collaboration and Interdisciplinarity**

The way in which different members in the design team at the firm collaborate, and the way in which they share files with each other and other disciplines relies on the nature and the capabilities of the software applications they are using. For instance, when they work with Rhino or Grasshopper, they often save versions of their files, so that a designer starts the concept design in Grasshopper; they send the file to other designers who can continue on top of this file by adding parts and hence, take the next steps in the development of the design geometry. Alternatively, they can design part of it, where, in the meantime, the first designer continues developing their part. The process continues this way until the team reaches a point



where they can merge all versions, and make a decision about the design options that will be taken forward to the next stage.

According to the participant, this way of working is really easy and smooth and has proved efficiency in the early stages of projects. Nevertheless, from a different perspective, this process reveals a multi-faceted problem; firstly, the coordination in this design scenario seems extremely complex and cumbersome. For instance, when a specific version of the design form is sent as a whole file to another participant, and the second participant starts developing a part, the first participant continues developing another part of the design. Thus, taken from the first participant's perspective, the second participant is working on the old version of the design. This situation requires a good memory when merging all the versions, as it becomes necessary to remember which of the files contains the latest version for each part. This problem might not be significant when working on simple forms, but when dealing with large-scale and complex forms, it becomes essential to address this problem, rather than just rely on human memory. Therefore, in such a case, designers need to find a more efficient way to support collaborative working at the conceptual stage. Another aspect of the problem is the increasing storage area needed to save different versions of the same file; this can be solved by relying on cloud-based systems and centralised models in order to allow for a shift from working on different versions of the design, to linking to a single version.

In the development stage, the reliance shifts to Revit, where the way in which contributors communicate differs significantly. In fact, the features of Revit enable the design team to abandon the exchange of files in favour of the development of a central Revit file, where different users from different computers can synchronise to this file. Within such methods, the 'design options' feature and the utilisation of 'work sets' in Revit gives each participant the capability to contribute to the development of the design by seamlessly adding their ideas, and concepts in real-time. Therefore, the design team arguably need to identify mechanisms that enable effective information sharing and work coordination at the conceptual design stage.

The design teams also collaborate with other disciplines, such as structural and MEP engineers. This was the situation in Cases 1 and 2; they also collaborate with external engineering consultants, especially when working with complex projects, and complex geometries, where such organisations can help to solve different issues, such as the rationalisation of complex geometry. Therefore, working with complex projects not only

requires more collaboration (as discussed in Chapter 3) but also requires a shift in collaboration to work beyond the borders of the organisation and involve external consultants. In this regard, the participant ensures, that in all cases, the software applications that they use make the collaboration with all other project stakeholders and external consultants simple and smooth. To ensure that collaboration is even more effective and smooth, external consultants should have a high level of experience and knowledge in parametric design and BIM, such that they are totally familiar with such kind of processes. To seek feedback from other consultants or disciplines, they send their files or geometries to consultants who examine and double-check to ensure that everything is working. From this, they provide feedback, which may take the form of notes containing detail about suggested updates and recommendations. In these cases, the design team relies on these notes to update the model. In some cases, feedback is embedded within the model, so the consultants identify the problems and issues, develop the model, and return it to the design team. This is similar to the way in which the design team at Case 1 interface with external consultants. However, this scenario raises an important issue, concerning the consistency of experiences of the different parties who are collaborating to design and rationalise a design form. In fact, according to the participant, this particular collaboration was achieved as external consultants had relevant experience that enabled them to interpret the models, and hence return appropriate feedback. Therefore, making sense of the experiences in collaborative work is subject to the same, or complementary, experiences of all collaborating parties.

In addition to the metro station façade scenario that shows the potential for parametric design in supporting collaborative work, E3 states that working with parametric design provides opportunities for designers to enhance collaboration and integration within the design process. They also state that a lot of robotics, which they use in fabrication, have their own plug-ins within Grasshopper. This reveals the potential of parametric design in integrating fabrication standards into the design process (Bhooshan, 2017; Holzer, 2015; Oxman, 2017b). Moreover, to support their arguments, E3 narrates other scenarios that show how parametric design enabled them to collaborate with the engineering team and external MEP consultants in some projects

#### ***6.5.5.1 Project Scenario: Façade Panelling System***

In this project, E2 was in charge of designing a panelling system for a similar façade to that of the Metro Station project; however, the main focus in this project was on the

constructability of the façade. Therefore, the parametric definition was developed earlier, and was similar to the metro station scenario. Using Grasshopper helped to generate differentiated panels for the façade in a short time. Later on, and similar to Case 2, the complexity of the façade required critical rationalisation to check the buildability of the panelling system. This is the point at which the structural engineering team started to become involved in the process. The parametric model was sent to the engineering team who used their own tool, that was integrated into Grasshopper in order to conduct the structural analysis and solve issues related to the thickness of differential panels and the different types of mullions required. Subsequently, they were able to embed their structural feedback into the parametric model to achieve continuity. In this case, the design team was able to continue editing their design after receiving the structural feedback, and thus, every time the design model was updated, the structural analysis updated itself automatically in real time to match the design update. This is an ideal example that shows how parametric design has the potential to push the existing limits of architectural design into relevant areas (Hesselgren & Medjdoub, 2011; Thomsen et al., 2015). However, this project also fails to exemplify digital continuity (Kolarevic, 2004; Oxman, 2017). According to E3, several versions of the same parametric model were saved in order to go back in history and explore the previous models. Meanwhile, the new models were embedded as the beginning steps. In other words, not one continuous model was used throughout the design process; instead, several versions were saved for design and for structural engineering purposes, which indicates that the digital continuity was broken. This is similar to the previous scenarios where the model was recreated from scratch in Revit, rather than imported to the BIM environment offered by Revit. However, in this project, E3 attempted to bridge this gap and enhance the interoperability between parametric design applications and BIM applications in order to enable greater continuity in the design process. For this specific purpose, E3 used a Grasshopper plug-in called 'Hummingbird'. This plug-in was integrated into Grasshopper and was therefore able to read the information about the coordinates and sizes of the panels in Grasshopper, and translate this information as families in Revit.

The potential of this scenario can be viewed from different perspectives. First, it demonstrates that, rather than just being an effective tool, Grasshopper can push the capability limits of other tools. In this example, using Grasshopper together with Hummingbird, enabled the creation of complicated Revit families that are beyond the capability of Revit. Second, this scenario shows the power of information, which The

Economist (2017) describes as the new ‘fuel’ and Oxman (2006) describes as a ‘new material’. In the previous scenario, information generated in Grasshopper represented the ‘raw material’ from which geometrical ‘families’ were generated in Revit. Furthermore, the whole scenario, highlighted a previous point about the availability of similar experiences and knowledge amongst all teams in collaborative work. This is considered the main influence to result in the successful coordination within a parametrically-driven architectural design and a structural design process. In this regard, E3 argues that the opportunity to allow for contributions from other disciplines in the parametric design process relies on their experience in parametric design, and hence, their ability to understand this new ‘language’.

#### **6.5.5.2 Project Scenario: Circular Bridges**

In this scenario, the designer (E3) explains how parametric design helped them in coordinating with the MEP external consultants. In this scenario, the designer created circular bridges that were made from curved soffits. The overall form of the bridges was very complicated so that the curved soffits were changing in shape in the plan and in section. This irregularity presented a big challenge, namely, how to fit the ventilation ducts and mechanical systems into this complex geometry without affecting the functionality of the systems. To deal with this situation, the designer imported the model, which included both the circular bridges as well as the mechanical elements, from Revit into Grasshopper. The flexibility of Grasshopper, together with the experience of the external consultants in using Grasshopper enabled the coordination required to address the problem. In this case, the designer was able to re-model the ducting system so that it was associated with the soffits of the bridges. They then shared the parametric definition with the MEP consultants, who were able to provide feedback within the same parametric definition. The feedback enabled the designer to identify the limitations and constraints in modifying the ducting elements, such as the standard sizes for the mechanical elements and the maximum bent angle allowed. In the end, both the design shape and the mechanical elements were modified concurrently, and the final model was sent to the MEP consultants who conducted their final test and approved the design. The designer indicates that the use of Revit to deal with this complexity would have been extremely cumbersome, and would have required far more time and effort, as each single modification would have required coordination with the consultants. Having identified coordination as the main source of complexity in the design process, this scenario shows the role of parametric design in facilitating coordination, and hence, in offering a considerable simplification in the design process. In addition, this scenario shows another aspect of

process acceleration that stems from the ability of parametric design tools to integrate design and mechanical platforms to automate changes. This can be a valuable alternative for the traditional coordination that relies on a loop of generation, evaluation, synthesis (Bernal et al., 2015; Lawson, 2006), and file versioning (as shown in Case 1).

## **6.5.6 Research and Development**

### **6.5.6.1 Training**

The firm seems to be aware of the criticality of updating the skills of their design team to remain informed of new advances in architectural and constructional technologies, and thus, they provide their design team with support and training. E3 also describes a similar experience in their previous work, where the design team were offered training sessions in parametric modelling software; however, E3 states that the sessions were unsuccessful, as they did not meet their goals. The reason for this was because the sessions were too time intensive for the trainees, who were part of the design team in an extremely busy architectural firm. Therefore, their main concern was to finish their duties for the projects they were involved in, so as to meet their deadlines. The participant stated that the deadlines were tight and trainees struggled to manage their workloads; therefore, they did not have the time or energy for training as well. E3 was able to examine this experience and analyse its problems, so that, they were able to develop a new strategy for training the design team to help them enhance their skills in parametric design. E3 relies on a strategy of providing only one session every fortnight in order to give trainees enough time to understand the software application they have been trained to use, absorb its philosophy, and link the new methods enabled by this software to their current work scenarios. Nevertheless, the new strategy also has similar problems due to workloads and deadlines. However, E3 ensures that it is much more effective than the training sessions in his previous position. They state that the sessions help in the dissemination of new methods to approach projects within the design team and the firm as a whole; however, they do not help trainees to master the software. This issue highlights the need to rethink the subjects introduced to students in architectural institutions in order to ensure consistency with the rapid growth of innovative methods in the architectural practice.

Furthermore, the firm provides their teams with weekly one-hour Revit training, where members of the expert BIM team provide sessions to help teams improve their knowledge in BIM technology. The sessions provide ‘tips and trick’ about different aspects in Revit, with a focus on phasing projects, from concept to development until the demolition. They also focus

on using design options, and on specific design aspects that are needed across many projects at the firm. This could include how to import terrain geometry from CAD software into Revit and hence, change it from ‘dead geometry’ into a ‘native terrain model’ inside Revit.

#### **6.5.6.2 Knowledge Acquisition**

The firm places critical importance on saving files, and documenting experiences and knowledge to help in continuously developing new methods, more effective processes, and better products. To enable this, they have a small research and development team who work on documenting processes from previous projects, identifying frequent problems with potential solutions, and articulating all knowledge acquired during the different stages of projects. They also take screenshots that show complicated situations, and how these situations were dealt with. Furthermore, they save scripts and parametric models for use and further development in later work. According to the participant, the potential of this developmental strategy becomes obvious when working on large scale projects, and those with a high level of complexity.

#### **6.5.6.3 Storage, Intranet, and Database (Digital Repositories)**

Similar to Case 1 and Case 2, the firm has a digital library saved on the firm’s server. The server allows everyone in the firm to access a wide range of files and folders saved in the library that contain bits or parts of scripts that were developed in previous projects and saved for later use in different projects. E3 states that the library is widely used, where designers and members from other teams use files and pieces of previous work to apply them within their current work. The content of the library relies heavily on contributions from the research and development team. This supports E3’s previous explanation of searching online for potential design solutions, as in the stadium project scenario. In this case, the Internet appeared to be a global digital library.

#### **6.5.7 Problems**

One of the problems that E3 reports, relates to the general culture, where highly advanced technologies and smart methods are utilised and developed by a minority of architects at the practice. However, the remaining majority, tend to stick with traditional methods of working, where they rely on CAD to develop design projects. This situation results in difficulties in collaboration; thus, as previously explained, collaborative work requires all parties to be familiar with new methods, otherwise, the whole team reverts to traditional methods. With

regard to parametric design, E3 argues that the limitation of the tool depends on how much designers want to limit themselves, as parametric tools offer a high level of freedom. However, to access the benefits, the level of control over each part of the design object will be sacrificed, especially when designing differentiated geometry. The problem with the misunderstanding (Jabi et al., 2017) and marginalising of parametric design (Schumacher, 2016) can be seen from two perspectives; the efficiency of the tools and the availability of relevant experience and knowledge to effectively use this tool. In the previous argument, E3 shows the problem from the user's side, namely the mentality, where users need to be open minded and sacrifice some aspect of the design in favour of gaining greater benefits from this tool. E3 stated that the software applications used, especially the parametric design tools, are still immature. This is why, in many cases, they need to use scripting platforms to develop software to match the needs of projects. For instance, when working on complex geometry, where the curvature of the design surface requires panelisation for fabrication purposes, the process starts by trimming a surface, then dividing the surface into sub-surfaces. In this case, Grasshopper divides the original untrimmed version of the surface, rather than dividing the updated trimmed surface. Solving this problem was cumbersome, as they had to rebuild the trimmed surface as if it was the original surface, or use a complicated process based on VB scripting to solve the problem. Another problem is that too many useful and essential commands in Rhino do not have counterparts in Grasshopper, which can result in additional work and time to find complicated alternatives. In the literature review, his problem is referred to as lack of compatibility with the host applications (Aish & Hanna, 2017). In fact, some tasks that can be done with single clicks in CAD, require the creation of algorithms to achieve such tasks. This is both cumbersome and creates cognitive barriers in parametric design applications (Aish and Hanna (2017)).

### **6.5.8 Future Expectations**

With regard to the future expectations of architectural practice in relation to technological evolution, the participant focuses on the growth of experiences rather than the technologies themselves. They state that there is a 'big future' awaiting these new technologies, once practitioners become familiar with, and start making sense of them. For instance, the increasing use of Autodesk 360 will make a difference in practice, as it enables users to model design forms, and save the history of the modification, with the capability to change the initial stages and automatically update the final result. In short, the participant argues that the rapid growth in architectural practice lies in the increasing involvement of architects

within existing technologies, rather than the development of the technologies themselves. In this sense, E3 supports the main tendency of this research; rather than calling for the development of technology and methods, they urge for more effective and efficient use of the technologies and methods that already exist.



## 6.6 Case Study 4

### 6.6.1 Introduction to the Firm and the Participant

Case 4 is an international architectural firm based in the UK, with other branches in the Middle East. The firm has already delivered a wide range of architectural and master planning projects where they focus on sustainability, and on the creation of social, environmental and economic values. Due to the limited reliance on digital technologies in this firm, alongside the successful and efficient use of advanced digital technologies in some projects, the firm is classified as ‘semi-advanced’.

The participant interviewed for this case study is an architect who has a degree in architecture together with a Master’s degree in mathematics. They have worked for some time in different engineering and architectural practices in various countries, where they gained experience in architectural design, structural analysis, construction technology, and BIM within a wide range of educational, commercial and master planning projects. They argue that their knowledge in mathematics has enabled them to take a major role at the firm, where they work on enhancing the reliance of parametric design and scripting in the design processes, alongside their role as a BIM specialist. The participant will be referred to as E4, as they are recognised as an ‘expert’ in parametric design due to their thorough experience in parametric design within different projects.

### 6.6.2 Digital Technologies and Tools

#### 6.6.2.1 *Software Applications*

In the early stages of the design process, the design team mainly rely on AutoCAD, especially in educational projects; later, in the design development stages, they rely on Revit, and Navis Works, which are analytical software packages that are used to perform clash detection, and to improve the coordination between the design and constructional stages. In some cases, E4 uses Dynamo, which helps them to speed up the workflow pace, and facilitate some activities within the design process. Moreover, Sketch-Up is widely used by many designers in almost every project. They also use Lumion and 3DS Max for rendering and visualisation, along with some other visualisation plug-ins, such as V-Ray.

According to E4, the stage at which Autodesk Revit is used relies on the project sector; more precisely, in the sport sector, they rely on Revit throughout the whole design and construction

processes. In the health sector, they use Revit from the design development stage until the end. Meanwhile, in residential projects, Revit is used only in the development stage, due to the lack of designers with specific experience in residential projects; this means that it is difficult to recruit people who are not familiar with such projects into the BIM working path. In this regard, E4 states that, in their previous company, Revit was used throughout the whole project from conceptual design to construction regardless of the type of building they were working on; thus, relying entirely on Revit made the work easier and faster.

#### ***6.6.2.2 Criteria for Software Selection***

The firm decided to rely heavily on Autodesk products, due to the availability of a wide range of high quality software applications. According to E4, the reliance on Autodesk gives the firm better options in terms of cost and interoperability. E4 agrees with the firm's decision to rely on Autodesk products. In this regard, they broadly discuss why they decided to move to Autodesk Revit, after extensive experience with Graphisoft ArchiCAD. They state that most of the architects they know, start learning AutoCAD and then learn ArchiCAD; although E4 had never used AutoCAD, they started to use ArchiCAD from the very first stages of their career. However, after they began to take major roles on large projects, dealing with structural engineers and coordinating with project managers and other stakeholders, they took a decision to stop working with ArchiCAD, and instead began to rely on Revit.

E4 is certain that ArchiCAD is better than Revit, in that it is simpler and more efficient at dealing with architectural projects, and coordinating and producing different views to produce high quality designs. However, ArchiCAD is not helpful when working with structural engineers, where different files need to be created. This highlights the problem with complexity, where working with other disciplines can result in confusion, as different files, information, and geometries need to be transferred, exchanged, shared. Furthermore, when ArchiCAD is used, too many of these activities need to be undertaken manually. When E4 started using Revit, they were able to simplify the coordination process, by sharing files with structural engineers, which gave both architects and engineers the opportunity to work together simultaneously.

A further benefit of using Revit is its compatibility with other Autodesk products, such as 3DS Max which they use for visualisation. Therefore, the firm relies almost entirely on Autodesk products. The only non-Autodesk product they use is Lumion, which is used for rendering and visualisation; it is also helpful in enabling effective and high quality

communication with other stakeholders. This explanation indicates the main orientation of the practice, where the key focus is on enhancing collaboration by automating coordination based on integrated platforms. This is arguably the main aspect on which software vendors need to focus when developing software.

In general, the firm is critical when selecting the software they need to use, so they avoid purchasing unnecessary software. To achieve this, they identify the working path of each project, and make decisions about the software applications that will be used at each design stage. This has the potential to identify a new sub-stage that can be part of Stage 1 (Preparation and Brief) in the RIBA Plan of Work (RIBA, 2013), which, in this case, involves deciding the toolset required for each project. In this regard, E4 offers an example, where, in one of the large project, they used Rhino, SketchUp, and Fusion at the conceptual design stage, then moved to Revit at the development stage, and then in the construction stage they used Revit and Navisworks. In addition, throughout the whole process, they use Access, Excel, and Dynamo, which are decided at the initial stage of the design to avoid any unpredictable costs.

### ***6.6.2.3 Hardware Technologies***

The reliance on highly-advanced hardware technologies is limited in the firm. However, some hardware technologies are used in projects, and this is based on client requirements and the project budget. They sometimes use technologies that allow a walkthrough in a virtual building within a 360 degree view range, where the walkthrough can be controlled by an iPad. Furthermore, they have a BIM server that is used to transfer information within a Common Data Environment (CDE).

### **6.6.3 Roles and Areas of Specialisation**

As in Case 3, the roles at this firm are similar to many traditional architectural practices. The firm has members from different disciplines within the built environment, although the majority are architects and engineers. Furthermore, E4 indicates that there are too many CAD draftsmen within the company who are only specialised in drawing, and who draw every single piece in all projects using AutoCAD. Despite the limited ability of drawings to connect design and making (Lawson, 2006), the simplicity of drawings, and their inability to respond to the increasing complexity of the current industrial world (Jones, 1992), drawing at this firm is still the essential method to communicate design. Thus, despite the array of digital

technologies available, the practice still rely on traditional approaches to architecture, which can be time and energy intensive (Cuff, 1992).

With regard to the role of E4, they state that, based on their mathematical knowledge, they are effectively contributing to the expansion of the scope of specialisation areas within the company by utilising parametric design and by pushing for more reliance on BIM in different projects. This can be traced to the power of participants in practice. Such power is gained through an individual's 'esoteric experience' (Blau, 1984, cited in Cuff, 1992) or through their 'persuasive ability' (Cuff, 1992), which may mean persuading the movement of someone or something in the firm in a desired direction (Zartman, 1976, cited in Cuff, 1992). In this case, E4's exceptional mathematical knowledge and their resulting mature skills in parametric design and BIM allows them to secure power and authority. Therefore, they can take decisions on behalf of their firm with regard to the technologies that should be used and the methods that need to be applied. This view is supported through the availability of a small BIM team at the firm, that contributes to the design and construction of some projects. The firm also has a small research group that undertakes research projects to improve the workflow within the company. This research group has experts in different related fields, such as sustainability and green buildings.

#### **6.6.4 Processes**

With regard to computational design processes, E4 narrated different project scenarios that show the value of using parametric design and BIM in some of the firm's projects. The parametric design-based project scenarios are discussed in this section, while the BIM-based project scenarios are discussed in section 6.4.5.

##### ***6.6.4.1 Project Scenario 1: Football Stadium Seating***

Unlike the previous example in Case 3 that shows how E3 adopted a parametric definition from the web that included all the rules for the seating area of a football stadium, E4 in this scenario decided to build the whole algorithm from scratch. The project was a football stadium, where one of the most challenging task was to design the seating area, which contained 90,000 seats. The complexity lay in ensuring a good view for each of the audience, which is a cumbersome process that requires complicated conclusions for every group of seats, or every row. In some cases, the calculations needed to be iterated for each seat,

especially on the bent location of the seating area, where each seat had a different orientation, different height, and hence a different view line.

To address this complexity, the designer (E4) used Dynamo to develop an algorithm that included all the rules and equations that were taken from the existing standards and regulations for football stadiums. The algorithm was developed in several stages; in the first stage, the designer imported the seating area developed in Revit into Dynamo, where the algorithm enabled the layout of all seats. In the second stage, the algorithm translated the location of each of the seats into coordinates (x, y, z), where each of those 3 coordinates were represented as parameters. In the third stage, the algorithm used these parameters to generate other parameters that represented the height of each seat from the pitch level, the horizontal distance between the seat and the focus point on the pitch, and the seating step width. In the fourth stage, the standard equations were embedded into the algorithm to calculate the C value (Figure 5) of each seat, which is the parameter needed to evaluate the quality of the view for each seat. In the last stage, the range of the accepted C value was fed to the algorithm (the minimum and maximum C value allowed), and therefore, all the related parameters and the whole shape adapted itself automatically to maintain the C values within the accepted range for all seats.

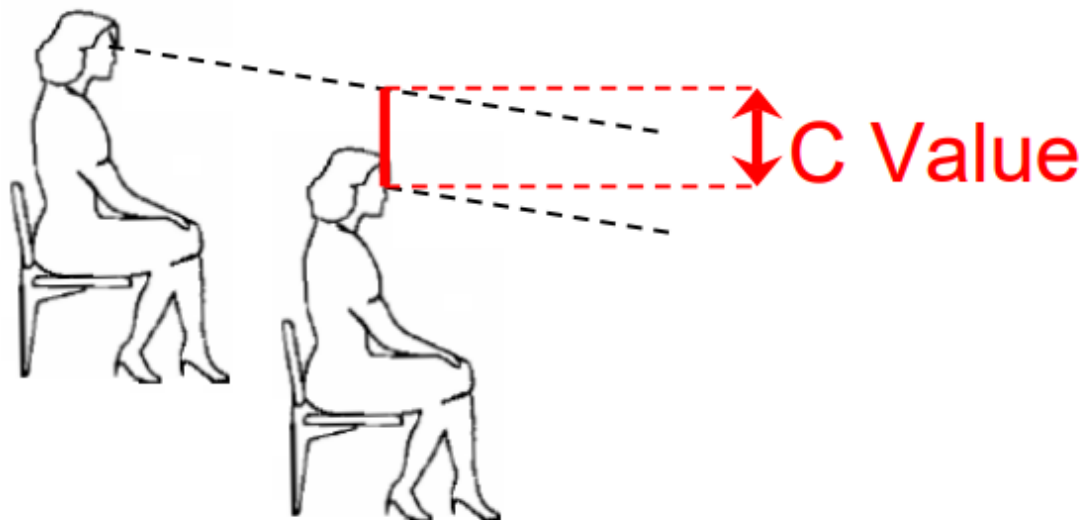


Figure 15: Illustration of C Value

According to the designer, designing the seating area using Revit could have been a ‘nightmare’, as the calculations needed to be reiterated hundreds of time in order to achieve

the same level of accuracy that Dynamo offered. This example shows again the potential for parametric design in automating repetitive tasks; this helps to eliminate doubt about its potential in supporting creativity in the design process by automating the rational tasks and hence, allowing more time availability for creative tasks. With regard to complexity, and the criticality of describing complexity in relation to the design stages, this scenario shows complexity in the initial stage where the algorithm is created. However, this resulted in simplifying later stages, where the optimisation was totally automated, as the shape and sizes were automatically modified to keep the C value within the predefined range. The scenario demonstrates that the generation, evaluation and optimisation stages that form a loop (as described by Bernal et al. (2015)) are totally integrated and automated through the associative parameters, within an algorithmic logic that is used to develop the algorithm in Dynamo. Moreover, this scenario illustrates that parametric design is used during the later stage of the design process and to design one part of the stadium. The designer was able to take the algorithm beyond the development and construction stage through to the operation stage. This was achieved by developing this algorithm further to enable automated pricing of the tickets based on the location, height, and angle of the view line of each seat.

With regard to the practical and managerial benefits of such kind of processes, this can be traced to Emmitt's (2014) project deliverables (time, cost and quality) and the need to balance between these three variables as putting extra emphasise on one, may negatively impact the other two deliverables. This was discussed in Chapter 2 and a question raised about the computational design method that can enable time savings without the need to sacrifice time and quality. According to E4, using Dynamo to generate seats from a parametric algorithm resulted in an approximate 90% saving in the time needed to achieve the same results using Revit. Therefore, the speed and accuracy of the seat layout demonstrates the capability of parametric design to accelerate the design process, and hence save time, while maintaining quality and full compliance to standards and regulations in the design product. In addition, this time saving can result in considerable cost savings as it reduces the working hours and enables a more efficient use of time. This balance between project deliverables can be enhanced through the reusability of this same algorithm in later projects, which enables the further acceleration of the process. In this regard, E4 states that the Dynamo script developed for the stadium project was saved for reuse in similar future projects, which may not necessarily be a stadium. In fact, any project that requires seats to be distributed on several levels can benefit from this same algorithm.

The Metro Station Façade project and the Circular Bridges project in Case 3 demonstrate the ability of parametric design applications to act as BIM tools, where constructional and MEP information and tables of quantities and costs can be generated from parametric design applications. In comparison, this example shows how parametric design can embed information about standards and regulations that is beyond the capability of current BIM applications.

In relation to the contradicting arguments raised in Cases 1 and 2 regarding the stage at which parametric design can be used, this example shows its ideal use at a late stage of the design process for generating an accurate and detailed seat layout. This is added to the ability of parametric design at the operational stage, when parametric algorithms allow for the automated generation of ticket prices based on the viewing quality of each seat.

#### ***6.6.4.2 Project Scenario 2: Site Topography***

In this scenario, the designer (E4) described how Grasshopper was used to generate a terrain within Revit. According to the designer, when using AutoCAD, the terrain is created as geometry, which is a long process that requires the creation of vertical lines and the generation of surfaces from those line; these surfaces are then exported into Revit. However, using Grasshopper, enabled the designer to take the coordinates of the points from the surveyors, feed those coordinates to Grasshopper to generate a list of points, and then send this point list to Revit, which generated an accurate form of the terrain out of the points coordinates. Using Grasshopper enabled the automated regeneration of the terrain when the topography of the site changed; this meant only inserting the new list so that Grasshopper could take the Z coordinates of each point to update the terrain. When using CAD, this update needs to create the geometry again, or shift the height of each of the points individually. This is another example of how parametric design can automate repetitive tasks. It also shows the power of parametric design in translating information into geometry. In fact, when using CAD, the geometry generated in Revit was created as geometry in CAD. In Grasshopper, the geometry was created as information, which, in this case, involved the point coordinates provided by the surveyors. This scenario, alongside the Metro Station project scenario in case 3, demonstrates The Economist's (2017) view of data as fuel, and Oxman's (2006) view of information as material. In fact, in this project scenario, information acts as a raw material, from which different elements of a building project can be generated. In the Metro Station project, the information was generated from the geometry of the metro station façade, which

was translated in Excel as table of sizes, quantities and prices. In this scenario, the information generated by the surveyors was translated into geometry in Revit through Grasshopper. This translation was enabled through the power of associative parameters that can drive this information across disciplines and across platforms, where, in each application, it can take a different essence.

## **6.6.5 Collaboration and Interdisciplinarity**

### ***6.6.5.1 BIM-based, Collaborative Design Processes***

Within a BIM-based design processes, two groups are created to conduct the project; the first group operates on the firm level, while the second operates on the project level. The company group consists of a few participants that work on producing standards, including, standard texts, Revit families, and libraries. They interface with clients and other project stakeholders to collect information for use in the evaluation of objects and families in their Revit Libraries. This enables the group to update the libraries with information based on project requirements. The libraries are vast, and contain a wide range of information and objects, such as, chairs, typical details, typical drawings, doors, windows, and curtain walls. They also guide the project group by continuously checking that the models and the inherited drawings, elevations, details and 3D views are compatible with the company's standards. This is a valuable example that shows how the Revit families generated from a previous project are saved for reuse in future projects. The example resonates with Emmitt's (2014) organisational and operational levels, and the importance of recognising the difference between the two. Thus, architects and other participants have the opportunity to capture knowledge from current projects in order to inform future projects. In this example, the BIM team operating on the organisation level acquire knowledge in the form of Revit families gained from previous projects and provide these families to the BIM team operation at the project level. However, this example does not exemplify recyclable processes or the building seeds concept; instead, BIM applications enable the recycling of Revit families as final products rather than the process of generating such families.

The project group is normally called the 'BIM champions', and consists of BIM specialists who work closely with the firm group and other project participants. They conduct the modelling, observe the integration and the information flow, and report problems to the company group on a regular basis. Members of the BIM champions group are carefully selected, so they are all trusted members with in-depth technical knowledge and experience in



Revit and Navisworks. According to E4, this careful selection of the project group is motivated by the intensity of the projects they simultaneously work on, where E4 cannot be on all projects, and at all meetings. Hence, they need participants who are highly-expert and who can conduct the work unaided, or with a minimal amount of supervision. Case 1 shows how the research group contains members with a high level of experience in digital technologies and computational design. They supervise the design team by providing knowledge and experiences, which allow them to achieve their tasks successfully. Case 2, on the other hand, shows how the design team have specialised knowledge and experience, and are able to manage the complexity of the different digital technologies based on their own experience. In this example, the situation lies between those two extremes; therefore, the technical knowledge alongside the experience of using BIM applications are necessary amongst all participants to reduce the supervision time from E4, whose role is still essential.

The way the BIM groups share data, information and models is various, as sometimes they use typical transmittal, and sometimes they collect the data in a CDE (Common Data Environment), where every single participant within every group places information, and models in the same portal, so that everyone has access to data and can download, and link to the main model. In some projects they start developing Revit models from the very first design stage. However, when collaborating with external teams, the stage at which they start modelling with Revit depends on the firm they are working with. For instance, when working with one of the large engineering consultant companies located in the UK, the development of BIM models starts at the design development stage when the concept design is complete; this is because, according to consultant company, developing BIM models at the early stage is a waste of time and money. On other occasions, they coordinate with other companies that have no problem with the adoption of BIM modelling at the initial stages. In fact, many other factors may affect such a decision, for example: the nature of the project, its size, function, complexity, and client's culture.

This scenario offers an explanation of a successful BIM-based process that is not provided by the previous case studies. This scenario shows the potential of BIM within a real project in enabling a high level of integration between different project stakeholders, the automation of the information flow, and the ease of coordination. It is this that challenges the definition of the design process. For example, in comparison with the generation, evaluation, and optimisation steps in the model by Bernal et al. (2015), in this process, the generation remains

manual. However, the evaluation and optimisation are automated, as each new item automatically fits into the whole design.

#### ***6.6.5.2 Collaboration with IT Team***

The IT department at the firm is advanced for an architectural practice in that it consists of a handful of knowledgeable and expert members, who oversee a wide range of responsibilities. They have close relations with all teams and employees throughout the company, where they listen to their needs, analyse the problems and issues, make some calculations, provide technical solutions, and allocate budgets for the realisation of the solutions. For instance, if a member of the design team requires a specific software application to perform a task within a project, the IT department conduct feasibility studies, communicate with the related software vendors, and allocate a budget for this application.

E4 narrates a series of examples to show how the IT members interface with the rest of the firm's employees. For instance, in one of the complex projects, the participant developed a script and needed to use nine computers throughout an entire night to run the script. The IT employees undertook the necessary management and coordination to secure the script, which ran until the early morning of the following day. In another example, the design process required different projects to federate automatically with Navisworks, while the automation had to take place at specific times during the night to avoid occupying different computers during the busy working hours. E4 gave the IT members instructions, which they applied and completed the job successfully, despite the fact that they are not designers. This example shows a highly efficient way of dealing with the time variable and highlights the central role of the machine in achieving this efficiency. In this case, the computers were set to achieve the complicated process overnight to avoid interrupting other employees. In this case, a practice can make effective use of all 24 hours of the day, and as such, it is not limited to the limited human ability to work. Therefore, the work can be split into human-driven work that can be achieved within the firm's working hours, and machine-driven work that can be achieved by computers overnight.

According to E4, one of the main issues when working in collaborative BIM processes involves the CDE growth in numbers, size and complexity. This is because the CDE has limitations on the maximum path links that each file can have, which depends on whether the server is in use and on the way that the folder is structured. In such cases, the IT members solve a problem through simplifying the paths, whilst at the same time provide explanations

for teams and individuals about the limitations of the CDE and the way it works. This example about the limitations in the maximum path links in CDE, demonstrates the additional knowledge required for designers when tackling complexity in technology. Despite the availability of the IT team, designers need to be aware of this limitation, and the necessity of simplifying the hierarchy of CDE contents in order to reduce the efforts of the IT team, and hence save time and cost.

#### **6.6.6 Adaptability of Tools**

The reliance on software developers, programmers and scripting specialists is minimal at the firm. In fact, they use a wide range of highly-advanced software applications, where the capabilities seem to be sufficient to meet their needs. Therefore, they rarely need to adapt software applications. However, the complexity and large scale of some recent projects have required the development of software. E4 has a broad knowledge in programming and scripting which has been influenced by their mathematical background. Therefore, they were able to develop a series of scripts in the Python programming language within the Revit-Dynamo platform in order to solve complex geometry problems within two stadium projects in North America and in the Middle East. E4 states that they are one of very few members who have programming and scripting skills, and hence, this experience enabled them to take major roles on those stadium projects. This is another example of the power gained through persuasive skills (Cuff, 1992). However, in this example, power is affected by the nature of each project. Therefore, E4 gained significant power and a major role when working with stadium projects, where their mathematical background and scripting skills were essential in tackling the complex geometry.

This example highlights a new development, where the centrality of any member in a design team can be constituted by the compatibility between their experiences and the specific requirements of a project. This brings the discussion back to Lawson and Dorst (2009), who argue that designer's activities vary based on their level of experience. In this scenario, this relationship between activities and experience seems much more complicated, as it shows a strong link between the design activities and the context of the project, so that a designer can be considered highly expert in one project and less expert in another. E4 also states that they are currently developing their BIM applications to automate the evaluation of the compliance of materials and structures with existing codes and standards. This is an important quality for

digital technologies as it exemplifies how they can be used to reduce complexity in the design process through automating standard activities.

In addition to using scripting to automate the evaluation of a building's compliance with standards and regulations, parametric modelling software can also be used for the same purpose. Indeed, E4 states that embedding rules derived from building standards into parametric models is one of their main strategies in using parametric design, and this strategy has been successfully implemented in various projects. While this was already exemplified in the football stadium project, E4 explained one of the methods that enable the development of this capability in parametric design applications. E4 states that they use a 'component' in Dynamo called 'Note' in order to add a script; this helps to create a function or rule within the parametric model that might not be available in the visual platform of Dynamo. This may embed building regulation information into the parametric definition. This specific feature in Dynamo and Grasshopper shows that the impact of such tools can be infinite, as designers can think of any idea or function, and translate this function into a scripting formula to push the limits of the software. However, this powerful feature requires scripting and programming skills that are, in most cases, beyond the cognitive scope of many architects.

### **6.6.7 Problems**

E4 discusses various problems that the design team encounter when highly-advanced digital technologies are utilised within projects. In most of the cases, the participant blames the human user of technology. For example, E4 explains that problems are provoked from the user's lack of experience in using technology, rather than the technology itself.

One of the main problems is that the design team struggles to provide training for new graduates who join the team. E4 argues that these graduates have sound theoretical knowledge but lack practical knowledge. This was surprising for E4 as these graduates are recognised by RIBA as Part 1 or Part 2 Architectural Assistants, or as Architectural Technologists. E4 gives an example of a graduate who recently joined the design team who was completing a Master's in BIM, but stated that the practical, technical and mathematical knowledge gained within the six-month period at the company was more valuable and realistic than the material they had been learning over the three years at university. E4 does not underestimate the importance of the theoretical knowledge, but instead argues that universities should rethink their courses to focus more on practical knowledge.

Despite the problems they encounter when hiring graduates, they also bring strengths through their advanced technological and digital literacies, which are often better developed than those amongst the highly-expert and experienced members of a design team. According to E4, dealing with experienced members is becoming harder over time due to their lack of technology-related knowledge. They state that it is sometimes impossible to convince an architect or an engineer who is retiring in a few years, and who has been using CAD for decades, to use BIM, and link to CDE, or to understand parametric design, and appreciate its potential. However, their experienced members have professional knowledge that forms the core of the work, and hence their contribution to all projects is also valuable. For this reason, the participant suggests that there should be structured opportunities to ensure that the experienced members and recent graduates work together, to support and enhance each other's knowledge and skills. This situation again raises the issue of culture in relation to experience and skillsets, as this seems to be one of the main challenges affecting the effective integration and use of technology in architectural practice. In addition, this relationship shows a subtle link between collaboration in practice and experience, and the knowledge of individuals. This link requires a policy to define how individuals can collaborate and complement each other through the diversity of their experiences and knowledge.

#### **6.6.8 Research and Development**

Unlike Case 1, who has two large research groups, this firm has a small research group that undertakes independent research to improve the workflows within the firm, and to acquire knowledge from different projects to feed later projects. This is addition to developing libraries and setting standards for the firm regarding minimum qualities and sustainability.

On most occasions, the work of the research group is separated from the project context. They tend to focus on reviewing previous work, provide case studies and identify frequent problems to enhance the quality of their buildings and processes. For instance, one of the members of this group spends most of their time developing Revit libraries by creating doors, windows and walls, and developing the related detail drawings, so that those objects can be used as blocks for incorporation into different projects, which thus accelerates processes. Moreover, providing ready-to-use blocks to accelerate later projects is one way to reduce complexity in subsequent work. Moreover, there is a sustainability specialist in the research group, who spends 30% of their time researching green buildings, including how to incorporate better materials into projects, and how to improve the energy efficiency of the

buildings designed and constructed by the firm. They also explore methods to contextualise such knowledge and criteria in projects, and to share the outcomes of their research with other teams.

The structure of this research group is more flexible than that at Case 1, as employees may join the group for a specific period of time to undertake research, while others may work on design projects alongside their research activities. In addition, some research may be taken within a project context; for instance, E4 has joined the group several times when conducting research. Their activities have included; developing scripts to solve complex geometry problems, automating information flows between consultants to communicate clash detections, and other problems within large projects. They have also been involved with research on developing BIM software to enable compliance with building standards and regulations.

In general, E4 states that the main goal of research in the practice is to accelerate processes by exploring methods that can make the workflows faster. This acceleration is mainly enabled through scripting, which is used to automate some activities within the design process in order to increase efficiency in the workflows throughout the different platforms. For this reason, they provide training, which can be in the form of group or one-to-one sessions, where sessions focus on BIM and parametric design, and different methods and techniques to share different sort of knowledge and enhance collaborative work.

In addition, E4 has a server containing different libraries. Those libraries contain Revit families, scripts, and case studies. The company allows everyone in the company to access the libraries and view precedent examples. Some members also supervise the search for relevant material for existing problems. Furthermore, they also have a BIM server that contains the CDE, which allows the whole company, including all the other branches, to access the central files and the different libraries, drawings, and tutorials. The BIM server is both useful and effective; not only for the coordination of the current project, but also for the opportunity it affords different employees to access materials and support. E4 states that, in order to continuously improve the library, they always observe the workflows, and how people use the libraries for knowledge and experience. For instance, most frequently, members use the library to access instructions about how to make a stair, or tutorials and detail drawings of balustrades, mullion types, or curtain walls.

### 6.6.9 Future Expectations

With regard to future expectations, E4 argues that the role of programming in architectural practice will grow due to increasing involvement of architects in this area. This will be crystallised when the new generation of architects, who are now students become senior architects and project managers. Therefore, E4 agrees with Dorta et al. (2016), Enyon (2016) and Prensky (2001) who argue that young designers or learners who are introduced to new technology at a young age will be more capable of making effective use of this technology in the future.

Furthermore, they state that, within the upcoming 10 to 20 years, CAD culture will be totally replaced by BIM culture, where people who used CAD will switch to BIM. E4 argues that this shift will be similar to the shift from painting and using pen and paper to using CAD. At the time, many people were concerned about the results of this shift, and its impact on creativity, the limitations, and the cost of computers. However, the participant sees the shift from CAD to BIM as more significant as it encourages designers to be involved in many sectors. In addition, E4 argues that that technology is not evolving at a constant speed. The participant explains that many people used mobile phones, but in a very short time switched to smart phones; later on, the evolution will start slow, whilst awaiting another jump in technology. The participant argues that the same applies to the technology related to architectural practice, in that there will be jumps when a new technology emerges and provokes radical changes in practice, and that this jump will be followed by few years of slow evolution.

## **6.7 Case Study 5**

### **6.7.1 Introduction to the Firm and the Participant**

Case 5 is an architectural firm located in USA. The firm has a wide range of members organised into project teams consisting of architects, structural engineers, MEP engineers and technicians. In addition they have a team specialised in computational design. The firm is involved in various projects in the USA and Eastern Asia, mainly China.

The participant is an architect specialised in computational design and the use of digital technologies in different projects within the firm. Thus E6 is considered an ‘expert’, due to their broad and in-depth experience in parametric design, gained through their 10-year professional experience.

### **6.7.2 Digital Technologies and Tools**

Various software applications are used in the firm; including CAD, BIM software and 3DS Max that is heavily used for visualisation in order to communicate designs with clients and other project stakeholders. In addition, parametric design is widely used by E5 and their team. In this regard, E5 states that parametric design was heavily used in a wide range of architectural projects that ranged in scale from a chair project to skyscrapers project and includes an large airport project. In all those projects, parametric design demonstrated a higher level of effectiveness and efficiency in tackling design problems in comparison to conventional design methods. More precisely, E5 states that parametric design has different aspects that leads to its adoption by designers. Firstly, parametric design can be relied on in the form finding and analysis of several design possibilities. Parametric design is also efficient when dealing with complex geometry where parametric design can help to rationalise the geometry to fabrication standards and techniques. Furthermore, parametric design can be used for documentation, construction and legal processes. Therefore, E5 agrees with E3 and E4 on the efficiency of parametric design in rationalising complex design forms. Moreover, they are assured of the value of parametric design in going beyond geometry and automating tasks for construction purposes. In addition, E5 argues that one of the most considerable aspects in using parametric design, is its ability to automate some parts within the design process by performing repetitive tasks. They argue that this cannot replace human input, but allows the computer, rather than the human, to be a repetitive machine, as was the case in conventional design methods. This argument corresponds to the previous discussions that emerged from Case 3 and Case 4. However, E5 indicates the value of parametric design



in supporting creativity; this can be achieved by taking away the cumbersome repetitive tasks from designer and passing them to the machine that can achieve such repetitive tasks. This gives the designer more time and effort to focus on the creative aspects of design.

### **6.7.3 Processes**

In addition to their 10-year experience in digital technologies and parametric design, E5 appears to have broad and in-depth theoretical knowledge. Unlike the participants in Cases 3 and 4, E5 was able to explain the impact of parametric design on the design process from both a practical and theoretical perspective.

Digital continuity in the design process (Kolarevik, 2004; Oxman, 2017) was discussed in the literature review; however, none of the previous cases were able to exemplify this digital continuity. In most of the cases, the parametrically-driven processes are interrupted at many points. However, E5 was able to give a thorough explanation about how this continuity can be achieved, and the main factor that often restricts this continuity. Thus, E5 provides two examples that differ significantly in terms of size and form complexity. In the first example, E5 worked on a chair project, where the design was based on one single parametric model throughout the design and fabrication processes. This was possible due to the simplicity of the project and the low number of materials and fasteners required. Understanding the fabrication processes enabled the team to code them into the rationalisation of the project, and then to code the extraction of the necessary data for the fabrication machines. Furthermore, a lot of custom bespoke codes were also written and integrated into the parametric model.

In the second example, E5 worked on a skyscraper project. At the time of the interview, the project was still under construction, when several parts of the design were built within one single conceptual, parametric model that included the design, concept and rationalisation. The documentation was also integrated into the parametric model; however it was partially integrated into a secondary model. Hence, this was a two-model process, although the second was automated from the first model. When the model was delivered to the fabricators, they did their own modelling where they were able to automate their processes and to streamline their production. This automation and streamlining was also based on the original model. In summary, various parametric models were created for the skyscraper project, while all models were generated and automated from the original model.

This is the most important point for consideration, which enables a firm to know where their practice is going. The previous examples show attempts to drive the whole design process using one single model that grows in detail and associativity throughout the process. Within this process, the parametric model saves the history of the evolution of the design object to enable all the design stages to be linked and associated, so that, when a change is made in the initial steps of the design, the whole steps (including the final result) will be updated automatically in real-time. Such a process challenges all the definitions of the conventional design process that divides the design process into linear or cyclical stages (Bernal et al., 2015; Lawson, 2011). In this scenario, the sequential logic of the conventional design process is totally changed, and the lines between the design stages are blurred, resulting in one single continuous stage. Furthermore, this process is opening up the borders between the design process and the structural analysis and quantity surveying processes that are also integrated into this continuity. This continuity was achieved in the chair project explained above, however, due to the simplicity and scale of the product, this case cannot be generalised. Therefore, the focus remains on potential, as such continuity was not totally achieved in larger and more complex projects.

Furthermore, E5 ensures that working parametrically enhances creativity; he states that architects are creative by nature as they are trained to be creative. As humans, designers have the ability to understand various information and design problems very rapidly, but they are limited in any rapid generation of solutions and iterations. Thus, parametric design is useful as it enables humans to run very quickly through different design possibilities and different processes. Such a process, allows a designer to understand the real domain and the real search base of design problems.

In addition, E5 provides a thorough explanation about the different impact of BIM and parametric design on design creativity. This explanation is based on their own personal experience as a designer who has been tried both methods on a wide range of projects. In this respect, E5 states that, within the realm of architectural design, the building does not start as such; it starts as an idea, concept, sketch, or form. Later, as the design develops, these concepts and sketches start to evolve, and slowly change into a building. Subsequently, when designers and other participants start to provide details, the building transforms into shapes, profiles and quantity take-offs, and only starts to become a building again when the construction starts. In such a context, BIM software applications deal with the building as a real entity throughout the different stages of the design and construction processes. These

applications do not respect the architect's understanding of the building's evolution throughout the design stages. In contrast, parametric modelling software approaches buildings in a way that is consistent to this concept; the building in a parametric model starts as a form, concept, or probably a script, until it becomes a real building. This profoundly explains how parametric design and BIM relate to the creative aspects within the design process. In fact, the explanation resonates with Lawson's (2011) contradiction between the symbolic representations in a digital system and the designer's mental symbolic representations. This is similar to Bernal et al.'s (2015) conceptualisation; they highlight the same difference between what is in the mind of the designer and what is represented on the computer. Therefore, BIM forces the designer to think of a building in the conceptual design stage where the designer is more concerned with abstract images, concepts and thoughts. At this stage, it is too early to be illustrated as a building. In contrast, parametric design respects this level of abstraction and allows the designer's ideas to be illustrated as parametric definitions with components and connections, which reflects the abstract images in designer's mind. Therefore, this difference can significantly affect the creative thoughts of designer, which is still subjective and open to different opinions and interpretations. In addition, this can relate to specific design situations, project contexts, and circumstances that are unique in every project (Cuff, 1992; Rittel & Webber, 1973, cited in Hudson, 2010).

With regard to the complexity of the design process and its relationship to parametric design, E5 argues that complexity is a matter of understanding. Things remain complex until they are understood and once they are understood they become simple. This also applies to parametric design systems, so that when a designer understands their logic and experience, the procedure of working parametrically becomes simple and hence more effective use can be achieved.

#### **6.7.4 Collaboration**

With regard to collaboration, E5 explains the possibilities and limitations of using parametric models collaboratively within a design process. He states that, until now, there is no possibility for in node-based parametric modelling software to have two users using the same parametric definition at the same time. However, there is still the possibility of developing a collaborative environment within the parametric design process. He gives examples from some existing software applications that they use in projects. These applications allow for live data streaming between different Grasshopper files. Furthermore, they use some

specialist website applications that allow two users to work on a cloud-based system where they can see (but not modify) each other's work. Therefore, the ability of parametric modelling applications to act as an integrated platforms is limited to the incapability of those applications to allow different users to work simultaneously. This means allowing information from different disciplines to flow across different applications and different teams, without allowing simultaneous interactions from different participants. According to E5, this flow of information can be enhanced within the parametric modelling application itself where designers can add 'Notes' and hence, embed information within the parametric model to help in the documentation of the design, and to enable other participants with the relevant skills to further develop work. This is a feature in parametric design that supports collaboration in the design process; however, this is linked to the tool, rather than to parametric design as a design method, as this information may be just plain text that is added to a parametric definition to clarify some steps. This resonates with E4's explanation about how they use this same 'Note' component in Dynamo; however, E4's example is more powerful, as the 'Note' component is used to add scripting formulas that can expand the functionality of the parametric design software.

The previous cases show how parametric design applications can be used for BIM-related purposes, such as 'allowing quantity take-offs from parametric models, integrating design and MEP platforms, and allowing automated coordination between designers and structural engineers'. This led to the assumption that parametric design applications can be seen as highly effective BIM applications. In this regard, E5 states that using parametric models to extract costs is quite easy and a lot of practitioners are doing it as quantity take-off is becoming a key point in the building industry. In addition, they state that the quantity take-offs can be performed across different applications so that the parametric modelling application can be linked to another application that is used to develop table of quantities and costs. This link can maintain the associativity between the two applications throughout the design process so that when the geometry changes in Grasshopper, for example, the associated costs in Excel change accordingly. With regard to time scheduling within parametric design, E5 argues that it is subject to the availability of sufficient information about the project. This information demystifies complexity over geometry and hence, helps to develop trust between different stakeholders within a project. In such cases, a lot of risk can be illuminated so that time schedules will naturally become more obvious, and deadlines can be met more easily.

In addition, E5 was able to give a variety of examples from an airport project where parametric design was heavily used. In that project, parametric design was successfully utilised to perform clash detection for the structure, mechanical systems, and cladding of the different buildings, in addition to performing the clash detection amongst the different fabricated or constructed elements. They also explained some particular cases where parametric modelling was used for clash detection, such as detecting interference between the fabrication machine and the element being constructed, or detecting interference between an element being extruded and the machine that was creating it. Therefore, they state that various levels of clash detection can be taken based on the parametric modelling, which essentially illuminates risks and hence, saves costs in the construction process.

Based on all the previous examples and cases that show the different roles and potential roles of parametric modelling within the design and construction processes, E5 states that parametric modelling software applications are developing quickly and changing into highly effective BIM tools. They state that BIM is a process not a technology; moreover, it is a method to take information across the different stages of a project, starting from the conceptual design stage through to documentation, construction, and also through to the facilities' management and operational stages of a building. From this basis, the effectiveness of parametric design in supporting BIM processes heavily depends on the ability to tie together the different applications used in the design process. In doing this, parametric modelling can be a highly effective tool for a BIM-based process. This 'tying' is already exemplified through the metro station façade project, where E3 was able to tie Grasshopper and Excel to enable geometry in Grasshopper to generate quantity and cost-related information in Excel.

In the previous case, E4 provides examples that show how parametric design applications not only support BIM-related activities within the design process, but can also go beyond by embedding information about building standards and regulations within the parametric definition. Thus, a designer can create associativity between these standards and the parametrically generated model. Despite E5's extensive experience in using parametric design on a wide range of architectural projects, they were not able to provide an example. However, they were able to logically explain this ability, stating that a lot of the regulations (such as building codes, zoning ordinances, ADA regulations, or sustainability codes) are very prescriptive and hence, very rule-driven and rule-based. More precisely, they are built on the logic of 'if the condition is X, you must do Y'. For this reason, E5 argues, that it is

possible to embed these rules and standards as constraints within a parametric definition, which has exactly the same logic.

### **6.7.5 Adaptation**

The computational design team led by E5 has a handful of scripting specialists who work on different projects to expand the limitations of CAD software applications. Similar to the previous cases, the role of those specialists increases when dealing with large projects with complex forms. Nonetheless, E5 ensures that, within their 10-year experience, parametric design was more effective than scripting in tackling complexity in design geometry. This can be attributed to the cognitive barriers of scripting (Oxman, 2017) and the difficulty in learning this new sort of knowledge that may contradict the creative basis of architecture. Indeed, E5 argues that a lot of designers in their current architectural practice are trying to immerse themselves in technology to improve their career. They need to learn scripting very quickly to be able to develop their tools. According to E5, parametric modelling is the first step towards simplifying programming and scripting and creates a visual interface that can make scripting more accessible by a wider range of designers.

### **6.7.6 Research and Development**

The firm does not have a research group; however, there are some architects who undertake research independently or within a project, which is similar to the research undertaken in Case 4. The research helps the different members of the design team to capture knowledge in order to inform later projects. Despite the profound theoretical knowledge of E5, they do not classify themselves as a researcher; however, they explore the current state-of-the-art digital technologies applied in architectural practice through the intensive reading of architectural journals, magazines and books in order to keep up-to-date with cutting-edge technologies. They state that this helps them to observe how the limitations of such digital technologies are rapidly expanding, and this helps them to develop their design work within the firm. Therefore, they were able to discuss the ‘building seed’ concept and the potential for parametric modelling definitions to act as a building seed. In this respect, they state that, in one of the last architectural projects they worked on, they used the previous project as the seed for the current project. They confirmed that this was highly effective and efficient, as the two projects overlapped and thus, they were able to work on both projects at the same time. In such a case, the knowledge gained from the previous projects facilitated the current project. This was due to the familiarity of the project situations experienced in the previous

project. Nevertheless, conceptually, E5 does not think that the ‘building seed’ is a new concept. They believe that it already exists; however, architects did not have the opportunity or the ability to coin a new name for this concept. They assert that architects naturally start their design by reviewing precedents from various projects, so that every time an architect conducts a precedent study on an existing building, they are actually looking for its inherent seeds in order to continue to develop on top of it. According to E5, the idea is to take a good idea and to continue to develop it to make it better, or to take a bad idea and make it better. Therefore, the idea always moves forwards and architects avoid reinventing the wheel. This is a powerful argument that leads to a different way of thinking. In fact, this argument resonates with Jones’s (1992) conclusion (in Chapter 2) where he argues that creative activities in design are skilled actions governed by the nervous system with no intervention by conscious thought. This makes it difficult for designer to provide a rational explanation of those activities. Similarly, in E5’s explanation, designers are already familiar with the building seed concept as they naturally review previous projects to search for seeds for design solutions that can inform their current project. However, as Jones argues, explaining what they are doing appears to be more difficult than expected. In this sense, Carlile’s (2014) introduction to the ‘building seed’ approach, and Mueller’s (2011) introduction to the ‘site seeding’ approach should not be seen as new concepts or methods. In fact, they are just new terms or metaphors to describe what architects naturally do. This shows the importance of the terminology used to describe process activities; this terminology helps designers to describe their mentally-driven designs activities in order to externalise their mental processes and secure contributions from external participants.

## **6.8 Case Study 6**

### **6.8.1 Introduction to the Firm and the Participant**

Case 6 is an architectural firm, with their main headquarters in Canada, and other branches in different cities across Canada and the USA. The firm works on projects on different scales, from interior design through to urban planning. The firm is classified as ‘developing’ as the vast majority of its teams and individuals rely on traditional methods. However, they have recently established a research group that is collaborating with a large academic group in order to achieve a rapid transition towards BIM implementation and facilitate greater reliance on digital technologies.

The participant is an architect who joined the firm two years before this interview. They came from a broad research background, having completed a PhD in architecture and planning. They also had a Post-doc, and worked as a research fellow at different universities. Their main research interest is integrated practice, BIM implementation and Lean construction. Their role at the firm is split into two parts, namely architect, and research and development professional, where they are involved in developing a strategy for BIM implementation. The participant will be referred to as R6, as they are classified as ‘researchers’ due to their research-based knowledge in parametric design that is associated with limited practical experience.

### **6.8.2 Technologies and Tools**

The staff working at the firm are ambitious, and look forward to developing and maintaining updates on tools and methods concerning cutting-edge technology, and state-of-the-art design approaches. Furthermore, they are working hard on the implementation of these innovative practices. According to R6, the interview is being conducted during a transitional period in the firm, where all innovations in the technologies, tools and design methods are in progress. In fact, in most of their projects, they are still using traditional tools and relying on traditional ways of approaching design projects; hence, they are still in the first stage of the implementation of these new practices. With regard to BIM implementation, R6 states that they are pushing the idea of using BIM-enabled technology, and have already started working with Revit on several projects within different departments. They state that their reliance on Revit depends on the type of project they are working on; for instance, in retail projects, the development of an intelligent model in Revit is the main requirement for clients, which



explains why they took this decision. According to R6, they have seen that the market is also making this choice, and as such, they feel they have to follow, otherwise, they will be in the other side. This shows an important motivation for architectural practices when innovating their methods. Whitehead et al. (2011) refer to the growth in client demand for technology as one of the main instigators for its rapid growth in architectural practice. In this case, the client demand for a Revit model can be attributed to the potential of the software to support the facility management during the operation stage of the building lifecycle.

In addition to Revit, they use a series of software applications, where each is used at a specific design stage. For instance, in the conceptual design stage, they mostly use SketchUp and 3DS max; however, at the development stage they also employ Cinema 4D for some projects. This echoes the approaches of other case studies (Case 3 and Case 4), who adopt Revit to facilitate the coordination with other project stakeholders. Dynamo is not yet deployed; however, a few people, including R6, use it in some cases, such as when modelling site work with topography if the project site is not flat, or when naming parts of a model. Furthermore, they have started to use BIMLink as a plug-in for estimating, in order to export and import quantities for doors and windows, and other items in projects. Moreover, in order to support the development of integrated practice and promote a culture of collaboration at the firm, they are trying to expand their reliance on BIM by pushing the use of different plug-ins, such as BCF (BIM Collaboration Format), Bluebeam, and Autodesk 360. This last application is used to coordinate work with their South American branch, where models are shared in cloud-based systems. In fact, this array of technologies clearly shows the potential radical shift in the knowledge and skillset required for a designer.

With regard to hardware technologies, the use of 3-D printers is limited to ‘important projects’. However, they use VR (Virtual Reality) equipment, which is based on models generated in Unity, 3DS Max or Cinema 4D. According to the participant, their use of VR is for marketing purposes only, where, in some projects, they use it to present their work to clients. This demonstrates that the use of some technologies may deviate from their original purpose. In this case, the VR equipment is mainly created to enhance the imagination and therefore enable more mature design decisions.

### **6.8.3 Roles and Areas of Specialisation**

In the main headquarters, the firm has about 200 employees from different departments and at different levels of integration within the firm; this includes directors, technicians,

architects, and project managers. They work together in a collaborative environment to carry out different projects. They have already identified their needs for BIM development, and R6 is in charge of managing this development project. In this regard, they state that they have a connection with another group, which is a committee that consists of directors who have a vision for the strategy of the firm, and will ensure that any BIM development is consistent with the firm's future direction.

Most of the employees at the firm are architects, interior designers and technicians who work together in projects. Thus, architects or interior designers sketch their ideas, and then send them to technicians who develop accurate CAD drawings. This is a classical way of working and one that the participant is trying to change. Architects are also in charge of the project management.

In terms of programming and scripting, the situation at the firm differs from Cases 1 and 2 where a wide range of software developers and scripting specialists integrate into design teams to adapt the tools used within the design process. In fact this firm only has one scripting specialist who has a background in architecture and video gaming; they work on scripting to make a connection between different teams, and to develop different applications when needed within the early stages of the design process. In some cases, they coordinate with other groups called 'Les Concepteurs', which consist of four designers who produce freehand drawings at the initial stages of the design process for most projects. Therefore, despite the large size of the firm, only one scripting specialist exists, which indicates a limited reliance on tool adaptation. Instead, they have a group of 'concepters' who take responsibility for providing creative design solutions by creating sketches at the conceptual design stage.

The firm also has an internal research group, which works in coordination with a larger academic research group. This academic group conducts research within the firm to inform the developmental strategies of the firm. The internal research group consists of several members, and most are architects including the scripting specialist.

Therefore, the 'advanced practices', such as Cases 1 and 2 rely on research and have large research groups to enable the firms to keep up-to-date with the cutting-edge digital technologies, to explore new methods, to push the limits of the possible, and to enable innovative design solutions and approaches. Meanwhile, the 'competent practices', such as Cases 3, 4 and 5, have limited a reliance on research as the technologies available seem

sufficient to develop high quality designs for their clients. In this firm, and despite their heavy reliance on traditional methods, they consider research important and give their research group the authority to take decisions and determine the direction of the firm, including the technologies utilised and the methods applied. This shows the firm's desire to innovate and develop their working methods in order to catch up with the state-of-the-art digital technologies in order to enhance the quality of their designs as well as their working methods. The emphasis on research with resonates with Cuff's (1992) statement about the power that can be gained in different formal and informal ways. One of the formal ways in which an individual in practice can gain power and enhance their decision making authority is through their status at the office (Cuff, 1992). In Case 6, the status of R6 as the head of the internal research group gives them power and authority, to not only determine the technologies and methods applied, but also to call for a change in teams and individuals by pushing them towards more collaborative and integrated work and a greater involvement in digital technologies that enable collaboration.

#### **6.8.4 Processes and Workflows**

The teams and individuals at this firm still rely on traditional methods but are working hard to implement BIM. In working with BIM, they set the process in advance, and make a plan about how they will work within the stages of the design process, and this will include who is going to work in these stages. They also investigate the flow of information across platforms and stages. Therefore, they have already started implementing BIM in some projects, where the project starts by creating freehand sketches to provide the initial ideas of the design project. They then discuss these ideas with each other and the senior designers in order to gather feedback until the concept arrives at a certain level of maturity, which is when they start using technology. At this stage, they divide the design process into two stages; the first is called the 'model for design', and the second is called the 'model for production'. In the 'model for design' stage, they take the sketches developed during the previous stage and start developing an accurate design model using SketchUp, AutoCAD or 3DS Max. The application will depend on the project and experience of the designer or technician in charge of providing the model. The process continues until the final concept design model is completed and approved, which is when they start working in Revit. In fact, the SketchUp model is not used as the origin of Revit, as it is only developed to determine the shape when it is complete; in contrast, the Revit model starts from scratch. This process is similar to that discussed in Case 3, despite the different names given for the stages. However, in some

design situations, the SketchUp model and the Revit model are developed in parallel, where the Revit model is made to validate some ideas or programs, which may question the interoperability issues that may emerge by using two parallel models, and the difficulties in coordinating design changes and updates manually across the two modelling processes. Moreover, in order to investigate a specific area of the design model, or to gain more interaction with the original model for particular aspects of the design, they have to return to SketchUp or to 3DS Max after the creation of the Revit model. This shows, in a practical context, the difficulty in conducting a design process and the need to work backwards in time to trace the intermediate difficulties every time unforeseen issues are identified (Jones, 1992). As mentioned earlier, this exchange between Revit and 3DS Max raises the issue of interoperability, which is a current issue for the research group at the firm. In all of the cases, the development of the BIM model continues in parallel with the project development. This case, together with the previous two cases (Case 3 and 4) show a strong link between Revit and the development stage. In fact, Revit is not used at the conceptual stage, and when the conceptual design model is terminated, the Revit model is created again from scratch, which results in separate linear design stages similar to the predefined stages of conventional design (Bernal et al., 2015; Lawson, 2006).

### **6.8.5 Collaboration and Interdisciplinarity**

Within collaborative work environments, most of the members at the firm still exchange pdf files with annotations when transferring information about projects. Given the options available, this is a comparatively dated way to collaborate. However, the willingness to develop and innovate is significant and in fact, they have started using Revit in several projects, where they develop a central model, and during the design process, everyone works on their own model, which they synchronise to the main model at specific times to keep the work coordinated. However, the central model cannot be obtained on demand, and is only available every Friday at 4:00pm for coordination purposes. The model is uploaded via FTP (File Transfer Protocol), which is, according to the participant, a very old fashioned method to share; therefore, they are trying to push the use of more advanced methods for sharing, such as cloud-based systems. This is a critical issue that shows the potential of CDEs and cloud-based systems. While Case 2 shows how complexity is mainly associated with the intensive coordination needed, especially in complex projects, the limited availability of the central model can be attributed to the need to reduce complexity by limiting the coordination to weekly sessions in order to leave the designer's mind free to develop creative solutions.

As explained in Chapter 2, this avoids overwhelming their creative work with intensive conditions and constraints that come from the structural, performative and financial priorities of other teams. This shows the potential of CDEs and cloud-based systems as they allow for continuous and timely coordination and synchronisation through automation; this avoids disturbing the creative work of designers.

To enhance coordination, every Monday morning, each discipline collects their models and checks with all other disciplines to make sure that separate design elements are working together. R6 is trying to push the coordination for clash detection, and visual coordination; however, there is not such capability at the moment, as the only coordination platform available is Revit. Moreover, they started to implement BCF (BIM Collaboration Format) in one of their projects, but this did not work, as the MEP team decided to return to working with CAD, and hence, the design team members found themselves obliged to return to the old (pdf exchange) methods. Such a situation is contrasted with that of Case 3, where the participant attributes the success in internal/external coordination to the availability of the right knowledge and experiences on both sides. In this case, the situation is different as the lack of experience in the MEP team results in pushing the design team back towards more conventional methods.

Furthermore, they have started to implement a new method of communication between architects based on 'Slack', which is an online platform for chatting and works in a similar way as MSN Messenger. Slack allows for the creation of a group inside the firm, and within this group, they can exchange everything; for example, someone who creates a new family or a feature in Revit can directly communicate this with people from the same group, so that the rest of the team can see, use, and interact with the new family by adding comments. Therefore, Slack is helpful in fulfilling the aim of the research group at the firm to centralise project information. It is a highly efficient alternative for the old way of sharing, that relies on attaching information to emails, which can be highly problematic, especially when large files need to be transferred. Furthermore, relying on Slack for collaboration allows for the real time notification of design team members about problems, and enables individuals to track the problem, and become automatically informed when the problem is solved. Despite these advantages, Slack is not implemented throughout the whole firm.

Moreover, they started using BCF (BIM Collaboration Format), which is an open file format, similar to IFC, that is dedicated to simplifying collaboration by giving BIM users the ability

to interact with each other by taking screenshots and adding comments. According to the participant, using BCF is simple, and does not require any specific instructions, which means that using this highly-effective technology does not come with any additional cognitive barrier. They use BCF to support collaboration between different employees using Revit, whereby, when any team member detects a problem, they can simply take a screenshot and add an annotation or comment. Therefore, any other member that connects to the model, can receive a notification and, by clicking on the notification, the system takes them directly to the area where the problem is detected. The individual can therefore see the problem and interact with it by either solving it, or by adding their own comments. Furthermore, they are starting to implement Bluebeam as a tool to communicate and coordinate, especially in site work.

With regard to the role of parametric design in supporting collaboration and the ability of parametric design applications to act as BIM tools (as discussed in the Cases 3, 4 and 5), R6 argues that using parametric design applications as BIM tools is subject to their ability to enhance interoperability between applications. This is the exact case explained in Case 3 about how Hummingbird was used by E3 to enable the generation of Revit families from Grasshopper. In this case, Hummingbird is the parametric tool that enabled interoperability between Grasshopper and Revit. Furthermore, the ability of parametric design applications to support interoperability echoes the previously discussed issue caused by using two parallel models; design model created in 3DS Max and the production model created in Revit. The discussion noted the resulting interoperability issue and the difficulty in manually coordinating design changes between the two models. In this regard, R6 states that one of the main purposes of the research they are undertaking within their firm is to find ways to facilitate communication between the design model and the production model. To achieve this purpose they are promoting the use of Dynamo due to its potential to enhance the operability between, or to totally integrate, the conceptual and production models.

### **6.8.6 Adaptation of Tools**

As mentioned, the firm only has one person with knowledge of scripting; this employee develops algorithms and writes scripts when needed. However, this need is rare. In fact, unlike the situation in Case 1 and Case 2, this firm is not yet at that stage where they can adapt tools, as they are still persuading employees to adopt these tools. The lower integration of scripting in this firm, as well as in the previous semi-advanced cases emphasises Oxman

(2017b) and Wortmann & Tunçer's (2017) arguments who see scripting and tool adaptation as a cognitive barrier for architects.

### **6.8.7 Problems**

Due to the nature of R6's role, who is involved in innovating and developing tools and methods at a firm that still relies on traditional methods, they are able to thoroughly discuss the wide range of problems and challenges that they encounter when trying to upgrade their practice and push the implementation of BIM and its different tools. In this regard, they state that their academic and research background enables them to understand that the main problem lies in the lack of communication between the different architects, as well as between the different disciplines. Therefore, their main focus is to push the utilisation of different tools to enhance communication, and to raise awareness of the need to develop more effective methods for sharing and exchanging information.

#### ***6.8.7.1 Human-Related Problems: Lack of Experiences, and Cultural Differences***

R6 states that most of the teams are still working in CAD, and using the traditional way of sending emails to exchange pdf files and annotations when communicating ideas and information. In addition, they are still using FTP to share models instead of relying on cloud-based systems or a CDE. Moreover, when the participant and their research team try to push the use of more effective tools, they encounter barriers in the form of: a lack of experience, diverse mentalities and thinking patterns in relation to design, in addition to different cognitive responses to technology, cultural differences and a general resistance to change. For instance, in one of the projects, the architectural team, together with the structural engineering group, and the MEP engineering group started working together from the very early stage of the project, where they developed the BIM Execution Plan, identified how they were going to collaborate, and discussed every single issue in advance. However, at the midway point in the project, the MEP group decided to stop working with Revit, and returned to CAD. From this point, they started to send CAD and pdf files again, which affected the whole project by pushing all contributors back to the old ways of sharing. R6 attributes the decision to their lack of experience in BIM practice. They state that they do not yet have qualified people to deal with this new technology, and similarly, R6 complains that most specialists, including the landscape designers and project managers, are still working with CAD and other traditional methods. This makes it difficult to understand how to coordinate between the models and plans. In this regard, the participant states that this resistance to

change can be attributed to a lack of security when sharing information across disciplines, which might threaten the confidentiality of those information. This resonates with the authorship and copyright issues (Bernstein, 2016; McPartland, 2014; Ruy, 2016) discussed in Chapter 4.

To deal with this problem, R6 and their development team have started to deliver training courses in Revit to the different members at the firm, and this is where they have started to understand the problem in more depth. According to R6, one of the main problems that restricts a mature understanding of the potential of BIM is that most of the CAD experts think in 2D when dealing with building projects, and therefore, they struggle to think in 3D about the building design and its different structural components. The participant also explains a dilemma, where on the one hand, the experts who have been working with CAD throughout their career (and tend to be over 50 years of age), find it difficult to adapt to using BIM tools; whilst on the other hand, junior architects, who have the capability to adopt this new method of thinking in 3D lack practical experience. This is the same point that E4 in Case 4 highlights. However, the participant in this case provides an example of a young architect in the design team who refuses to deal with technology and prefers to use traditional methods. In this regard, R6 argues that it is about attitude rather than age.

#### ***6.8.7.2 Machine-Related Problems: Lack of Interoperability and Immature Platforms***

Unlike E4, who places blame on technology users, rather than technology, R6 is more objective, as they agree with the impact of human-related problems on the uptake of technology. However, they also recognise issues with the technologies themselves. Their identification of the problems are based on broad and in-depth academic background within the same field. Therefore, they state that the main problem is the lack of interoperability between the concept and production. This is exemplified in the situation described earlier where some design problems arise after the Revit model is already developed, and is exported back to 3DS Max, which results in information and geometry loss when taking the model back again to Revit. To tackle this problem, E6 is exploring new modes of data flow to facilitate interoperability; for instance, they are promoting the use of IFC format to enhance interoperability. They are also investigating the potential of parametric design in offering a shared platform for different information; however, they find parametric design more helpful at the conceptual design stage, rather than the later development stages. Furthermore, in an attempt to automate the estimation process, R6 is researching new ways to embed all



information within one single platform rather than using various platforms and coordinating them. The problem lies in the fact they only have Revit as the platform for sharing models and information, which is linked to the budget of the firm. In addition, they tried using 'Forbit' to ensure a smooth exchange between the design and productions models; however, they had some difficulties, as the platform was not mature enough to support this kind of communication.

### ***6.8.7.3 Managerial Problems***

With regard to management-related problems, the main issue arises when working collaboratively within integrated platforms, where the structure that relates to how to pay becomes extremely complicated, as it is difficult to accurately identify the different contributions provided by the different disciplines, and the extent of their contribution. In addition, R6 states that this issue is not only a managerial problem, but also becomes a design problem as it has a direct impact on the way they work. They also state that this is not only a problem at this firm, but also an issue for the industry as a whole. Therefore, they emphasise the need to revise how the practice allocates payments for each discipline when working on shared platforms. This issue echoes the copyright and authorship problem that emerges in collaborative and integrated work (Bernstein, 2016; McPartland, 2014; Ruy, 2016). It highlights the potential of 'granular models' in tracking the contribution of all participants in design (Michalatos, 2016). In the case explained here, it can help to accurately identify contributions and hence provide fair payments.

In an attempt to solve this problem, R6 and their team have tried to implement 'AGIL', which is a platform for managing work in collaborative environments that relies on the determination of roles and responsibilities, together with the criticality levels for each role. However, the implementation was extremely difficult as it needed time, which was problematic given that employees were struggling to meet deadlines. This is similar to the issue raised in Case 3 where the parametric design training courses did not achieve their intended goal for the same reason. In general, R6 states that the successful utilisation of these technologies takes more time than expected.

## 6.8.8 Research and Development

Due to the appetite for development and innovation at this firm, they conduct extensive internal research, and participate in external research to improve their methods, and participate in the development of the whole practice.

### 6.8.8.1 *Hierarchy of the Research Groups*

R6 is part of two research groups - an external academic group and an internal group. The academic group conducts research in collaboration with another industry-based research group. Both groups share the same goal, which is to enhance the knowledge exchange between academia and practice. The academic group offers academic resources and knowledge, while the industry-based group offers industrial resources and knowledge. Therefore, to develop all the required elements for their research, they adopt a series of architectural and construction practices as case studies, which includes R6's firm.

The firm wanted to have their own internal research group, so that any development came from inside the firm conducted by a group of internal researchers who were familiar with the firm, knew the projects they were working on, and their methods applied in architectural projects. As such, the internal research group was established to carry out project-based and independent research with the aim of developing more effective and feasible methods in approaching architectural projects with a focus on BIM implementation. One of the main developmental methods of the internal group is to introduce the design team members to cutting-edge, BIM-related technologies that can be used to support collaboration and to facilitate the information flow, such as (amongst many others) BCF, Slack, Forbit, and so forth. When the amount of research required goes beyond the capacity of the internal group, they seek help from both the academic and the industry-based groups, who offer the resources and knowledge needed to complete the research.

In summary, the research is based on mutual benefits, where the firm gets support and academic and industrial knowledge and experience from the academic and industrial groups to develop their methods. In return, the firm acts as a case study for the research undertaken by both external groups. This research helps in generalising the benefits for the whole industry. This way of conducting research within practice differs from Case 1, as it enables more interaction with external practices and academic teams, which may lead to more mature and effective research. Furthermore, it enables the conduct of research at a minimum cost.

However, working this way requires a high level of transparency, which might face barriers in terms of the cultural differences, where some practices might find it threatening to the privacy of their working methods, and the confidentiality of their current projects.

#### **6.8.8.2 BIM Implementation Research Plan**

The research plan of the internal research group is based on three steps, where each step takes a year. In the first step, they had to build their knowledge as they realised that they did not share the same understanding of BIM. In the second stage, or second year, they selected some pilot projects to work on to test the applicability of the new methods and report the results. In the last stage, which is just taking place at the time of the interview, is to extend the utilisation of the new technology and the implementation of BIM to many projects in the firm. However, by the end of the first year, they realised that this process could not be linear, but rather needed to operate as a loop. Therefore, they started to conduct a ‘Post-Mortem’, where at the end of each year, they conducted a report to reflect on the process they had been through, so they could identify negative and positive points, and revise their needs for the next year including what they want to develop. This can be linked back to the lack of experience and diverse mentalities, which makes it difficult to implement BIM to enhance collaboration and integration over a short period of time.

#### **6.8.9 Future Expectations**

R6 thinks that some architects feel threatened by this technological evolution, and that their role is becoming less important than before. They state that instead, an architect is the person who coordinates, and orchestrates the whole process. The architect is also the individual with the holistic vision of the project. Therefore, R6 believes that architects need to understand that the practice is moving towards increased integration between disciplines, and that synthesising this integration is key for success. In this case, the role of the architect will remain the same; however, there will be significant adjustments for this role in order to adapt to a new reality.

## **6.9 Case Study 7**

### **6.9.1 Introduction to the Firm and the Participant**

Case 7 is an Architectural firm, which has three business locations in Canada. The firm has 160 employees, including 85 at the main headquarters. They have developed architectural projects from different types; mainly industrial, commercial and institutional, and have recently started to become involved in residential projects, specifically in Canada.

The participant is an architect with a broad research background accompanied with 17 years of experience in the building industry, where they have been involved in a variety of architectural projects within a wide range of architectural practices in different cities around Canada. They are the director of integrated practices at the firm, where they explore new ways to approach architecture, and investigate how technology has an impact on the practice. This helps to keep the company up-to-date with state-of-the-art technological advances in architecture. The participant will be referred to as 'R7', due to their broad, research-based knowledge in parametric design and the limited use of this design methodology in their firm.

### **6.9.2 Technologies and Tools**

Similar to Case 4, the selection of the appropriate software application in relation to the project requirements is critical at this firm. R7, states that very complicated and difficult decisions have to be made due to the availability of a vast array of software applications, and the high cost of these applications. In general, the firm is in line with the North American market, which is Autodesk-centric. Therefore, the main three applications that they use in almost all projects are Revit, AutoCAD and SketchUp. In parallel, they use Photoshop and 3DS Max for visualisation and rendering. In major projects, they use Deer Office, which is a content management platform, which they use as an 'equivalent codebook'. The participant also uses Solibri for model checking, together with Navisworks. In addition, some employees use Catia.

During their work at the firm, as well as in their previous work within several other architectural firms throughout Canada, they have been promoting the use of Dynamo. In fact, Dynamo is not yet used in projects at the firm, due to the lack of the experience and knowledge amongst design team members. However, there are two experts in Dynamo, which includes R7, and they use it in an experimental context, to develop scripts to automate

some processes. Thus, in addition to the variety of benefits of using parametric design in real projects (explained in the previous cases), R7 states that parametric design is used to provide experiments within the process of searching for new methods. This is motivated by R7's broad, research-based knowledge in parametric design that enables them to understand its potential and hence raise awareness amongst teams and individuals at the firm. In this regard, R7 highlights two major purposes for using parametric design - automating processes, and building better buildings. This demonstrates the dual benefit of parametric design as it affects the quality of the design product as well as the quality of the design process. In addition, R7 states that they rely on Grasshopper and Dynamo to solve problems that cover a small portion of a project, or sometimes just to explore. They also state that Grasshopper is used as a facilitator for some activities, and they are trying to enhance the reliance on Grasshopper to ensure it is employed as a solid decision-making tool. Due to the limited use of parametric design, R7 acknowledges that they were unable to see this impact due to the fact that parametric design is not widely used in their practice. With regard to the ability of parametric design applications to act as BIM tools, R7 states that Dynamo was used in their practice solely for BIM-related purposes.

In terms of hardware, they have not had the chance to use 3D printers yet; however, they widely use 3D scanning in-house, and have developed expertise in this technology. They also use VR in some projects, but, like the situation in Case 6, VR is used as a marketing tool, rather than a decision-making tool. This facility is used with their clients to enable them to play around and navigate the virtual space of a project. This again shows how the use of some technologies in practice can deviate from the purpose for which these technologies are developed. In this example, the VR system is used for promotion rather than to enhance maturity in design decisions and support collaborative work, as shown in the literature (Dorta et al., 2016).

### **6.9.3 Roles and Areas of Specialisation**

At this firm, there is no BIM department, and they do not have BIM-specific roles; however, they have distributed responsibilities for the use of BIM and its tools amongst the teams themselves; this is where the standards and the protocols are significant. In fact, their strategy in implementing BIM relies on having solid standards to comply with, rather than having solid mechanisms for quality control and quality insurance. Therefore, they try to have equalise the design team, rather than having a team behind the design team that 'babysits' the

team and ensures the models are appropriate and coordinated. This shows a significant difference in comparison to Case 4, where the BIM processes relies on two groups of BIM specialists, where the firm group supervise or ‘babysits’ the project group in BIM implementation. In the case of this firm, the design team themselves have the knowledge to conduct a BIM-based process. In this regard, R7 takes some of the responsibilities that a BIM director would have, in that they are responsible for making sure that all the templates and families are managed, and that the protocols are in place, in addition to ensuring that they are able to capture the best practices in establishing the firm’s standards.

As they are dealing with complex programs and developers, they believe that they have to be able to develop tools. Therefore, they have two members who have this kind of advanced digital literacy, and R7 is one of them. Those two specialists work on programming and parametric modelling, and recently started using ‘pyRevit’, which is a scripting platform in Revit that relies on Python programming language. Moreover, they have a graphic artist who is responsible for renderings and visualisation, as well as managing the 3-D scanning. They have also a highly advanced IT team that consists of two highly expert members.

#### **6.9.4 Processes and Workflows**

Similar to the previous case studies, the design processes at this firm vary in relation to the project context; however, R7 explains the most frequent scenario, which is the same as several of the previous cases. Thus, at the outset, designers start with SketchUp, or AutoCAD, and then develop project costs throughout the stages of the process with the client, to get it to a level of development and thus secure approval for the general concept and the layout. Consequently, they start to translate the model into Revit, and then transfer it to a traditional Revit process, where they start to develop the project and consult the engineers by sharing the model. Similar to Case 6, the model is shared once a week every Friday on an FTP server in order for the coordination to be checked by all participants.

With regard to parametric design, they use it in a limited number of projects to automate some activities within the design process. R7 states that creativity can be achieved in parametric processes when a designer has the right knowledge, the right skills and the right techniques. It is this type of knowledge that can enable a designer to harness novel approaches and tools to achieve creative design solutions. This is similar to E3 the focus on the user of parametric design applications and their ability to provide creative design solutions using this tool. However E3 attributes success to the attitude and open-mindedness

of the designer, rather than to having a parametric designer with the appropriate experience and knowledge,.

### **6.9.5 Collaboration and Interdisciplinarity**

The IT department members at the firm are both advanced and collaborative. They set up a network to ensure that the three branches of the firm are working from the same platform. As such, they have their own independent network that is highly performing and fibre-optic. Typically, when the design team work with an external team, they ensure that the smaller firms do not let them take the lead, but instead dictate the type of infrastructure, and how to set up their project. As a result, they have been using a traditional way of sharing information each week, through FTP, and WeTransfer. This is another example of the issue raised in the previous cases when collaborating with other teams that have less experience and less advanced technologies. However, R7 states that this ‘old way’ of sharing models has recently changed. Currently, their minimum is to provide an area on an arm server with access to a VPN (Virtual Private Network) to connect to their server. This enables work on a central file, where each person has their own remote desktop inside the network in order to work collaboratively with others. Thus, they provide the infrastructure product to support collaborative work. This technology was implemented in a recent project with a smaller client, who was young, very collaborative, and positive towards interacting effectively with technology.

At the moment, they are starting to explore cloud-based platforms, such as Collaboration for Revit, and BIM 360 team; however, engaging this technology comes at a cost that a smaller firm such as this may not be able to afford. In fact, according to R7, the cost of securing access to Collaboration for Revit is \$900,000 per user per year, which is extremely expensive for a small firm. Thus, the firm has started to study the feasibility of a buying pass, which will help them to leverage the server and establishing a stable infrastructure to enhance efficiency in collaborative work. In fact, the firm is ambitious and appreciative of the potential of supporting collaboration in their projects; for this reason, they have spent tens of thousands of dollars in the past ten years to secure a high speed internal network.

In having such a subtle infrastructure, together with the VPN and a high speed internet, they are looking at different ways in Microsoft to create visual desktops so that employees can work from any place to control access and models, and keep these models on the servers to allow other people to participate in their development. Nevertheless, the implementation of

this technology faces contractual and procedural barriers, where according to some members, the culture of fully sharing risks the confidentiality of their work. This is the same issue as that raised in Case 6. According to R7, these issues are easily resolved through technology, but less easily resolved in employees' minds. Thus, R7 in this case, like E4, blames the users and not the technology for issues.

### **6.9.6 Adaptation of Tools**

A wide range of software applications are being used at the firm; however, they are not at the level of digital literacy that allows them to develop software to match their mode of work. In fact, they only have two employees who have knowledge in programming and scripting; instead, they develop scripts and programs for research purposes only. Therefore, similar to parametric design, and in addition to the potential for programming and scripting, they are also used within the process of searching for innovative design methods and approaches.

Nevertheless, in one of their large infrastructure projects, they were able to ensure effective use of their programming knowledge, where they had to clean up plans and views, copy them, create a new sheet and then put the plans and the views on the new sheet. The problem lay in the fact they had 70 models and 50 different sites for the project, and therefore, had to repeat the same process of cleaning up, creating and placing for 26 models. This was extremely cumbersome, and time and man-power consuming. To tackle this problem, they created a Dynamo script that was able to iterate the same process automatically for the whole 26 sheets. As a result, they saved tens of working hours. This is another example that shows how scripting can accelerate the process by automating repetitive tasks.

### **6.9.7 Problems**

R7 states that the biggest struggle now at the firm is to consolidate the expertise, not only in BIM, but in all technological advances throughout the firm. However, a multiplicity of problems arise when such technology is brought into practical use, where, in most of the cases, the participant blames the employees' experience, knowledge and culture, rather than the technologies themselves.

#### ***6.9.7.1 Lack of Human Resources***

Despite the increasing momentum around BIM adoption within the firm, as well as within the whole industry, the firm is still anchored in very traditional approaches to project



development. R7 is therefore continuously exploring different technologies and methods around the areas of BIM and parametric design, amongst others. Unfortunately, they seem to be the only member at the firm able/willing to conduct such research. In fact, their academic and research-based knowledge enables them to evaluate the firm's approaches in overrunning projects, as opposed to the different technologies available to identify the problems and hence, inform areas of development. This shows the importance of having a research team, rather than an individual researcher in relation to the firm's size. In fact, the literature shows the need for collaboration, and states that, without this it is difficult to ensure effective use over the mere of adoption of technology (Kocaturk & Medjdub, 2011). This can also apply to research that investigates the potential of technologies, where the vast range of the available digital technologies and methods require collaborative research within research teams and groups. It is also important where members from different backgrounds or diverse areas of focus can collectively build and transfer knowledge and develop new approaches to effectively use technologies and inform future projects.

According to R7, in most of the cases, the technologies are well-developed and mature; however, they require appropriate experience and knowledge in order for them to make sense, which reflects the results of the shift in skillset that Oxman (2017) mentions in the literature. For instance, the firm has already developed a central network, with a server that contains the different materials and knowledge gained from previous projects for use in different, later projects. The problem with the essential server is that they have to rely on employees to first identify knowledge, then import it, and hence, they have to know where it is, and import it, and ensure that the data is updated so that they are using the right version. This is a cumbersome process as it requires the intensive management and awareness of how it works. This shows one important aspect of complexity when advanced technologies are utilised, namely, where the firm has the technological capability, but not the skilled staff to address complexity using these technologies, and thus, to run the process effectively. The participant does not have the capacity to be in every single project, to confirm the progress and outstanding tasks. Furthermore, keeping the database credible and up-to-date, requires employees to not only search for information, but to also update it within a project context and push it back to the database so that it can be used to inform later projects. This is the process-related aspect of complexity that, again, highlights the necessity for sufficiently qualified users. Consequently, R7 states that the technology exists, and is capable and

effective, but the biggest challenge is that it requires expertise to capture and use it effectively.

### ***6.9.7.2 Lack of Experience***

With regard to the interoperability that the literature highlighted as a significant problem (Ceccato, 2010; Hesselgren & Medjdoub, 2010), R7 ensures that, at the firm, they are already using the same platform to work collaboratively, and hence, the interoperability between different applications is mature and the practice is able to work around this problem. Again, R7 states that the problem is not technology-related, but human experience-related. Therefore, the main focus should be on making sure that people have the capability to be effective in such a technological environment. Nevertheless, employees can see this environment as a constraint because they are limited in their capabilities. This echoes the views of C2 who asserts that designers are limited to software capabilities not experience capabilities, and where the software application used acts as a dictator of the design forms, which significantly affect the design creativity. Therefore, R7's argues that a designer's limited capability acts as a barrier between technology and creativity.

Moreover, some employees demonstrate its efficiency by employing these technologies to develop projects. However, most struggle to know how to use tools, and to understand what they are trying to do with those tools in order to get the job done. They may attribute their struggle to the complexity of the technologies; however, R7 is certain that when people understand how such technologies work, they will not seem that complex. This argument suggests that the most effective way to reduce complexity is to increase knowledge and experience. This resonates with the discussion in Chapter 2 which identifies ambiguity in the design problem as one aspect of design complexity. In this case, the ambiguity of new technologies for the non-expert result in a false feeling of complexity. In this regard, R7 claims that designing a project is more complicated than using Revit. Nevertheless, the design team, who have been working for the past four project on a Revit platform, are asking to return to old ways of working, which will result in forcing all other teams to re-adopt traditional methods. This reflects the situation in Case 6. In general, R7 states that there is a difficulty in influencing the perception of technology amongst some employees, which makes dealing with these individuals the biggest challenge in adopting technology.

These problems add to challenges within the general culture and mentalities of people that were discussed in Case 6, where some members do not accept the idea of fully sharing their

model as they find this a threat to the confidentiality of their work. In addition, R7 reports that the general atmosphere is also an important aspect of the problem. They state that they have been working in several architectural firms around Canada, and find that the vast majority are still using traditional methods.

### **6.9.7.3 Managerial Problems**

Emmitt (2014) asserts the importance of carefully selecting computer software and hardware to match the specific requirements of the office, and R7 highlights this same criticality on the project-level. One key problem, according to R7, is the choice of appropriate software applications for particular projects, and this issue stems from the vast range available. This issue was highlighted previously in this case when the firm purchased too many software packages in the past that were not used in projects; this proved a considerable waste of money. In this regard, R7 states that they do not have a clear strategy to select the necessary software. This reveals another unexplored, but connected problem, namely, managerial complexity. This is a key area as architectural practices need to study the feasibility and functionality of each application amongst a vast array available, and to identify the appropriateness of each application to the specific nature and requirements of a project, which may already be complex and ill-defined (Chaszar & Joyce, 2016). This study should take into account the sort of experiences that exist in the design team as well as other teams that they need to collaborate with during the process.

Similarly, when discussing the problems of parametric design and the barriers that restrict its effective use, R7 blames the human user, rather than the machine. In general, R7 claims that the appetite for using such a smart process is low in their geographical area. They attribute the difficulty in implementing parametric design to the lack of related experiences in design teams, the lack of relevant cognitive knowledge, the difficulty in learning its operation due to the complexity of the tool, the lack of trust in the potential of parametric models, and the feasibility of adopting this design strategy from a wide range of other available methods. All of these aspects explicate the misunderstanding (Jabi et al., 2017) and marginalisation (Schumacher, 2016) of the potential of parametric design in practice. Therefore, R7 argues that the parametric design tools currently available are highly mature and adequate, and therefore, the limitations of the tools are imposed by the capacity of the team.

### 6.9.8 Research and Development

Conducting research to improve practice at the firm is one of the main roles for R7. In this regard, they are involved in exploring different ways to approach architecture, to observe how technologies work, how they can impact their practice, and to ensure the firm is keeping the breast of the latest advances. Currently, one of their main foci is to build strategies and methods to enable BIM implementation across the firm.

Despite the increasing momentum around BIM adoption within the firm, as well as within the whole industry, the firm is still anchored in traditional approaches to project development. R7 is, therefore, continuously exploring different technologies and different methods around the area of BIM and parametric design. They are also exploring the ability of those approaches to enable rapid iterations and hence concurrent design, and to determine the way they provide the capability to leverage data to make decisions. Unfortunately, R7 seems to be the only employee trying to leverage and reuse these lessons learnt on projects for later work. For this specific goal, R7 developed a Wiki page for the firm hoping that people would use it as a way to formalise their knowledge, and learn lessons. They could also utilise a plug-in in Revit that enable the creation of a direct link between the different elements in a Revit model and the specific items in the Wiki page. This is a valuable potential that also demonstrates that R7 operates on a strategic, rather than on a specific project level. Thus, the Wiki page enables knowledge and experiences to be saved and re-used in different projects while the link created between Revit and the Wiki page represent the knowledge acquisition methods that Emmitt (2014) emphasises operate concurrently on both levels. However, the Wiki page as a whole was rarely used, and instead, members accessed their information from other sources, which can also be attributed to the lack of experience and knowledge, and a general mindset that resist dealing with unfamiliar technology. The Wiki page shows an attempt to encourage a shift in skillset and the sort of knowledge required for a designer. In fact, with these attempts, including the Wiki page, R7 is trying to build a wide range of knowledge in a very short time. This method does not seem to have worked and in fact, designers and architects require far longer to absorb a wide range of complicated technologies and to start making sense of them within project contexts.

Furthermore, R7 is exploring the amount of time that design team members are spending on redundant tasks when using CAD or Revit. They are also looking at what people do on a daily basis in terms of where they spend most of their time. In this context, R7 relies on their

knowledge in Lean to determine the best way to generate value, and hence, encourage employees to focus on value-added tasks. Therefore, they have started to appreciate the potential impact of parametric design tools, and begun to explore parametric design tools, such as Revit Dynamo. They have also started to explore different online platforms that provide such applications and plug-ins, such as Flux. According to R7, these parametric tools have the most potential value because they enable the reuse of scripts to formalise redundant tasks, and hence have exceptional value to the design team as their features help to save a lot of time in the design process. This is also another example of strategic thinking as it shows that R7 is trying to identify redundant tasks and recurring activities in order to find methods that automate these tasks and activities, and therefore, identify the mechanism to accelerate processes. For this reason, they have realised the reusability of the parametric definition and its potential in formalising redundant tasks. In this same context, R7 states that they are developing a ‘Script Bank’ to save scripts for use in later projects.

### **6.9.9 Future Expectations**

Despite all the challenges that the participant explains in the previous sections, they are optimistic about the future. They state that BIM is an opportunity for architects to regain ‘the master builder’ role. This addresses an issue raised in Case 7, where architects are concerned about the possibility of losing their role when BIM is fully implemented. Furthermore, this future expectation resonates with Lawson’s (2006) complaint about the separation between designers and builders caused from shifting from vernacular design to design by drawings. From R7’s perspective, BIM helps in bridge this gap by establishing a subtle correlation between designers, fabricators and constructors.

While R6 refers to integration as key for success in future practice, R7 in this case refers to information as key. Therefore, they state that architects represent the genesis of information, as they control and define information from the start. They argue that the client has a need, and it is the architect who provides an answer in the form of BIM translated information. Thus, if architects proactively pursue that information, and identify the approaches to leverage the information, they will regain their essential role within the AEC industry.

## 6.10 Case Study 8

### 6.10.1 Introduction to the Practice and Participant

Case 8 concerns a software development firm, and was chosen to enable an exploration of the latest software applications that may have the potential to address some of the problems raised in the previous case studies. The same themes were discussed in all the previous cases; however, the themes will be different for this case to reflect the fact that this case study is a software development practice rather than an architectural practice. More precisely, rather than discussing the processes, collaboration methods, adaptation of tools, research and problems, this case study is directed at the way in which tools developed in this firm can enable smarter processes, more efficient collaborative environments, and greater flexibility in the tools for architectural practice. This is in addition to the potential for these tools to address the problems and limitations raised in the previous cases. Thus, the case will analyse the tools from the perspective of a software provider.

Case 8 is a multidisciplinary firm located in USA, and is specialised in software development. The teams in the firm mainly consist of a mix of experienced software developers and building professionals who work together to develop intelligent tools to support collaboration and integration between the different teams in building projects within the AEC industry. The firm is developing an online platform, which is a data-rich, collaborative platform for teams of architects and engineers working together on building projects (Flux.io, 2016a); it is ‘the fabric’ that aims to create agile workflow in building projects by enabling data to be exchanged seamlessly (Flux.io, 2015). The platform is a web-based interchange point that contains a wide range of simple and lightweight software applications that are intended to support real time collaborations between team members, allowing each team member to stay in sync (Flux.io, 2015).

The main aim of the different applications provided by the firm is to enhance interoperability between different software applications used in the current AEC industry. The applications are available online, and can often be used directly from firm’s website by creating an account and signing in.

The participant interviewed for this study is a senior architect, who has 10 years of experience in architectural practice, with substantial experience of computational design, and its application within architecture. They hold the position of the Director of Design

Technology team at the firm. The participant interviewed for this case will be referred to as S8.

### **6.10.2 Roles and Specialisations**

At the moment, the firm has about 35 members with a variety of specialisations and backgrounds. The majority are application engineers, software engineers, and web designers, but they also have a chief technology officer, a VP (Vice President) of engineering, a chief executive officer, and a chief financial officer. The firm is divided into departments and teams, such as the design department team, the business development team, and the product development team; in addition, there is a team for geometry, one for infrastructure and another for data.

The firm has all of the components that a traditional software company would have; however, as the services they develop are dedicated for architects and engineers, the firm contains members from the building industry. For instance, the participant interviewed for this study is an architect licenced in the USA and the UK. They have a structural engineer in their team who is also licenced in the UK. In addition, there is an individual on the same team with a mechanical and electrical background and a strong focus on sustainability, whilst another individual is also an architect with a strong focus on complex geometry and web development. All teams and departments work together with a high level of collaboration and integration in order to continuously develop their tools in response to the needs of the architectural and building practitioners they deal with.

### **6.10.3 Technologies and Tools**

The firm's online platform contains a series of simple and light-weight software applications built on top of popular applications that are widely used in the current building industry, such as, Autodesk Revit, Google Sketch-Up, McNeel Rhino-Grasshopper, Revit-Dynamo and MS Excel. In addition, they have recently developed other applications to support integration with AutoCAD, 3DS Max, Google Sheets, and Google Earth. The platform also includes a wide range of bespoke applications; some of them contain just a few commands, or even a single command so that the data can be neutralised into a simple, light-weight format that can be seamlessly transferred across different project platforms. This shows the potential for data to act as fuel (The Economist, 2017) or as a design material (Oxman, 2006). While the site Topography Project scenario in Case 4 shows how the data can act as a raw material to

generate geometry, this case shows how the data changes from one form to another across different software applications. Therefore, the applications on the firm's platforms allows for the import of data from one application, and the neutralising of the data when it changes into a 'raw material'. This enables its export into other applications where it generates a different sort of information.

The main focus of the applications developed by the firm is to enhance interoperability between the different applications that they are built on. In other words, the firm creates direct connections between these applications in order to speed up and simplify the flow of information between different design and engineering platforms. Most of the tools can be used directly online without the need for installation on local computers, while in some cases, some applications require the installation of lightweight add-ins.

One of the main components of the online Platform is 'Flux Lab', which is a destination site that hosts and showcases the latest experimental features and solutions from the firm (Flux.io, 2016b). It contains a series of design tools and applications that are built and developed by their development team. For instance, the 'Flux Uploader' is an application that allows users to export any sort of data or shape into the firm's cloud-based environment that contains the main files so that multiple users can exchange data and geometry with the 'click of a button'. This is arguably a more efficient way of sharing data than traditional methods that are more time-consuming way and require the uploading, sending and downloading of files. This is a way of sharing demonstrated in most of the previous cases, particularly amongst the advanced practices. This method of sharing also helps designers to avoid interruption in the design process, which can be one way of reducing complexity, allowing for more focus on creative tasks. Similarly, the platform contains plug-ins that are dedicated to interoperability, such as; 'Excel >Grasshopper', 'Revit to Excel', and Revit >Grasshopper. All of these applications allow for direct connections between different popular applications.

The applications available on the platform are vast; therefore, to avoid repetition, further applications are discussed in the following chapter and address their potential from the perspective of an architectural practice.

#### **6.10.4 Collaboration and Interdisciplinarity**

The firm's employees call their work location 'The Factory', where members work together within a highly collaborative and multidisciplinary work environment. In fact, collaboration



is an essential part of their culture, which is important because the enhancement of collaboration in the AEC industry is one their core roles.

The firm provides tools to support practitioners within the design and construction processes of different projects. For this mission, the Design Technology team, which consists of ten individuals, interfaces with professionals from the AEC industry in order to identify potential situations where the firm can assist. The Director of the Design Technology team interacts with teammates as well as all other teams and departments within the firm in order to share the information they generate. This working process allows the firm to maintain the continuous improvement and development of their tools and applications in order to respond to the rapidly evolving industry. Furthermore, the firm tends to be highly collaborative with other software developers; for instance, they have an open line of communication with large software vendors, such as Autodesk and McNeels, and are always open to opportunities where they can collaborate. Therefore, apart from collaboration amongst members within the firm, the firm collaborates with practitioners from industry as well as with other software vendors. The purpose of this collaboration is to innovate new methods and tools to enhance efficiency in design and construction processes. Thus, this approach could be defined as collaboration on a local, and industry or global scale.

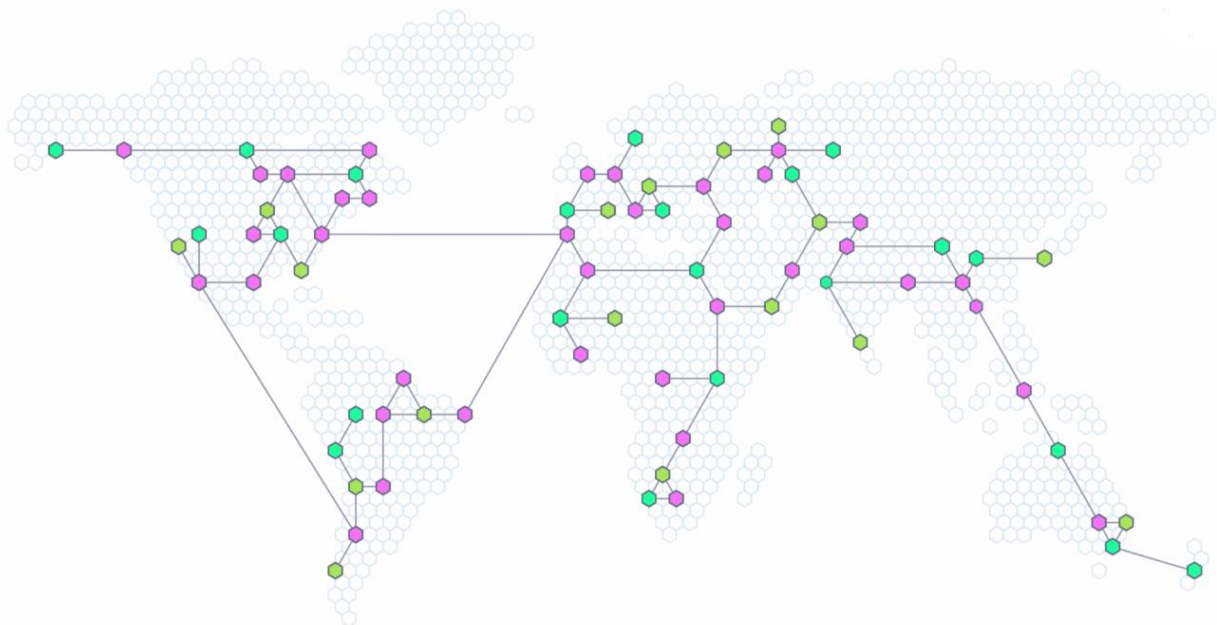
### **6.10.5 The Potential of Utilising Flux Tools in Architectural Practice**

Having reviewed the structure of the firm and some of the different applications available on the Platform, and having discussed the collaboration methods at the firm, this section explores the potential benefits, purposes and contexts of these tools for architectural practice. In addition, more tools within the firm's platform are explored in this section.

#### ***6.10.5.1 Supporting Collaborative and Interdisciplinary Processes***

In addition to the highly collaborative and multidisciplinary work environment within the firm, they also support multidisciplinary teams in architectural practice by developing novel collaboration methods in their practice. For this goal, they provide cloud-based systems and tools that allow different participants on a building project to seamlessly share data and transfer diverse sorts of information. This is one way to enhance integration between disciplines in practice where these cloud-based systems allow for collaboration on an enterprise level. Meanwhile, on a wider level, they make their design tools available online, which gives users the ability to develop their own tools collaboratively on top of the existing

applications developed by the firm. This reflects Carlile's (2014) view regarding the way in which software developers work. In this case, the existing software developed by the firm can act as seeds for the additional software developed by the user. According to the participant, there is the potential for substantial user engagement in development of the tool; however, this has not yet been fully implemented. Furthermore, the applications are presented on the firm's YouTube channel (Flux.io, 2016b) with some design experiments that show how the applications can be used. The users can post questions, and provide feedback and comments; in doing so they interact with each other as well as with the firm's teams. Despite the low level of interactivity, this represents the potential for a highly-effective collaborative environment on a global scale (Figure 16).



**Figure 16; The platform enables collaboration based on a cloud-based system (Adopted from <https://flux.io>, date)**

According to S8, the platform they develop not only allows for collaboration across different applications, but also across the applications themselves; for example, they allow for collaborative working between different Grasshopper environments, between different Dynamo environments, or between different Sketch-Up Environments. This can be helpful in different situations; for example, S8 explains that the platform enables multiple people to work together on the project, so that if one person is out, everyone else can continue the work.

### 6.10.5.2 Seamless Data Sharing

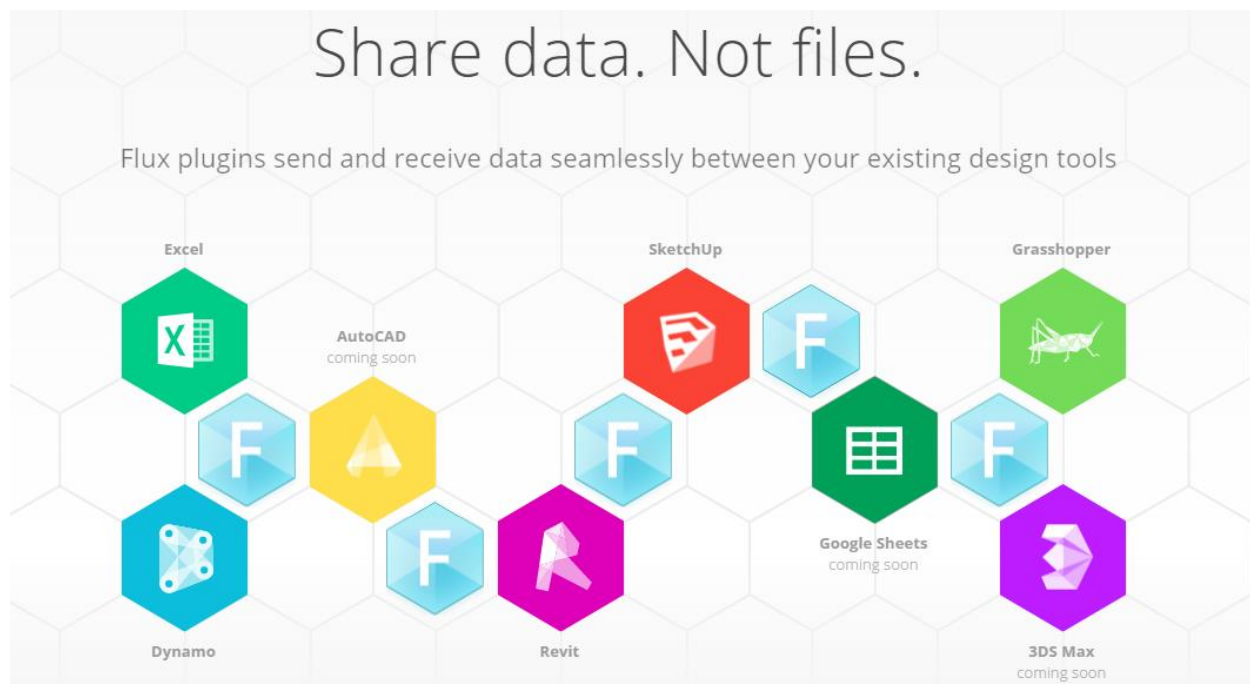
As current architectural practice is moving rapidly towards more collaborative work environments, within such environments, each participant is often involved in a specific part of a project utilising a specific project platform. According to S8, in the current industry most of the practitioners in such a collaborative environment use a traditional way of sharing data within their design process. They explain that,

*... they, for example, save out their files to another file format, bring it to another analysis application to share with another project stakeholder, to then transfer it over to some FTP or cloud-based system, and then somebody else downloads it, and then changes the file format into another format, and then render analysis. Within every exchange and every file, there is aggregation of data, and also [a] loss of data, and sometimes, the aggregation of data is beneficial, but most of the time it is not. They are essentially checking over blocks from [one] file to another, and so on.*

The participant describes the exact scenario shown repeated in most of the previous case studies, and is concerned about the aggregation of data that results from this classic way of sharing and the impact on file storage and the capacity of servers. In fact, this is only one aspect of the problem; another important aspect is discussed in Case 3, as this method of files sharing often results in a situation where different users work on different versions of the same file. This makes the aggregation extremely complicated, as they need to know which part of the design object is updated, and which file contains the most updated version of each part. This can make the process extremely complex. Therefore, it is this cumbersome and time-consuming way of data sharing that the firm is trying to change. The concept of the firm is to enable data, rather than file transferral so that the data can be normalised, sent to the platform, then another participant or stakeholder in the firm can download or recall that data without the need to download the whole block (Figure 14). This can be a more effective way of sharing data, as it helps in minimising file storage, and speeds up the process by dealing with lightweight data. This process works in the same way and with the same efficiency for both the design and construction processes.

The issue of interoperability is one of the main concerns for both practitioners and academics. This is mainly provoked by the need to use different applications to respond to the diversity of each project and the range of experiences and cultures in architectural practices (Ceccato, 2010). In fact, the way that the firm's tools only allow relevant information to be transferred across applications suggests a new level of interoperability, which is currently understood as the ability to export files from one application to another without the loss of information or

geometry. The applications at the platform help to go beyond this definition, by allowing for the concurrent evolution of the same design object using different applications. Furthermore, Whitehead et al. (2011) state that the perfect software that can do everything does not yet exist. In this regard, the firm seems to be starting to respond to Whitehead et al.'s (2011) concern, in that they are developing a new way of sharing, that allows multiple applications to work together as if they are one single application, or several dialogue boxes for one big application. Moreover, this way of sharing can lead to a renewed understanding of integration, which, in this case, means the integration of applications.



**Figure 17; Flux platform to enhance interoperability between different applications (Adopted from <https://flux.io, date>)**

### 6.10.5.3 'Simplicity'

On the online platform, the term 'simplicity' is used. Most popular dictionaries do not provide a definition of this term; however, according to Wiktionary (2016), "simplicity is the act of establishing a simple interface for something that is complex". This definition represents a description of the potential role of the platform within architectural practice and the AEC industry as a whole. This ability to simplify processes is revealed in the previous section, as the platform offers a seamless way of transferring light-weight information across processes. The various digital technologies and software applications that are currently used

in architectural and constructional practices result in a considerable increase in the complexity of the digital methods applied (Oxman, 2006). In this regard, S8 states that,

*The building constraints are constantly increasing, such as tighter time lines, smaller budgets, more stringent environmental performance requirements, and stricter building codes. As a result, complexities become naturally inherent in the AEC industry. In such a situation, the digital systems need to be more complex in order to be more effective.*

This highlights the source by showing how the complexity of digital technologies is inherited from the complexity of the processes. It offers a response to the inquiry raised in Chapter 4 regarding the purpose of complexity. In addition, it reveals the importance of concurrently defining complexity and simplicity in the design process when investigating the technological impacts. Thus, digital technologies are growing in complexity in order to become more effective at simplifying different aspects of the design process.

#### **6.10.5.4 Process Acceleration**

Due to the increasing complexity in the tools and methods applied in the current building industry, most practitioners rely heavily on highly-collaborative and multidisciplinary work environments to manage complexity. According to S8, this way of working within the platform increases collaboration and efficiency; he states that,

*... this situation is similar to the aviation industry, where the more an airplane is on the ground, the less the airline organisation makes money from it. Similarly, the more building industry practitioners spend time dealing with the issues of complex tools and the coordination of different platforms, the less the building company is being effective.*

Therefore, the firm helps to speed up the whole process in order to enhance efficiency within the design process. This is achieved in the way that information can be transferred, where users can employ the platform to transfer data rather than files, where they normalise the data elements, send them to the platform and then other participants or stakeholders in the project team can recall the necessary data from the platform without downloading the whole block. This way of working can significantly minimise time wastage by enabling access to data in an appropriate way and timeframe. It can help participants to minimise large file storage which can result from saving different versions of the same file on different platforms. As a result, a significant reduction of cost and working hours can be achieved.

#### **6.10.5.5 Back in time**

Flux platform has the ability to save the history of any piece of data that goes through it. For example, if one of the users sends different versions of the same data during the design process, they can go back throughout the history to choose any of the previous versions of the data. The interesting feature is that the previous versions are time-stamped, so the selection of one of the previous versions can be based on the time it was created. These features can be seen as a way to respond to the ambiguity of the design problems (Chaszar & Joyce, 2016), and the resulting difficulty in conducting a design process, which stems from the need to work backwards in the design process every time an unforeseen problem emerges (Jones, 1992). In this case, the feature in the online platform can make ‘backward working’ simple.

Similarly, there is an application called ‘Flux Capacitor’, which allows an architect working on geometry to access the history by returning to a previous version or evaluating the evolution of a design, for example. According to S8, this kind of process can remove the concept of archiving files and save the time that is normally wasted on searching through archives. This feature responds to one of the problems identified in Case 3, in that the Flux application allows for the integration of different versions of the design object within one single file in order to facilitate searches throughout the history. This is useful for cases, such as Case 3, where each version is saved as a different file, and thus a search for a particular version requires a strategy for file naming, and means opening and closing several files to locate the right version. This feature also has the potential to address the difficulty in adopting precedent solutions for problems (Rittel & Webber, 1973, cited in Hudson, 2010) as discussed in Chapter 2. Furthermore, while the literature shows the potential of parametric design applications in recording the history of the formation process (Harding & Shepherd, 2017; Jabi et al., 2017; Oxman, 2017b), this feature enables easy and straightforward access to the formation process and to understand the development path of the designed form; however, there are additional features, as this case exemplifies, where the version is associated with a time stamp that can show the exact time of each update.

#### **6.10.5.6 Security**

According to the participant, the confidentiality and anonymity of users’ data is fully protected on the platform. In fact, they use traditional code-sharing so that every piece of data that goes through the platform is encrypted for security reasons. They are also pursuing higher security certification levels. In addition, the data is not accessible by any individual

who works at the firm. For Cases 6 and 7, an essential problem is caused by preferences for sharing data in BIM practice, where many members refuse to share their work, as they find this a threat to confidentiality. This problem becomes more significant when those members return to their old methods, and in such cases force other teams back to traditional data-sharing methods. The firm in this case offers stable security rules to address this problem.

#### ***6.10.5.7 Connection to databases***

The firm does not have a central database as they do not aggregate data; instead, they link their users to other databases. In fact, the main goal of the firm can be described as developing communication between different systems, rather than creating their own system. For instance, the platform has an application called ‘Site Extractor’ that enables an architect to access a map of the project site and draw a window to select a region that contains the building site and its surroundings. The application will then automatically generate a 3D model of the surrounding buildings with their real heights. To do this, the platform does not contain any maps or information about, the height of each building for example, but rather links users to the OpenStreetMap website that contains this sort of information. This same application can also automatically achieve a topographical survey of the site by linking users to the NASA website that contains the contour lines of most parts of the USA. This is another aspect that can notably simplify the process, by speeding up the pace, and hence reducing the cost, working hours and energy waste; this arguably results in enabling energy-efficient processes

#### **6.10.6 Ambitions**

According to S8, the team and individuals working at the firm are ambitious and claim that their role is to ensure the viability of intelligently-designed buildings to benefit billions of people and upcoming generations worldwide. Hence, the firm believes that their teams do not just provide intelligent tools for practitioners to utilise, but rather, help to change the way buildings and cities are designed and constructed (Flux.io, 2016a). The basis of the firm’s claim is arguably traceable in the previous examples that show the potential of their platform in supporting collaboration, integration, and efficiency in the design process.

# CHAPTER SEVEN

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## 7 Discussions and Framework Development

### 7.1 Introduction

Having analysed each case individually in the previous chapter, this chapter relies on the cross-section analysis to discuss the final findings from all the cases in relation to the literature review. The discussions are structured and categorised consistently with the taxonomy developed in the last literature review chapter (Chapter 4). At the same time, the chapter shows how the final theoretical framework was developed.

### 7.2 Digital Technologies and Methods

Amongst the wide range of digital technologies and computational design methods available, the main question that arises is how to select the most appropriate tool that matches the specific practice and project needs, and the particular situations in which the different technologies can be used more effectively and efficiently. This is a critical discussion that affects the main focus of this research, aiming to enhance the efficiency of digital technologies in design.

The criticality in selecting the right technologies for the project is emphasised by E4, where the selection is based on an in-depth study of the work path, employees' experiences, and the feasibility of buying new licences. Similarly, R7 emphasised this criticality and reported that the selection of the wrong application has resulted in significant unnecessary expenditure in the past, where applications were unused after the purchase of licences. Therefore, enhancing 'digital' efficiency starts by selecting the right tool for the right purpose at the right time.

#### 7.2.1 Digital Technologies and Methods and the Nature of the Design Project

One of the main factors that affect the choice of the technologies used is the nature of the project. For instance, the desire to design complex projects urges designers to use specific software applications, or particular computational design methods, such as scripting, algorithmic design and parametric design. This was shown in Case 2 where the tendency of the firm to challenge the limited levels of form complexity that was designable and buildable, prompts the use of Autodesk Maya and Maya Script. This is a highly efficient tool designed



to generate complex and curvy building shapes that characterise this firm. The link between computational design methods and form complexity was also shown in Case 1, where form complexity and the large size of the airport project required the involvement of a team of software developers within the design team throughout the process. In this case, the technology used is scripting which was needed to adapt the tools and expand their limitations in order to solve the various problems caused by difficulty in generating and rationalising this complex form. Similarly, within the same case, the iconic nature of the Pavilion project and its complex shape required the use of algorithmic design, where an algorithm was developed to populate the curved, sand-like patterns around the main core of the pavilion. The suitability of parametric design for this kind of complex shape was demonstrated through the consensus among all participants on the efficiency of parametric design in tackling complex geometry. This suitability was emphasised in the literature (Aish & Hanna, 2017; Harding & Shepherd, 2017; Oxman, 2017), and was exemplified in the case studies through different project scenarios, such as the Metro Station façade and the Circular Bridges.

### **7.2.2 Digital Technologies and Methods and Design Stages**

The cases show that the nature of each software application constitutes the design stage at which it is most effective. For instance, Case 2 shows how the flexible and intuitive nature of Autodesk Maya makes it suitable for the conceptual design stage, and the rational and mathematical nature of Rhino, makes it suitable for rationalisation at a later stage. Meanwhile, the accuracy of AutoCAD makes it appropriate for detailing at the technical design stage. In comparison, most of the other cases showed a subtle link between Autodesk Revit and the development stage, where different software are used at the conceptual stage, such as Rhino, Grasshopper, Sketch-up and AutoCAD, in order to provide the conceptual model for client approval. Thus, the model is subsequently re-created in Revit for design development, where the nature of Revit helps to coordinate design with the structural engineering teams and other project stakeholders. This same scenario was shown in Cases 1, 3, 6 and 7. However, Case 4 illustrates the stage at which Revit can be applied, and the relevance of the type of project, whether residential, institutional, or commercial. It is also affected by practitioner mindsets; for example, the engineering consultant in Case 4 insists on avoiding using Revit in conceptual design and only starts to use it from the development stage onwards. In comparison other firms, such as E4's previous firm, have no problem in using Revit from the first stage of the design process.

Furthermore, the literature shows a robust link between parametric design and the conceptual design stage. The case studies shows a high level of conflict with regard to the flexibility and efficiency of parametric design as opposed to the design stages in which parametric design is used. The researchers, namely R1, R6 and R7, generally only related parametric design to the early design stages. In this regard, R1 explained the effectiveness of parametric design in the conceptual design stage due to its ability to generate a wide range of design alternatives, while at the same time, asserting the difficulty of using it in the design development stage. They argue that a designer, at this stage, needs to focus on one of those alternatives and take it forward for development and detailing, as such, relying on parametric design becomes complicated. This was attributed to the lack of completion in parametric design systems (Turrin et al. 2011), which makes it extremely difficult to include all building components in a parametric model. However, a totally contradictory view was provided within the same case by C1, who has experienced parametric design in several projects within her current work at the firm. They ensure that parametric design was not used at the conceptual design stage, but rather at the development and detailing stages. The experts' perspective on the situation differs significantly. E5 asserts that they use parametric design in a wide variety of architectural design projects including different types and sizes, and in all cases, parametric design proved efficient and effective in facilitating and automating the design process and in enhancing the quality of the design product within all the stages of the design process. This view was demonstrated by examples given by the other two experts; for instance, E3 explained that parametric design was used at a late stage of the Metro Station Façade project in order to provide a detailed division of the façade's panels, alongside a table of quantities and panel cost in Excel. This was associated with number tagging that enabled automation within the parametric model for construction purposes. The same expert also explained how they used parametric design on the Circular Bridges project to coordinate the complex geometry of the bridges and their mechanical systems. This was achieved in collaboration with the mechanical consultants at a late stage of the design process. Similarly, E4 explained that they developed a parametric definition on Dynamo to generate 90,000 seats at a football stadium; this occurred at the development stage. Furthermore, they used the same parametric definition to automate a ticket pricing system, which appeared to be useful for facility management at operational stage. Moreover E5 discussed two scenarios (the chair and the skyscraper projects) to show how parametric design was used from the very first design stages and throughout the design process. These previous examples demonstrated the efficiency in using parametric design, which can be achieved at all design stages.

### 7.2.3 Interoperability

An important aspect that affects the selection of technologies and software applications is the interoperability among those applications. This is because architects in practice may come from different cultures and experiences, and hence, might be more comfortable in using one particular application over another (Ceccato, 2010). This raises the issue of interoperability in collaborative work where different applications are used by different architects. This issue adds to the previous one where the selection of the software applications relies on the nature of the project. In this case, one application might be more effective than another in relation to the nature of the project in hand (Ceccato, 2010). Therefore, prior to using multi-software programs within one project, it is necessary to understand and experience the way these programs ‘talk’ to each other (Hesselgren & Medjdoub, 2010).

Amongst those firms classed as semi-advanced and developing, interoperability was the main issue when using different software applications. In contrast, this does not seem to be an issue in advanced practices. Meanwhile, the software development firm in Case 8 potentially contributes a new level of interoperability as its applications focus on sharing just the required information across disciplines, and allow for different participants to work concurrently together using different applications. In this regard, Case 8’s software seems to move towards the provision of agile tools that are capable of allowing several software applications to operate as one single application. Nevertheless, despite their potential, such smart applications do not seem to be widely used within the practice. This was shown in the recurrent example across different cases; rather than relying on the same model that grows in detail and maturity as the design develops, the design process relies on two strictly separated stages. In the first stage, a conceptual design model is developed and approved. In the development stage, a Revit model is created from scratch for coordination with other project stakeholders. This shows the lack of interoperability between the different software applications, which is used at the different design stages. R6 refers to this issue as the lack of compatibility between the design model and production model. Even the advanced practices appear to be affected by this issue as the same scenario occurred for Case 1, where a Revit model was started from scratch despite the availability of highly advanced digital technologies.

To deal with this problem, different attempts were discussed in the case studies to enhance the interoperability among the different software applications used. For instance, in Case 7,

the firm decided to rely entirely on Autodesk products, as they are all provided by the same software vendor, and hence the interoperability is mature. This view is challenged in Case 3, where AutoCAD is used to provide the conceptual model, and Revit used to create the design development model from scratch despite the fact that both applications are produced by Autodesk. In this case, highly advanced digital technology and experiences are required to solve this problem. Unfortunately, these experiences solely exist in advanced firms. For instance, in the airport example (shown in Case 1) the software development team use scripting to solve the interoperability issues among applications, where the functionality of the applications was tweaked for greater compatibility with the other applications used. A different approach is provided by R6 who is pushing the use of parametric design software (Dynamo) in order to support interoperability between the design model and the production model. Within the same context, E3 appears to be more advanced in using parametric design applications to support interoperability, where they use a parametric modelling plug-in called 'Hummingbird' in order to enable the information generated in Grasshopper to be translated into families in Revit. In this case, a mediator software is used to enhance interoperability between two software applications that are significantly different in nature.

#### **7.2.4 Technologies, Methods and the Firm's Digital Advancement**

The previous discussion shows the importance of using advanced digital technologies and that these technologies are both capable and effective, thus helping to make more sense of the computational design methods. This will give the advantage of adopting tools in order to expand their limitations, and hence, the limitation of the form complexity. In addition, it will enable designers to solve interoperability issues among technologies to support collaborative work. However, the choice of appropriate technologies and applications for appropriate situation is limited to the availability of these technologies and applications in a firm. This issue was emphasised by C1, who attributed the difficulty in working in their previous firm to the limited number of software applications used. The difficulty lay in coping with the complexity of unfamiliar software that shifted C1 from their creative work. This raised the budget issue that Holzer (2015) emphasises, namely the high cost that is associated with BIM implementation, which includes the expensive licencing of the software applications, the necessary update of the network systems, and the expenditure required for training. This was reflected in Case 7 who explained the extremely high budget allocated by the firm to update servers and networks and the highly expensive licence needed to purchase a pass for Collaboration for Revit.

The efficiency of digital tools can be affected by the availability of the right experiences and knowledge within the firm. In fact, dealing with this vast array results in a shift in the experiences and knowledge required (Oxman, 2017). In fact, some of these technologies can result in cognitive barriers (Aish & Hanna, 2017; Wortmann & Tunçer, 2017) that restrict the effective use of such technologies. This was shown in the developing cases through the lack of experience in BIM integrated practice in Case 6, and in the use of networks and servers in Case 7. These resulted in difficulties and inefficiencies when these methods and tools were applied.

### **7.2.5 Digital Technologies & the General Atmosphere**

The case studies showed that the selection of digital tools utilised in projects is highly affected by the general atmosphere. This could be the general culture in the geographical area, market demand or a shift in the whole industry towards integrated practice. In this context, R7 claims that the appetite for using smart processes and technologies is low in the geographical area, and this results in difficulty when promoting the use parametric design in their firm. Similarly, R6 states that the general market is moving towards the use of Revit to enhance integration in architectural practice, and because of this, they decided to follow the market by enhancing their reliance on Revit in order to avoid being left behind. In addition, Whitehead et al. (2011) mentions the increase in client demand as one of the factors that affects their technology-related decisions. This was reflected in Cases 1 and 6, where the Revit model was part of the client's requirements who needed it for facility management during the operational stage of the building. In general, architectural practice is shifting into a shared interdisciplinary interface comprising architects, engineers, planners, and fabricators (Thomsen et al., 2015) and this is why BIM is gaining exceptional recognition on a global scale. This tendency was reflected in all case studies, where relying on BIM, promoting its importance, purchasing the technologies needed to enable BIM implementation, and developing software to enhance the efficiency in BIM platforms are the main concern of most participants.

### **7.2.6 Maturity of Digital Technologies**

The choice of technologies can be affected by the maturity of those technologies that in turn affects the effectiveness of their use in design projects. This was revealed in the discussion in Chapter 3 concerning the design-related, graph-related and cognitive-related problems of parametric design, which shows the immaturity of the applications. This immaturity was

emphasised by E3 who discussed a wide range of limitations in parametric design, such as the abnormal behaviours of Grasshopper when manipulating a panelling system, and the lack of compatibility with the host application (Rhino), which was also emphasised by Aish & Hanna (2017). This immaturity appears to be the main reason why parametric design is still unpopular, and explains why it is still misunderstood (Jabi et al., 2017) and marginalised (Schumacher, 2016). Therefore, it could be argued that the maturity of BIM applications is the main aspect that makes BIM more popular than parametric design.

### **7.2.7 Traditional Methods**

Despite the potential of digital technologies, which contrast with the various limitations of traditional drawings (Jones, 1992; Lawson, 2011), most of the case studies showed a heavy reliance on traditional methods for collaborating, and communicating design ideas and information. In developing firms, the vast majority of architects as well as in the whole region are still anchored to traditional methods. In semi-advanced practices, such as Cases 3 and 4, only a handful of specialists in scripting, parametric design and BIM exist despite the large size of the firms. Even in advanced firms, many scenarios were reported which demonstrate that the traditional methods are still applied for designing, collaborating and sharing. This shows the importance of traditional methods and supports the researcher's assumption that new computational design methods cannot replace traditional methods. Instead, they can augment and enhance the efficiency of traditional methods by facilitating or automating some specific activities within the traditional design process. This was demonstrated in different project scenarios where the project model was created using CAD, and parametric modelling software was used to automate some activities, such as the generation of the football stadium seats, and the generation of the façade panels alongside the associated table of information. This shows the flexibility of parametric design that can be fit within a traditional design process to automate repetitive tasks without disturbing the whole process.

The previous discussions showed the various aspects needed for consideration by architectural practitioners in order to enable the selection of the right digital tools that match the project, practical or global situation. This shows the importance of the 'digital' in developing innovation and methods, and their relationship to all other elements of the theoretical framework.

## 7.3 Experience and Knowledge

A vast array of various and heterogeneous digital technologies are being utilised in the current architectural practice. Those technologies represent the tools that the practice relies on in developing novel approaches and methods. Where this development is resulting in the need to develop experiences to deal with those tools, those experiences, in turn, often require specific sort of knowledge that might be beyond designer's cognitive base.

### 7.3.1 Experience and Knowledge and their Relation to Digital Technologies

The literature and case studies show that getting the benefit of the potential of 'digital' requires an appropriate interaction between human-designer and machine, which reveals the reciprocal relationship between digital technologies, experiences and knowledge. In that respect, the literature shows how using scripting requires programming knowledge that might be a cognitive barrier (Oxman, 2017b; Wortmann & Tunçer, 2017). Similarly, achieving efficiency in BIM requires architects to have profound tectonic knowledge (Holzer, 2015). This is added to the specific knowledge needed for designers to deal with the 'mathematical language' of parametric design applications (Aish & Hanna, 2017). These types of knowledge often represent cognitive barriers (Oxman, 2017b; Wortmann & Tunçer, 2017) that may threaten the efficiency of different computational design methods.

In the case studies, the subtle link between technologies, experiences and knowledge can be traced to the problems reported by participants in the semi-advanced and developing firms regarding the difficulty of implementing technology in the different cases. In most cases, participants placed the blame on humans, rather than on technology. According to R7, technology exists, and is capable and effective, but the biggest challenge is that it requires expertise to capture and use it efficiently. R7 explains an example where a highly advanced network system with a server were established and put into use within the firm, and this is where the 'the shift in skillset' problem emerges (Oxman, 2017). According to E4, the use of CDE requires a designer to have the relevant knowledge to ensure an effective use of this technology. For instance, they need to be aware of the limitations of the file path links that the CDE system can support in order to eliminate the cumbersome work required of IT team to continuously simplify file path. Within the same context, R7 states that designers were able to use the server to search for information required for their design work; however, they did not have sufficient knowledge to keep the database credible and up-to-date; they struggled to know how to use tools and understand its potential, and hence, many requested to return to

the old ways of sharing information. A similar example was shown in Case 6, where after successful involvement in a BIM process, the lack of relevant technological experience amongst the MEP team members saw them revert to using CAD. This had the knock-on effect of forcing all other teams to revert to traditional methods of sharing.

The link between technologies, knowledge, and experience can be traced in arguments provided by both the experts and researchers when reporting the problems they encounter when using parametric design in their firms. In that sense, R7 attributes the difficulty in implementing parametric design to the lack of related experiences in design teams, the lack of relevant cognitive knowledge, and the difficulty in learning its operation due to the complexity of the tool, in addition to the lack of trust in the potential of parametric models, and the feasibility of adopting this design strategy from a wide range of other available methods. Meanwhile, R1 argues that the parametric design tools currently available are highly effective and adequate, and therefore, the limitations of the tools are imposed by the capacity of the team. Similarly, E3 argues that the limitation of the tool depends on how much designers want to limit themselves, as parametric tools offer a high level of freedom. However, to access the benefits, the level of control over each part of the design object will be sacrificed, especially when designing differentiated geometry. Clearly, this sacrifice requires a shift in the mindset from 'direct manipulation' in CAD systems (Aish & Hanna, 2017) to remote control in parametric systems, which requires experience.

In general, the previous comments support one of the main tendencies of this research by emphasising the need to change the way technologies are used, rather than suggesting new technologies. Moreover, the previous discussion shows the stable link between technologies, experience and knowledge that should be shown in the framework.

### **7.3.2 Imbalance of Experiences and Knowledge**

The essentiality and sensitivity of developing experiences and knowledge in architectural practice is often revealed in collaborative work environments, where the lack of experience and knowledge in a specific team or a specific individual or team in collaborative work may result in pushing all other teams down to using traditional tools. This situation was discussed in Case 6, where the lack of experience in the MEP team led to this team deciding to revert back to using CAD, rather than BIM. In this case, all other teams were forced to use the traditional way of sharing pdf files and annotations, rather than relying on centralised information in the integrated platform. This example shows the necessity of balanced or



parallel experiences among different teams within a collaborative work environment. In the previous example, the implementation of BIM failed due to the imbalance in experiences, where the lack of experience in one of the teams pushed the other teams to traditional methods of sharing. R7 is very conscious of this issue; when they work with a smaller firm that has lower levels of experience in using networks and cloud-based systems, they ensure that the smaller firm does not take the lead. This consciousness resulted from previous experience, where the lack of similar technologies and experiences resulted in a situation where the smaller firm started to dictate the way information is shared; hence, the firm found itself using traditional methods, such as using FTP, and sending pdf and CAD files, as in the previous example.

This uncovers a link between experiences and collaboration, where making sense of the experiences in collaborative work is subject to the same, or complementary, experiences of all collaborating parties. This same link can be traced through successful scenarios. For instance, the successful collaboration between the designer and the MEP team in the Circular Bridges project in Case 3 was related to their advanced and harmonious experience in parametric design. This same factor resulted in the successful coordination between the design team and the engineering team in the Façade Panelling System project within the same case.

The imbalance between experiences and knowledge amongst different participants can also be traced in Case 4, where graduates come to the firm lacking essential knowledge about design and construction coupled with a broad and in-depth knowledge of digital technologies and methods. On the other hand, the highly expert members of the firm have profound knowledge and experience in the professional aspects of design and construction coupled with a lack of understanding of the principles of new digital technologies. This makes collaboration extremely difficult, where participants from different cultures and with different mindsets need to work together without understanding each other's languages. This again enhances the link between experience and knowledge and collaboration.

### **7.3.3 'Experience and Knowledge' and Power**

The relationship between experience and power (Cuff, 1992) was discussed in Chapter 2, and exemplified in several cases in Chapter 6; however, the previous discussion about the imbalance of experiences and knowledge in practice inspires a different angle from which this relationship can be viewed. Case 4 contained an explanation of E4's power that was

gained from their mathematical knowledge and substantial experience in parametric design and BIM. Meanwhile, C2 has similar experience and knowledge that has not resulted in a similar power. On the contrary, they have found themselves struggling to survive within the digitally immersed work environment of Case 2, where a vast array of digital technologies exist. This inspires a new link between power and imbalance in experiences and knowledge; in the first example, the power that E4 gained has not only resulted from their ‘persuasive ability’ (Cuff, 1992) to develop algorithms and manage BIM implementation, but also from a lack of similar experience amongst others in the firm. This enabled E4 to have a major role in different projects, whereas other participants viewed E4 as a ‘unique architect’ with ‘esoteric experience’ (Blau, 1984, cited in Cuff, 1992). In the second example, C2’s power was affected by the general atmosphere of the firm in Case 2, where the existence of similar experiences and knowledge in the majority of architects means that C2 is perceived as an architect with average experience.

Another aspect that might affect the power of an individual within an architectural firm, is the nature of a project and its unique requirements. This can also be traced in Case 4, where the complicated form of the two football stadium projects raised the need for their scripting experience that is needed to tackle complex geometry in those particular projects. This indicates that the power of an architect within a project can be constituted by the compatibility between their experience and the specific requirement of the project.

### **7.3.4 Experience and Knowledge Development**

The previous discussion highlights the criticality of developing experiences in digital technologies in practice. This criticality stems from the novelty of these digital technologies together with their significant potential. For this reason, several attempts to develop digital experiences were shown in different cases and the difficulty of this development was revealed. E3 narrates several stories about training courses in parametric design that they provided to the design team at their firm as well as in their former firm. In most of the cases, the courses failed to achieve their goal due to the workloads of designers and their commitment to different tasks and deadlines within different projects.

A valuable example about how experiences can be developed in the long term is shown in Case 1, where the research group that consists of members with special and high level digital literacies support the design team in leveraging technologies within their design tasks. This led to the assumption that, in the long term, designers in a team would be able to deal with

technology to support their design tasks without supervision. In that sense, the same participant (R1) unconsciously demonstrated this assumption by explaining that, four years ago, design teams were provided with parametric design specialists to support the team in dealing with complex forms. Currently, designers themselves have parametric design skills and hence, they can do the job unaided. This shows how experiences can be provided for designers by highly specialist members in the firm, which works effectively in the long term.

As a result, in order to increase effectiveness of digital technologies, architectural practice needs to deal with the novelty of tools, experience development, and knowledge acquisition as one single, multi-faceted issue to be able to develop the appropriate strategies for this situation. Therefore, the digital technologies and methods, experiences, and knowledge will be shown in the framework diagram as one single node, consisting of three 'sub-nodes' with dual-directional arrows to emphasise this link. The node will be referred to as DEK, as shown in Figure 18.

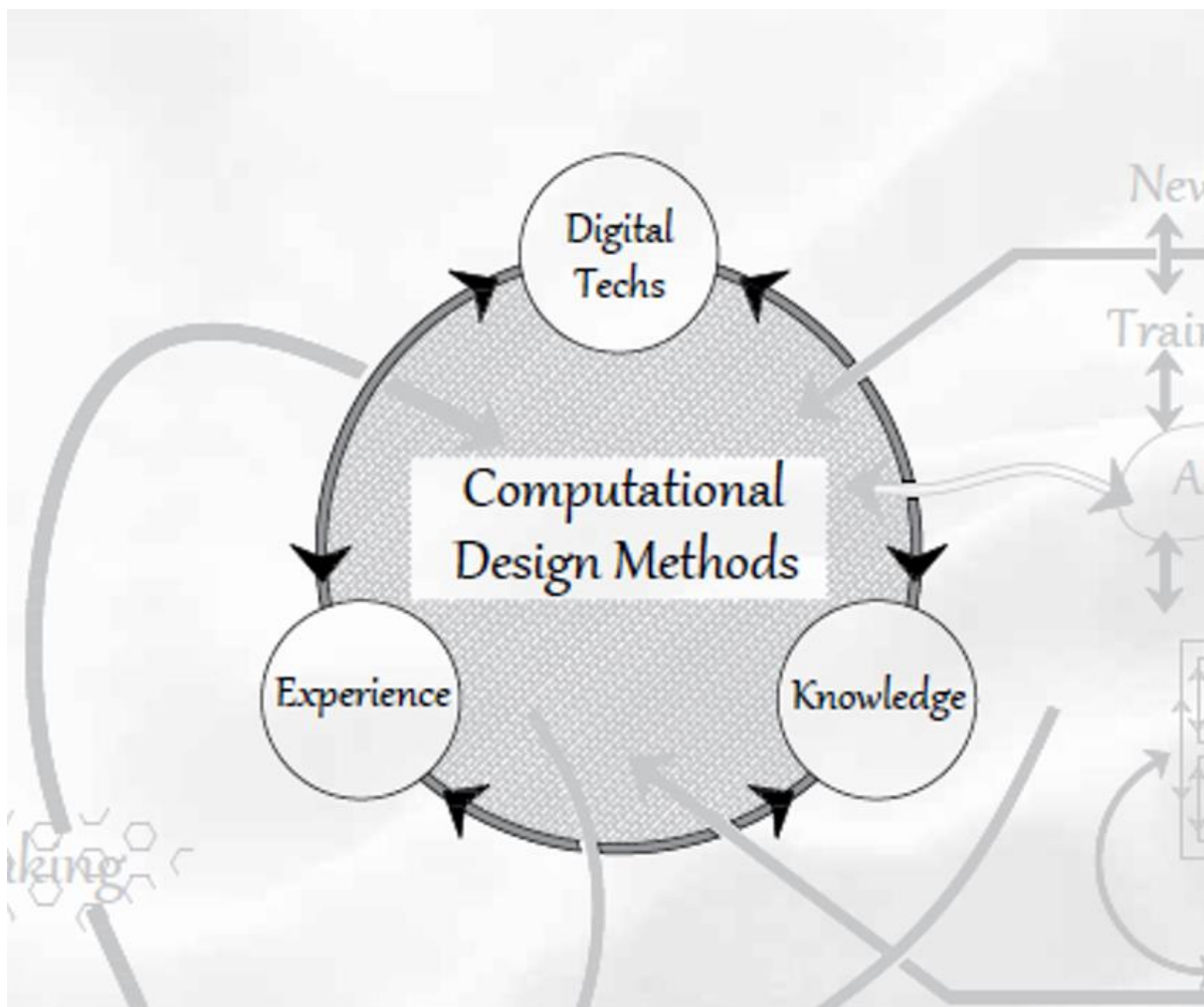


Figure 18: DEK Node: 'Digital', Experience and Knowledge

## 7.4 Collaboration and Interdisciplinarity

While the literature advocated the need to work collaboratively to successfully address the multiplicity and complexity of new technologies (Kocaturk, 2013; Kocaturk & Medjdoub, 2011; Thomsen et al., 2015), the cases demonstrate this increasing need in practice. In general, a wide range of scenarios shows that traditional collaboration is still applied, even in advanced firms. For instance, Case 1 illustrates how employees collaborate, the way in which they share files, and the nature of the material shared differs based on the nature of the project, its size, and the nature of the collaborating teams and consultants. However, despite the heavy reliance on various technologies at the firm in Case 1, they often rely on traditional methods of collaborating and sharing files and information. The analysis of those methods revealed correspondence with the activities defined in conventional design.

### 7.4.1 Problems of Collaboration

The reason why traditional collaboration methods still apply is addressed by R6, whose academic and research background enables them to understand that the main problem in their firm lies in the lack of communication between the different architects, as well as between the different disciplines. Therefore, their main focus is to enhance collaboration by pushing the utilisation of different tools to enhance communication, and to raise awareness of the need to develop more effective methods for sharing and exchanging information. R6 mainly attribute this problem to the lack of experience and a sceptical mentality amongst some members within the firm. This is added to different cognitive responses to technology, cultural differences and a general resistance to change. For instance, when R6 provided Revit training as part of their role in managing the switch to BIM implementation, they started to understand the problem more deeply. They state that one of the main problem is that most of the CAD experts think in 2D when dealing with building projects, and therefore, they struggle to think in 3D about the building design and its different structural components. This is a problem of mindset that echoes the previous juxtaposition between the experts' and graduates' professional and technological knowledge, as described by E4. From a wider perspective, R7, similar to R6, complains about the resistance to change and the anchoring to traditional methods for collaborative work in their firm. However, R7 connects this problem to the general ambience amongst practices in their whole region, where the vast majority of architectural firms are still relying heavily on traditional methods.

### **7.4.2 Collaboration in Parametric Design**

This focus on collaboration and the move towards networking, CDEs, sharing and information exchange reveals the importance of collaboration. This echoes Kocaturk's (2013) perspective who thinks of collaboration as the main engine for innovation in contemporary architecture. Therefore, supporting collaboration is one of the main features that should be considered in judging the effectiveness of any design approach. In this regard, the case studies showed a variety of examples where parametric design was used to support collaborative work, such as the Metro Station Façade and the Circular Bridges project scenarios. However, E5 assures that there is currently no possibility in node-based parametric modelling application to enable two users to apply the same parametric definition at the same time.

In general, as E3 states, the opportunity to allow for contributions from other disciplines in the parametric design process relies on their experience in parametric design, and hence, their ability to understand this new 'language'. Consequently, as E4 states, if the structural team, for example, does not have parametric design experience, the design team needs to change the work to a CAD model before sending it to the structural team. This results in a break in the design continuity that parametric design offers, and resonates with the previous example about the withdrawal of the MEP team from the BIM implementation plan in Case 6. Hence, it further emphasises the subtle link between collaboration and experience.

The previous discussion shows again the dilemma caused by the imbalance of experiences and knowledge in collaborative work. This dilemma resonates with the findings of Kocaturk and Medjdoub (2011) who argue that innovative architectural practices should not focus merely on adopting technology, but on harnessing digital technologies to structure and coordinate collaborative and multi-disciplinary design intelligence. This suggests that dedicating digital technologies to support collaboration is one of the essential ways to enhance the efficiency of the 'digital'.

### **7.4.3 Successful Collaboration**

Despite the difficulties in establishing an effective and efficient collaborative work environment, some examples of successful collaboration scenarios were shown in the case studies. One of these examples was the fruitful collaboration between the design team and the IT team in Case 4, where the close relationship enabled the IT members to listen to the designers' needs, analyse their issues, provide technical solutions, and allocate budgets for

the realisation of those solutions. The value of this collaboration lay in achieving tasks that were beyond the scope of the designers' knowledge and experience.

Although the vast majority of designers in developing firms still appear to be anchored in traditional methods, there is still a desire to achieve success in collaborative work. This was shown in Case 6, where a wide range of technologies have started to be used to enhance efficiency in collaborative work. This includes using 'Slack' to enable chatting and real-time notification of changes, and BCF to enable screenshots within cloud-based models in order to speed up the coordination amongst project participants.

This can be linked to the previous section that shows the impact of the general atmosphere on the selection of technologies. In fact, the increasing tendency to enhance collaboration and integration in practice is affected by the similar tendency that exists in the AEC industry as a whole (Hesselgren & Medjdoub, 2010; Thomsen et al. 2015).

#### **7.4.4 Collaboration Beyond the Organisation**

The design scenarios discussed in the advanced firms cases as well as in Case 3 show how collaboration can go beyond the enterprise borders when dealing with complex forms, where the main focus is to make the forms buildable. In all these cases, very similar scenarios were narrated that show how external engineering consultants become involved in the design process in order to rationalise complex design forms and secure their buildability. Moreover, in some cases, collaboration goes beyond the borders of the whole industry by collaborating with academic institutions and software developers. For instance, the research group in Case 1 conducts extensive collaboration with software vendors where they exchange information and experiences to improve tools and methods from both sides. They also collaborate with other research groups around the world. Similarly, the research group in Case 2 has conducted extensive collaboration with different internal and external teams and groups, including academic institutions. The software firm in Case 8, also extensively communicates with software vendors as well as practitioners from the AEC industry. This is added to the potential explained in the same case where users can collaborate with the developers of the platform by building their own software on top of existing software. These examples lead to the definition of a new level of collaboration, namely collaboration on a global scale.

Other examples of the global scale of collaboration can be traced to the case studies; for instance, R1 argues that the most interesting thing about Grasshopper is the 'amazing

community' behind it, which makes reference to the social networking enabled in Grasshopper's official website, where users from around the world share their ideas, answer each other's questions, and share their models to gather feedback. From this basis, E3 provides a valuable example of how using social networking can give positive results in architectural design projects. This was shown in the Stadium Seats project, where E3 successfully adopted a Grasshopper parametric definition from one of Grasshopper social networking websites. The definition enabled the automated and direct generation of the stadium seats, and as such, E3 was able to adopt work by others, rather than build a whole story from scratch. This example highlights the potential for collaboration on a global scale, and it is seen in this study as an example of a building seed (Carlile, 2014).

#### **7.4.5 Levels of Collaboration**

Based on the case studies, collaboration in architectural practice is established on four main levels; the design team level, the enterprise (the practice) level, the industry level, and the global level. On the team level, different members within the design team collaborate by sharing information and exchange experience to solve design problems. This level is mainly related to the conceptual design stage as shown in the different collaborative scenarios discussed in Cases 1 and 2.

In the later stages, collaboration shifts to the enterprise level, where other teams start to work together with the design team, such as the structural engineering team. This type of collaboration is referred to as interdisciplinary practice in the literature. This level was exemplified through the scenarios within different cases, where the structural engineers work together with the design team to achieve the rationalisation of complex forms. The level of complexity constitutes the stage in which structural engineers start to involve. In this regard, Case 2 shows scenarios, where this involvement started from the very initial stage of the design process due to the high level of complexity of that project. This same sort of complexity required early involvement of software developers in the Airport Project in Case 2. In those two cases, the complexity of the projects resulted in eliminating the team level of collaboration. Theoretically, the performance-based design process, requires early involvement of different disciplines (Turrin et al., 2011), and hence, again, eliminating the team level of collaboration.

At the industry level, the collaboration goes beyond the borders of the enterprise, where an architectural practice collaborates with other practices to solve highly complicated design

problems. This level is strongly linked to the form complexity. As shown in the case studies, there are enterprises that are specialists in rationalising complex geometries that collaborate with different practices, such as in Cases 1, 2 and 3 to make complex projects buildable. This sort of collaboration is the main factor that results in pushing the borders of the possible in form complexity as discussed earlier.

At the global level, collaboration goes beyond all borders, so that practitioners from different types and levels of experience, and from different places around the world get use of the advances in digital technologies and social media websites to exchange experiences and knowledge. This was shown in the social networking enabled in Grasshopper website that is discussed in Case 1. This social networking enables any practitioner to post a problem and get a wide range of feedback from different practitioners. This is also exemplified in the way Case 8 members interact with the users of its online platform to guide those users in tackling problems related to online platform.

#### **7.4.6 Collaboration for Innovation**

The novelty of the new digital technologies and the design methods being developed is resulting in more focus on innovation in order to get effective use of those technologies and methods. The advanced cases show innovation as one of the main purposes for collaboration. For instance, the research group in Case 2 has intensive communication with academic institutions, where they organise different events and conduct research to explore the cutting-edge technologies and methods available, and investigate strategies to apply those methods in real projects. Similarly, Case 1 has an intensive line of communication with software vendors, from which they get inspirations about potential benefits of software. At the same time they provide feedback from their practical perspective, that helps software vendors in developing their applications based on real situations from practice. This sort of collaboration can be beneficial for the architectural practice as a whole, as the software that will be developed based on Case 1's feedback will be used by any architectural practice around the world. One more example is shown in the way Case 8 communicates with different practitioners from the AEC industry, where they listen to their needs and develop their applications based on those needs. In addition, they communicate with popular software vendors to get new ideas and hence, develop their tools further. Moreover, the complicated hierarchy of the research groups shown in Case 7 shows the potential of this sort of collaboration. In this case, the internal research group gets experience and knowledge from



an academic research group to enable innovation within the firm. At the same time, the academic research group uses the firm together with other firms as case studies to enhance the credibility of its research.

Therefore, collaboration is the main component of any innovative strategies that aim in enhancing the efficiency of digital technologies in practice. In this case, any architectural practice needs to focus on collaboration, and needs to recognise the different levels and the purposes of collaboration. In this case, an architectural practice needs to push collaboration beyond the borders of the enterprise, and find methods to collaborate with other enterprises, consultants, software developers, as well as academic institutions. This requires considering collaboration as a new culture in contemporary architecture that needs to be introduced to practitioners from their early career as well as from their undergraduate study.

## **7.5 Integration**

To respond to the increasing need for collaboration in practice, new integrated platforms are being developed that act as central platforms of information and experience exchange, such as BIM applications and CDEs. The idea of integration has historical roots. A few decades ago, a vast array of machines were used in human daily life, where each machine has a specific function, such as, sound recorders, video machine, TVs, phones and faxes, etc. Later, the advances in digital technologies enabled the integration of all those functionalities into one single machine to make life easier, where a computer machine or a smart phone, for example, act as a video, a sound recorder, as a phone book, and many other functions. This same shift started to be applied in the software industry, as the new software applications are integrating functions. The motivation of this integration is rooted in the need of enhancing interoperability amongst different and heterogeneous software applications being used. This is to respond to the different natures of those technologies, their different efficiency in relation to the project different contexts, in addition to the diversity in experiences and cultures that may exist in one single architectural practice (Ceccato, 2010). The case studies showed a variety of scenarios for integration and information sharing that range from traditional to highly advanced.

### **7.5.1 Traditional Methods for Sharing**

Despite the potential for Case 8's online platform to significantly enhance integration in practice, the majority of the firms within the study, including the advanced firms, still rely on

traditional methods to share in a collaborative work environment. This was shown in the 'loop' of generation and evaluation explained in Case 1; rather than using cloud-based systems to share files, the design model is sent by email to the external engineering consultant firm who provides feedback and sends the model back to the design team, who, in turn, responds to the feedback and resends the file. Therefore, the process iterates in the same manner until approval is confirmed. A similar scenario was described in Case 2, where the complex design model provided by the design team is sent to the engineering consultants, who modify the model and simplify it for rationalisation. This same issue raised an important question in Case 3, where different designers work collaboratively on the conceptual design stage. In this case, they use email to send different versions of the same file, and then each of the designers work on a specific part of the model to manually merge all the versions into the final conceptual design model. An issue was noted that, when the first designer sends a model to another designer, and then continues developing the model, the second designer would be working on the old version of the model; this makes it difficult to manually merge the file, especially for large and complex projects. In developing firms (Case 6 and Case 7), the situation is the same, where the vast majority of designers and other members are anchored in traditional methods, which lacks the potential for appropriate communication amongst projects participants; however, R6 and R7 are dedicating their theoretical and research-based knowledge to changing this situation. These scenarios support the arguments shown in Chapter 1 so that, despite the existence of highly advanced integrated platforms and software applications, the classical and cumbersome methods of sharing still apply, i.e. the available digital technologies are not utilised efficiently.

### **7.5.2 Enhancing Integration**

The main aim of this research arises between the existence of highly advanced hardware and software technologies, and the fact that most architectural firms still rely on traditional methods. In this case, enhancing the efficiency of digital technologies requires finding ways to make an efficient and effective use of integrated platforms in practice. Therefore, different examples were investigated in the case studies to show how architects respond to this need. According to E3, the main tendency of the firm is to facilitate coordination by using integrated platforms to allow the seamless exchange of information, and for this reason, they are using Revit in almost all projects. In addition, they recently started to enhance their reliance on cloud-based systems. This proved to be fruitful in one of the complex projects as it facilitated the collaboration between design teams involved in providing the conceptual

model, and the external engineering firm involved in rationalising geometry against construction standards. Similarly, E4 states that the most critical aspect on which they are focussing in their current firm is to support integration between different architectural and engineering platforms. For this reason, they have started to implement BIM in some recent projects, where two BIM teams were established, one operates on the organisation level and the other operates on the project level. Furthermore, as discussed earlier, E4 argues that supporting integration is the major factor that constitutes the selection of software applications for use in projects as well as across the firm. Consequently, E4 took the decision to stop using ArchiCAD and moved to Revit as they found it more effective in supporting this tendency. In Case 2, C2 explained the difficulty in using AutoCAD which was noted at the construction stage where, in one of the projects, they had to take about 100 different sections in a complex project to solve complex geometry problems on construction site and to avoid significantly deviating from the original design. C2 explained that the coordination became easier when the design team shifted from using AutoCAD to Digital Project. This enabled them to integrate design and structural processes using one single model that enabled the automated extraction of drawings and schedules at any time. As for the developing firm, where the lack of communication and integration can be more severe, R6 and R7 are dedicating their research-based knowledge to solve this issue. Case 7 shows that the firm has dedicated a large budget to set up a new network with high speed internet connection and an arm server with access to a VPN (Virtual Private Network) to connect to their main server. In addition, R7 has started to explore different cloud-based platforms to enhance integration, such as Collaboration for Revit and BIM 360. They also started to provide a feasibility study to investigate the efficiency of purchasing licences for their systems that could help designers at the firm to leverage the server and establishing a stable infrastructure to enhance efficiency in collaborative work. This same tendency was shown in Case 6, where the firm started using a wide range of technologies and online platforms, such as BCF, Slack, Bluebeam to enhance efficiency in those integrated platform.

All the previous examples show the criticality of enhancing integration in architectural practice, which can be traced to the future expectations of some of the participants. For instance, E4 predicts a radical shift from CAD to BIM, and this will be more significant than the previous shift from paper-based design to CAD, as architects will have to be involved in different sectors. As for R6, they think that the practice is moving towards an increased

integration between disciplines, and that synthesising this integration is a key to any success in future practice.

### **7.5.3 Problems of Integration**

Pushing the practice towards greater integration comes with a wide range of problems, and this was widely discussed in the previous chapter as it affects the efficiency of the digital technologies used to support integration. The first problem stems from the lack of experiences and knowledge, where designers find new systems complex and hence, in case 7, requested to revert to using traditional methods of sharing file, such as WeTransfer and FTP. This was discussed earlier in this chapter, where another related problem was raised, namely the imbalance in the level of experience and knowledge between different teams working within integrated platforms that results in pushing expert teams back to traditional methods (as explained in Case 6).

The second problem stems from the high cost of these integrated platforms. This was highlighted in the literature, which discussed the expensive licence of BIM software associated with the need to develop highly capable network system alongside ensuring the expenditure needed is available for training (Holzer, 2015). This was shown in Case 7 through the feasibility study conducted by R7 and the extremely expensive licence required to pass to ‘Collaborate for Revit’ to support the BIM implementation.

Another problem stems from the lack of confidentiality sensed amongst expert project participants who had relied on CAD throughout their career. This was shown in Case 6 and Case 7, where many members refuse to fully share their models and information with other participants as they see this way of collaborative working as a threat to the privacy and confidentiality of their work. This attitude is also potentially linked to the age of the members who refuse this way of working in that they are normally over 50 years of age (as described in Case 4 and 7). This issue echoes the copyright and authorship issue (Bernstein, 2016; Ruy, 2016) that was discussed in Chapter 4. R7 emphasises that the integrated platforms are highly mature with the potential to support collaborative work. Therefore, according to R7, the only barrier is the mentalities of the expert practitioners, which can result in resistance to change, and hence, restrict the effective use of integrated platform. Moreover, R6 explains another essential problem which stems from managerial difficulties. They state that any integration faces a barrier in the form of procedural and contractual problems, and this is due to the difficulty in determining the amount of participation by each team, which is the main issue

that results in the resistance to such change amongst some individuals. While, Michalatos (2016) introduces the notion of ‘granular ownership’ to solve this problem, this method does not seem to be recognised in the case study firms.

#### **7.5.4 Parametric Design and Integration**

The criticality of integration in architectural practice (Bhooshan, 2016; Sprecher & Ahrens, 2016) has motivated the author of this research to investigate the capability of parametric design in supporting integration. This was first investigated in the literature review chapters. In addition, various examples were shown through project scenarios in different case studies to demonstrate this capability in parametric design. For instance, in the Metro Station Façade project, E3 explained that they used Grasshopper to generate the differential façade panels. At the same time, a table was automatically generated in Excel that contained information about the panels, their sizes, fabrication prices, and number tagging to facilitate the assembly on site. In the Circular Bridges project scenario, E3 explained how they used Grasshopper to coordinate work with the MEP team in order to automate the simultaneous manipulation of the curvy circular bridge and the mechanical systems without affecting the functionality of those systems. In another example, E5 explains that they used Grasshopper to design a chair while all the fabrication information concerning the chair and the assembly of its parts were integrated into the parametric model. E5 also explains how they used the same parametric software to coordinate design and structural design information in their Skyscraper projects. All of the previous examples in addition to other examples explained in the case studies showed the ability of parametric design applications to act as integrated platforms where information for designers, engineering and construction and quantity surveyors information can all be integrated into parametric definitions. This demonstrated that parametric design applications can, by no means, be considered highly effective BIM tools. This was confirmed by the researchers, as R6 stated that any software that links data to geometry can be considered BIM software and this is why they are pushing the use of Dynamo to enhance compatibility between the conceptual model and the production model. In comparison, R7 affirms that Dynamo was used in their firm solely for BIM purposes.

The ability for parametric design applications to act as BIM tools was, in the first place, questioned in the literature, and inspired from the fact that all BIM applications naturally rely on parametric principles (Holzer, 2015). However, the case studies showed that such applications can go beyond the limitations of current BIM applications by embedding other

types of information, such as standards and regulation-related information. In this regard, an interesting negotiation between E4 and E5 can be traced in Cases 4 and 5; E5 was asked whether parametric design applications can be used to evaluate the building compliance to standards and regulations. Even though they could not give an example from their practice, they ensured that it is possible because, in most cases, the building codes are based on the logic of ‘if the situation is x, then do y’, which is the same logic that underpins parametric modelling. To answer the same question, E4 states that embedding rules derived from building standards into parametric models is one of their main strategies in using parametric design, and this strategy was successfully implemented in various projects. They provide a valuable example to demonstrate this capability in parametric design. This was shown in the Stadium Seats project where E4 was able to use Dynamo to generate the seats based on information from building standards that were embedded into the Dynamo parametric definition. This is another powerful example, that not only shows that a parametric design tool can act as a BIM tool, but that it can go beyond the capacity of the current BIM tools. In this example, a new sort of information is embedded into the parametric model that is beyond the seven dimensions explained in Enyon (2016), McPrtrand (2016), and Luthra (2010). This might be considered the eighth dimension. These examples show that parametric design tools can be highly effective; moreover, they help to embed the sort of information that goes beyond the capacity of current BIM applications.

This capability in parametric design applications resonates with the discussions on the merits of parametric design in Chapter 2. These merits were split into two parts: firstly, parametric design as a design methodology in terms of its impact on facilitating the flow of information, and hence, automating changes in the design process, and secondly, the merits of the node-based software applications used in parametric design and their impact in illustrating and visualising the design process. This gives the opportunity to objectify and recycle the design process. In other words, the merits of the design method and digital technology were differentiated as each has totally different impacts. This same differentiation can be applied to BIM as a method and as technology. BIM can be seen as a method to manage coordination amongst participants from different disciplines throughout the whole project lifecycle, while BIM technologies and applications offer an integrated platform that ‘enables’ this coordination. Therefore, any software applications that can support this tendency can be considered a BIM software. The discussion above, shows that the capability of parametric

design applications in associating different types of information into design geometry within parametric definitions makes those applications, by no means, BIM applications.

### **7.5.5 Integration and ‘Digital Continuum’**

While Kolarevic (2004) argues that using parametric design results in a digital continuum from design through to production, this continuum stems from the integration of different design, structural, and fabrication processes into the design process (Oxman, 2017b). As this continuity appears to be of great potential in increasing the seamlessness and acceleration of the design process, it was thoroughly explored in the case studies. In this regard, Case 8 shows a highly effective way to integrate architectural and engineering platforms by offering cloud-based systems to share files and information. They developed an online platform that contained a wide range of small and simple software applications in order to allow for information to flow among different popular software applications in a seamless and automated manner. The system allows practitioners working together on building projects to only share the necessary data amongst different applications, rather than sharing whole files. This feature was thoroughly discussed in the analysis and findings of Case 8 and revealed a new understanding of interoperability. Thus, rather than focusing on minimising the loss of data when files are transferred from one applications together, the applications in Case 8 push interoperability further by allowing different software applications to behave as if they are different dialog windows of one single application. The firm also takes the connection to a further level by connecting the applications on the online platform to different sources of information, such as OpenStreetMap and NASA, in order to immerse design models with integrated and live information about site topography and surrounding buildings.

The digital continuum (Kolarevic, 2004; Oxman, 2017b) appears to be of great potential in increasing the seamlessness and acceleration of the design process, thus, it was thoroughly explored in this case studies. R6 states that one of the main purposes of the research they are undertaking within their firm is to find ways to facilitate communication between the conceptual model and the production model. To achieve this, they are promoting the use of Dynamo due to its potential in enhancing the interoperability between, or to totally integrate the conceptual and production models. Moreover, E5 argues that this ability in parametric design relies mainly on the size and the complexity of the project. For example, when designing a chair, they were able to achieve the design and rationalisation within one single parametric model, where extraction of the necessary data for the fabrication machines was

seamlessly coded into the rationalisation process due to the small number of materials and fasteners required for a chair. However, when designing a skyscraper, a parametric model was created for the conceptual design and the rationalisation, and a second model was created for the documentation, which was automated from the first model. Later, the fabricators created their own model to automate their processes and to streamline their production. Again, the automation was based on the original model. A similar process was described by E3, where several versions of the same parametric model were saved to provide the ability to go back in history and explore the previous models; meanwhile the new models embedded the beginning steps.

The previous examples demonstrate attempts to drive the whole design process using one single model, which grows in detail and associativity throughout the process. In such a case, the sequential logic of the conventional design process is totally changed, and the lines between the design stages are blurred, resulting in one single continuous stage. Furthermore, this process is opening up the borders between the design process and the structural analysis processes that are also integrated into this continuum. All of these aspects will result in significant acceleration of the design process. While this continuity was achieved in the chair project explained above, this cannot be generalised, as this continuity was not completely achieved on larger and more complex projects.

## **7.6 Information**

The ability to integrate platforms between different disciplines is enabled through the automated flow of information offered by different software applications. In this regard, most of the cases show that BIM is gaining attention amongst all case study practices, but especially amongst the developing practices. In this regard, the main tendency of the developing practices is to centralise information and push the reliance on cloud-based systems to share information between members and disciplines.

The heavy reliance on information and information exchange results in changes to the materiality of the design process (Oxman, 2006). Traditionally, the material used in the design process consists of drawings, models, and other elements that are used to communicate design ideas and build up the design object. In BIM and parametric design processes, the information is becoming the main material that can automatically generate the drawings and models.



Case 8 shows a highly effective way to conduct a seamless and automated flow of information, where the focus is on sharing just the necessary data and not whole files. This to replace the cumbersome process of sharing by email and changing the format, then changing it again and aggregating unnecessary data. Therefore, the platform that Case 8 developed can eliminate the impact of increasing file storage and the related limitations in the capacities of servers. Such an approach is rarely used in most of the practices within the firms in the case studies. However, while investigating the potential of parametric design and its benefits in the architectural design process, various examples were shown from different project scenarios that reveal how parametric design enables the data to act as ‘the new oil’ (The Economist, 2017) and as a ‘new material’ for designers (Oxman, 2006). For instance, in the Metro Station Façade project (Case 3), the data generated from the geometry created in Grasshopper was translated into a table containing information about the panels, including their sizes, prices and locations, within the whole façade. In the site topography example (Case 4), information about the coordinates of the different points in Grasshopper were translated into site geometry in Revit. Furthermore, E3 used Hummingbird in different projects, which enabled the data generated from Grasshopper to be translated into geometrical families in Revit. This shows how, within parametric design systems, data acts as the ‘raw material’ that can change from one form to another across different applications.

Within the same context, another interesting negotiation between E4 and E5 can be traced in Cases 4 and 5. E5 states that parametric design applications allow designers to add ‘Notes’ and hence, embed information within the parametric model to help in the documentation of the design, and to enable other participants with the relevant skills to further develop work. Nevertheless, a ‘Note’ can have a much more powerful impact and in this regard, E4 states that the ‘Note’ is used in Dynamo to add a script that helps to create a function or rule within the parametric model that might not be available in the visual platform of Dynamo. This specific feature in Dynamo and Grasshopper shows that the impact of such tools can be infinite, as designers can think of any idea or function, and translate this function into a scripting formula to push the limits of the software. From the previous discussion, the data included in ‘Note’ was translated to a system, which was the script. This shows another example of the potential for driving data in parametric design. Thus, rather than using data to generate static elements, such as geometry and table of costs, the data in this example was translated into a dynamic system that can push the limitations of the software applications in different contexts.

The previous three sections enhanced the collaboration, integration and information link established in Chapter 4, where collaboration is mainly based on the use of integrated platforms that rely on the automation of information and data amongst participants. Therefore, similar to the development of the framework, these three elements will be included in the framework as one single main node that consists of three sub-nodes. This node will be referred to as the ‘CIA’ node. In addition, the relationship that was established between collaboration and experiences, knowledge and technologies will also be depicted in the framework, as shown in Figure 19.

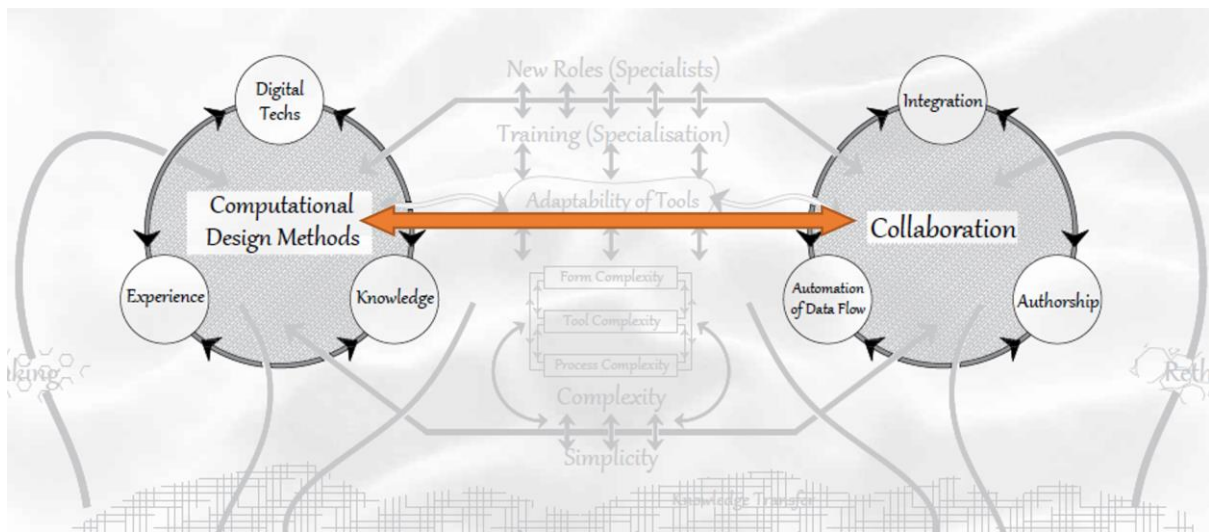


Figure 19: DEK and CIA Nodes

## 7.7 Adaptation of Digital Tools

The advances in digital technologies are not only resulting in developing smart and highly-effective tools, they are giving designers the capability of tweaking the tool or entirely building new tools to match specific design context (Burry, 2013). This capability is enabled through scripting (Wortmann & Tunçer, 2017) and parametric design tools (Tedeschi & Andreani, 2014) as discussed in the literature and the case studies. Where Mueller (2011) refers to tool design as one of the levels in a typical computational design process, the adaptability of tools were described in Chapter 3 as a paradigm shift in the design process. Tool design is a new level that is being added to the design process, allowing designer to develop the tool in parallel to the development of the design object (Whitehead et al. 2011), rather than using the same tools for each project.

### 7.7.1 Purposes for Tool Adaptation

Tweaking or designing tools is often required when the complexity of the design project goes beyond the capability of the existing tools. This was discussed in Case 2, where the uniqueness and the symbolic nature of the Pavilion project required developing an algorithm through scripting to design the complex shape of the pavilion. It was also discussed in Case 1, where the complexity and fluidity of the Airport form required the involvement of five software developers to tackle its complexity and to solve the interoperability issues. In Case 2, the role of a scripting specialist is essential in most of their projects as the complex and fluid design forms are part of the identity of the firm. For this reason they rely heavily on Maya Script. While Whitehead et al. (2011) argues that tools should be developed in parallel with the development of the design project itself. In this context, the projects discussed in Case 2 show the tendency of the firm to provide a simultaneous test of form complexity limits and tool capability limits in almost every design project.

Another example that shows the use of scripting to expand the limitations of software applications is shown in Case 4. In this case, intensive effort is spent on scripting and parametric modelling in order to adapt BIM software to automate the evaluation of building compliance to standards and regulations. This was revealed in the Football Stadium Seats project, which also shows the potential of scripting in accelerating the design process; E4 argues that generating the stadium seats out of the Dynamo script enabled them to save 90% of the time needed to achieve the same task using CAD. E4 also states that the capability of embedding building codes and standards information into scripting and parametric definitions is a result of independent research, which reveals another sort of purpose for using scripting, namely, scripting for research purposes. This shifts the discussion to the ‘researchers’ (R6 and R7), where scripting was used for the same purpose. For instance, R7 conducts some research where they use scripting to develop tools that are able to automate, and hence, accelerate some specific tasks within the design process. The potential of this research was highlighted in one of the projects, namely to clean up plans and views, copy them, create a new sheet and then put the plans and views on a new sheet. The script enabled the automation of the iterated process of applying those steps for 26 models; instead of repeating the same process 26 times, the steps were coded into the script that enabled the same steps to run automatically 26 times to achieve the task. This example also shows another example of how scripting is used for the purpose of accelerating some activities within the design process. Another example of the use of scripting for research purposes was discussed in Case 6, where

R6 conducted research to explore methods to use Dynamo in order to enhance compatibility between the design model and the product model, which is one of the main problems at the firm. This reveals another purpose for using scripting, which is to enhance interoperability amongst the different applications used in architectural projects. This same purpose was shown in the Airport project in Case 1, where enhancing interoperability between the wide variety of software applications used was the main task for the software development team.

Finally, in Case 8, the main purpose for the whole firm was to develop an online platform that contained various small size applications. These applications allowed for a direct link among different popular software applications to enhance interoperability, as discussed in the previous sections. The applications are developed through programming and scripting; in addition to the availability of several software developers at the firm, the platform enables the users themselves to build their software on top of the existing software on the platform.

### **7.7.2 Tool Adaptation and Firm's Advancement**

While the capability of designing tools using scripting is viewed as a new cognitive barrier for designers (Oxman, 2017b; Wortmann & Tunçer, 2017), the case studies show that tool design is a high level of digital literacy and mainly available in large and advanced practices, such as Case 1 and Case 2. Therefore, the case studies show the rarity of this kind of skill in semi-advanced and developing firms. For instance, a limited number of scripting specialists exist in Cases 3, 4 and 5, while only 2 specialists exist in each of Case 6 and Case 7 despite the larger size of those firms. On the contrary, in the advanced practices, scripting and programming is widely used due to the complexity of the projects they deal with and the wide availability of software developers and scripting specialists. In Case 2, scripting is often provided by members from the research group, where all members have coding skills. This is added to the availability of those skills within some architects in the design team. In Case 2, most of the design team members have this sort of skills. Meanwhile, Lawson (2011) argues that software used by architects is not developed by architects; nevertheless, the examples of scripting in these cases showed the significant involvement of architects in software development. Thus, although the software applications are not developed by architects, they are tweaked by architects for architectural purposes.

### **7.7.3 Parametric Design as Scripting**

An important aspect of parametric design is the tools used to enable parametric reasoning to solve design problems (Ercan & Elias-Ozkan, 2015; Janssen & Wee, 2011; Tedeschi &

Andreani, 2014)). The capability to automate the generation of several design possibilities is enabled through different sorts of scripting and programming including object-oriented programming, functional programming, and visual programming (Ceccato, 2010; Wortmann & Tunçer, 2017). However, the new parametric design tools that are currently emerging have a significant impact in their own right that can be differentiated from the impact of parametric design as a design methodology as emphasised earlier.

The cases studies showed the significant impact of scripting and programming in offering designer the capability to adapt the tool to match the specific needs of a design project. However, these needs face the cognitive barriers previously outlined. The participants were asked if parametric design can be used as alternative to programming and scripting. Only the Researchers and the Experts were able to see the blurring lines between parametric modelling and scripting, where the Competent Users could not see this link. Conversely, all the Researchers and the Experts used the term ‘visual scripting’ to refer to parametric modelling applications. They all consider a parametric model as a method of scripting using a visual platform.

Similarly to Tedeschi & Andreani (2014), E5 argues that parametric modelling tools have a great potential in making scripting accessible to a wider range of designers. More precisely, they state that parametric modelling enables ‘the non-computer-literate’ people to conduct scripting. They also argue that this potential enables designers to immerse themselves with technology by giving them the ability to adapt their own tools, and use them in their projects. In the terms of this research, using parametric design tools represents a way to remove one of the major cognitive barriers from designers (Wortmann & Tunçer, 2017) by giving them access to a new method to adapt their tools. This can be achieved by using an intuitive and friendly visual platform for scripting and programming (Janssen & Wee, 2011) without the need to learn the coding and symbols of traditional programming language (Wortmann & Tunçer, 2017). This is a feature that characterises the tool used in parametric design, and not parametric design itself.

This potential was shown in the different project scenarios explained by the experts in Cases 3, 4 and 5. These examples were referred to in the previous sections; however, they can be viewed from different perspective in this section. In fact, the parametric definitions used to generate the ‘Site Topography’, ‘Metro Station Façade’, ‘Circular Bridges’, ‘Chair’ and ‘Skyscraper’ are all examples of how parametric design applications can be used as design

tools: to generate site topography; to generate table of costs and associate it with the façade panels' geometry; to associate ducting systems to circular bridge geometry; and to integrate design, fabrication and assembly information for the chair and the skyscraper. This leads to the assertion that parametric design applications that enable the generation of those tools are not only smart tools that support design, but that they can actually be viewed as 'meta-tool'. i.e. tools to design the design tools.

#### **7.7.4 Levels of Adaptation**

Similar to the levels of collaborations discussed above, the cases studies reveal four levels in which tools are being adapted; design team level, enterprise level, external team level, and global level. At the design team level, the design team themselves have this kind of digital literacy that enables them to develop software applications to match their specific project needs, such as in Case 2, and in some few examples discussed in Cases 2, 3 and 4. At the enterprise level, developing tools is achieved by an internal research group, such as in Case 1, where the research group consists of a few members that have programming skills. Those members take the responsibility to develop software based on the specific needs of the design team members. This can also exemplified by the tools (the parametric definitions) developed by specialists in Case 2, which were separated from any project context so that they can be used in any future project. At the external team level, external specialist consultants develop software to fulfil the requirements of projects designed by other architectural practices. The global level in which tools can be adapted can be traced in Case 8, where the firm develops a wide range of software applications based on intensive communication with practitioners in the AEC industry from different parts of the world. This is added to their communication with popular software vendors. They provide bespoke software applications to allow specific functionalities based on specific requests from the practice. The global level of tool adaptation can also be traced within the same case to the potential for user involvement in the development of software applications provided by the firm. Furthermore, and regardless of the previous levels, scripting can be conducted within the context of a design project, such as the Pavilion and the Airport project, or independently as part of a research, as discussed above.

With regard to the framework, tool adaptation is highly related to the 'DEK' node as it is naturally made to adapt the technologies. In addition it requires specific experiences and knowledge. Moreover, the previous discussion shows the stable link between tool adaptation

and the CIA node, as it is related to all levels of collaboration. Therefore, 'Adaptability' will be presented within the framework as a connection between the DEK node and the CIA node due to its relation to both as shown in (figure 20).

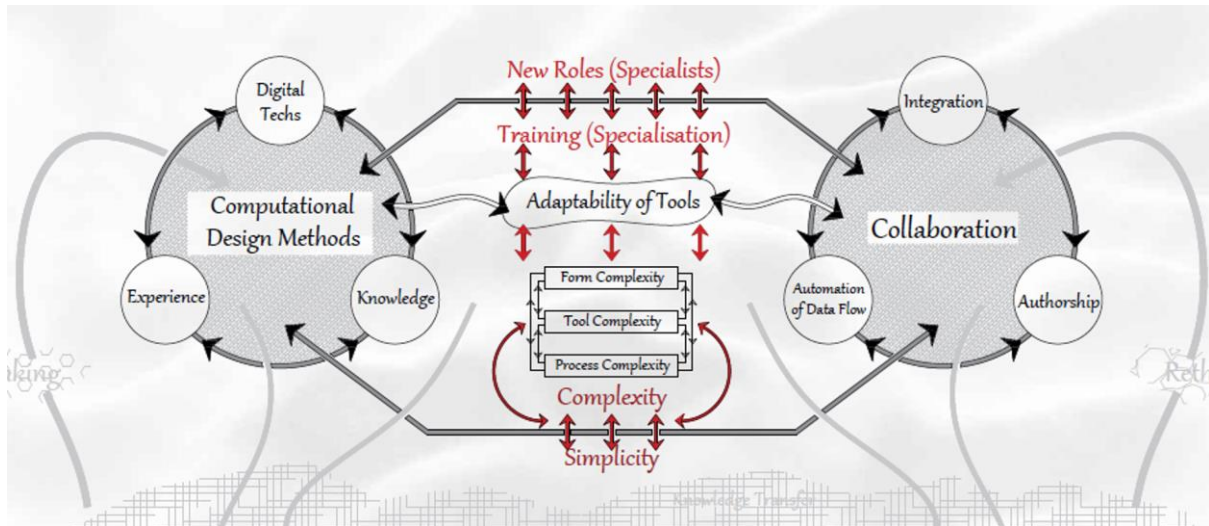


Figure 20: 'Tool Adaptation', 'Roles' and 'Complexity'

## 7.8 Roles

Due to the increasing complexity in the technologies being used in architectural practice and the multiplicity and different natures of those technologies, together with the new sort of methods and processes being developed, new roles are emerging in architectural practice to deal with this complex situation. While Cuff (1992) relies on observation for a wide range of architectural practices in USA in order to expound the social dimension of architectural practice and to identify the different roles that exist, the computational design literature reviewed in Chapter 4 shows that the increasing complexity in computational design processes has resulted in the emergence of new roles and new heterogeneous areas of specialisation within design teams (De Kestelier, 2013; Foster+Partners, 2013a), such as software developers, parametric designers, geometry specialists, sustainability specialists, BIM technicians, and 3D visualisers or scripters (Ceccato, 2010; De Kestelier, 2013; Hesselgren & Medjdoub, 2010; Katz, 2010; Whitehead et al., 2011). These can be described as unfamiliar roles in conventional design as none of the above roles was mentioned by Cuff (1992).

### **7.8.1 Roles and Firm's Advancement**

In the case studies, the roles that exist in the different cases were explored; this exploration enhanced the differentiation between the roles within the firms based on the level of advancement in digital technologies within each firm. For instance, the majority of the 'unfamiliar roles' were found in advanced firms (Cases 1 and 2), where several software developers and scripting specialists take major roles in different projects, as discussed in the previous section. This is added to geometry specialists, mathematicians and aerospace engineers, which are all roles from non-architectural backgrounds. In semi-advanced and developing firms, the situation is different, as most members of team are architects and engineers with a very limited number of scripting and parametric design specialists.

Nonetheless, the case studies show the 'unfamiliar roles' that exist in all practices regardless of the firm's advancement. For instance, all firms have researchers, although they differs in number and in their levels of influence. Thus, in advanced practices, whole research groups exist with researchers from different types of expertise and backgrounds who intensively intervene in most projects. In developing firms, the role of researchers are also essential as their decisions have a significant impact on practice, dictating the technologies that need to be purchased, the budgets that need to be allocated for these technologies, and the methods that are needed for application, as shown in Cases 6 and 7. However, the number of researchers is very low in developing and semi-advanced firms compared to the large number of researchers who exist in advanced firms.

Despite the novelty of the BIM specialist role, this appears to be essential in all cases, or there are, at least, persistent attempts to enhance the essentiality of the role of BIM specialists. In Case 1, the BIM team have recently started to get involved in all projects at the firm and take a leading role. In Case 3, the role of BIM specialists is increasing which is motivated by the firm's desire to enhance integration in their design projects. In Case 4, two BIM groups were established at the organisation and the project levels in order to implement BIM in some (recent) projects. This is similar to Case 7, where BIM also started to be implemented within some recent projects; this was based on designers with knowledge and experience in BIM. As for Case 6, a large budget is allocated with intensive supervision from the research group in order to achieve a rapid transition towards BIM implementation, where the re-consideration and re-allocation of roles is considered.



## **7.8.2 Roles and Contexts**

The literature shows a robust link between an individual's role and their knowledge and experience, which affects the power of those individuals and their eligibility to take decisions on behalf of the firm (Cuff, 1992). The literature also shows that architectural projects represent a 'temporary overlap of authority' and may result in rivalry for power within the project teams' (Emmitt, 2014, p. 46). In this regard, some situations in which the significance of power is affected is based on an individual's experience and knowledge, and on a specific context that relates to a specific project or situation at the firm. This echoes Cuff's (1992) project and organisation levels, and Emmitt's (2014) strategic and operational levels. On a project level, the importance of the architect's role can be affected by the nature of the project, which is exemplified in previous sections, where the mathematical knowledge of E4, and their profound experience in BIM and parametric design enabled them to adopt a major role in the stadium project. It was also exemplified in Case 1 where R1 argued that the importance of the role of the research project varies based on the nature of each project. This increases when the project is very complicated and requires an expansion in the functionality of the tools or the use of unfamiliar methods. The organisation or strategic level was shown in R6's essential role and the power they have gained through their formal position at the firm (Cuff, 1992). This importance stems from the firm's strategy that appreciates the role of research in developing the methods applied and the technologies used towards the full implementation of BIM.

## **7.8.3 Varieties in Allocation of Computational Design Roles**

The previous discussions showed the different roles that exist in the case studies, which are based on the advancement of digital technologies available in each form. They also show how the importance of the role are affected by project-related contexts as well as by organisational contexts. However, two aspects are still overlooked; the variations of those roles based on the policy of some specific practices, and the permanence and temporality of those roles.

### ***7.8.3.1 Supervision vs Equalisation***

With regard to the impact of an enterprise policy on the allocations of roles, two different and contradicting ways of allocating roles were investigated; the first relies on employing specialists with exceptional digital experiences and knowledge to supervise the design team, and the second relies on providing training to support the experience and knowledge within

design teams. For instance, due to the nature of Case 1's projects, they have a large internal research group that contains members who are experts in narrow areas of digital technologies and who support design teams in dealing with these technologies. Despite the availability of similar groups at Case 2, the situation is different as the design team members themselves are experts in a variety of software applications and scripting methods. This same comparison can also be applied to Case 4 and Case 7, whereby Case 4 relies on a team of BIM specialists to drive BIM-based projects, while at Case 7, the design team themselves have the relevant experience at various levels to drive this kind of process. This is due to the tendency of R7 to establish equality between design team members in collaborative work, rather than splitting people based on their experience level, as occurs at Case 1.

### ***7.8.3.2 Permanent vs temporal Roles***

In general, these differences shown in the previous discussion resonate with the question raised in Chapter 3 regarding the temporality and the permanence of those new roles, as they could disappear over time as specialists' experiences are injected into design team members, so that the designers themselves become able to deal with the technologies unaided. This was answered by R1, who explained how the focus in implementing parametric design is shifting from the reliance on parametric design specialists to the reliance on the parametric design experience amongst the design team members themselves. Similarly, many of the roles that are currently emerging in architectural practice might be temporal and might expire over time. The architectural practice is passing through a transitional era (De Rycke et al., 2018; Haidar, Underwood, & Coates, 2017; Kocaturk, 2017); resulting in the emergence of unfamiliar tools and inexperienced working methods. Such a situation requires special members that take the role to deal with the ambiguity in tools and processes. The main purpose of those roles is to fertilise those knowledge and experiences into different members within design teams. When this mission is accomplished, these roles may disappear. For instance, a BIM coordinator role (Holzer, 2015) may gradually disappear when members from design and construction teams get equipped with this sort of knowledge and experience, so that they will be able to perform the BIM coordination unaided. In this case, new roles may emerge to deal with the next generation of technology, where the same process will recur.

#### **7.8.4 Future Role of Architect**

The previous discussion regarding the shifts and changes of roles over time raises questions about the expected shifts and changes in the architect's role in future practice. This was investigated in the case studies through arguments provided by the researchers who explained their predictions with regard to the future role and within the rapid evolution of digital technologies and methods. While Jones (1992) and Lawson (2006) highlights the separation between designing and making caused by the reliance on drawing in design, R7 states that BIM is an opportunity for architects to regain 'the master builder' role. This addresses an issue raised in Case 6, where architects are concerned about the possibility of losing their role when BIM is fully implemented. While R6 refers to integration as key for success in future practice, R7 in this case refers to information as key. Therefore, they state that architects represent the genesis of information, as they control and define information from the start. They argue that the client has a need, and it is the architect who provides an answer in the form of BIM translated information. Thus, if architects proactively pursue that information, and identify the approaches to leverage the information, they will regain their essential role within the AEC industry.

While the roles of individuals in architectural practice are naturally connected to the specific knowledge and experiences of those individuals, the previous discussion illustrates the robust link between role and collaboration where the roles should be selected to work collaboratively in a coordinated and harmonious manner, in addition, some roles are dedicated to enhance collaboration and integration amongst individuals within the practice or within a project. Therefore, the 'roles' will be presented in the framework as a connection between the 'DEK' and the 'CIA' nodes (Figure 20).

### **7.9 Complexity**

The literature shows that the utilisation of digital technologies in architectural design is resulting in increasing complexity in the design processes (Oxman, 2006; Turrin et al., 2011). While such an argument lacks depth and specificity, the complexity was thoroughly discussed throughout the cases studies and the design experiments. Chapter 2 shows complexity as one of the main features of design (Chaszar & Joyce, 2016; Cross, 2011), which increases in practice due to the large number of voices involved in design decisions (Cuff, 1992). Chapter 3 shows the impact of different computational design methods on complexity in the design process. Meanwhile, a contradiction was revealed in Chapter 4

while discussing complexity in computational design processes; thus, BIM was seen as a method to automate the flow of information (McPortland, 2014; Sacks et al., 2011) in order to facilitate and synchronise the coordination amongst different interdisciplinary teams (Eynon, 2016). While coordination is viewed as the main aspect of complexity in architectural projects (Emmitt, 2014), the ability of BIM to facilitate this coordination should be seen as a way to simplify the design process. This also applies to parametric design due to its potential in simplifying the process by providing a direct link between the formation process steps and the final results (Harding & Shepherd, 2017) in order to automate and synchronise design changes (Jabi et al., 2017). This was challenged by other examples that show how complexity increases due to the involvement of different types of heterogeneous and conflicting knowledge at the conceptual design stage (Thomsen et al., 2015; Turrin et al., 2011). To eliminate this confusion, the following discussions address this contradiction by identifying three aspects of complexity and explaining how they affect each other.

### **7.9.1 Aspects of Complexity**

The literature and the case studies reveal three linked aspects of complexity, which involve the complexity of design form, the technologies and tools used, and the processes involved. Form complexity stems from the irregularity and curvilinearity of design forms that are designable and buildable (Kolarevic, 2004), and the differentiation amongst different parts of the design form (Jabi et al., 2017; Oxman, 2017b). In comparison, tool complexity stems from the additional knowledge and experiences needed to deal with these new tools (Oxman, 2017b), such as the programming knowledge needed for scripting (Wortmann & Tunçer, 2017), the tectonic knowledge needed to deal with BIM applications (Holzer, 2015), and the mathematical and algorithmic knowledge required to leverage parametric design applications (Aish & Hanna, 2017). Finally, process complexity stems from the increasing coordination required when the new methods are applied, such as BIM, when intensive coordination and information exchanges are required. The literature and the case studies show robust relationships among these three aspects of complexity. This requires a critical discussion to enhance the specificity in describing complexity in computational design.

#### ***7.9.1.1 Form complexity vs process complexity***

The complexity in the design process can be inherited from the complexity in the design form. This was discussed in Case 2, that shows how dealing with highly-complex forms require early involvement of structural engineers that are specialists in rationalising complex

geometry. The rationalisation in this case becomes a complete design stage that consists of several sub-stages, where structural engineers in collaboration with architects start to reduce arbitrary in the complex shape, analyse the form structurally, and then create different versions of the shape. In this case, a complex problem usually arises, where architects need to deal with the deviation of the rationalised form from the original design form. Furthermore, Cases 1, 2 as well as 4 show that complexity in the design process lies in its coordination, which becomes more significant when dealing with complicated, large size projects, and especially when working with participants from different disciplines. Another source of complexity in large and complicated projects, is the need to ensure software developers are involved in the design process, as the requirements in such projects usually exceed the capacity of existing software, and hence, require a scripting specialist to tackle geometry and resolve interoperability issues amongst applications, as shown in Cases 1 and 2.

#### ***7.9.1.2 Tool complexity vs process complexity***

The previous discussion addresses the relationship between form and process complexity. It explains how complex forms require complex processes. Those complex processes, in turn, require complex tools that provide the capability for users to deal with complexity in the design process. While process complexity mainly lies in the intensive coordination required in collaborative work (Emmitt, 2014), BIM technologies were utilised in all of the cases that automated this coordination. In this case, the BIM applications are the complex tools that are used to automated the coordination, and hence, to tackle complexity in the design process. This link can affect the decision about the applications required for specific projects. For instance, in Case 2, C2 explains the cumbersome process of coordinating design and construction processes on site that resulted in the manual taking of about 100 sections to secure the compatibility between the construction progress and the original design. For this reason, they started to use Digital Project, which enabled the development of a central model and from which all the required plans and sections could be automatically extracted.

This was another example to illustrate the potential of BIM software in facilitating coordination and hence the benefit of using a complex tool to simplify a complex process. The football Stadium project in Case 4 was another example that demonstrated how the cumbersome process of manually creating the stadium seats, while conducting complex calculations to secure compliance with building standards. This was replaced with a seamless and automated process in which E4 embedded the calculations and standards into the

Dynamo script to automate the generation of the seats. In this case, Dynamo is the complex tool that was utilised to simplify the complex process of stadium seat distribution. All of the previous examples show how tool complexity is inherited from process complexity, or in other words, complex processes require the utilisation of complex tools and technologies.

### *7.9.1.3 Tool complexity & form complexity*

With regard to form complexity, there is a misunderstanding about the source of this complexity in the literature, which shows that forms, that are originally simple, are becoming more complex in computational design. To clarify this misunderstanding, three zones of complexity in architectural forms can be identified; the simple zone, which includes simple forms, such as Euclidean forms; the complex zone, which includes complex and non-Euclidean forms; and the impossible zone, which includes forms that are extremely complex so that they are unbuildable. The misunderstanding lies in the delusion that complexity is coming from the complexification of simple forms. The truth is complexity is coming from the other side; from the simplification of the impossible forms to make them just complex. i.e. the increasing complexity of digital tools is resulting in shifting forms from the impossible zone into the complex zone. Just as recent as three decades ago, building forms like the Guggenheim Museum by Gehry technologies (Kolarevic, 2014) and the complex shape of the Pavilion shown in Case 1 were located in the impossible zone. It is the complexity, and hence, the efficiency of the digital technologies that is resulting in developing innovative methods to deal with such kind of forms and therefore, to shift them into the possible or the complex zone. Furthermore, this strong relationship between complex forms and complex tools can be traced to the consensus amongst all participants in the case studies regarding the fact that parametric design is the ideal tool to tackle geometric complexity in building design.

The ideal example to show how all three aspects of complexity and their mutual impact can be investigated, is the Airport project in Case 1. In that project, and due to the extreme complexity and fluidity of the design form, a team of software developers joined the design team throughout the design process in order to add new functions to the software applications used as well as enhancing interoperability among these applications. This scenario shows how the complexity of the technologies used was insufficient to tackle the form complexity of the airport. This required an increase in tool complexity by adding extra functionalities to enhance the effectiveness of the applications (the tools). In turn, this meant increasing

complexity in the design process where another level was added, namely tool design. Such an example shows how the mutual effect of all aspects of complexity can be revealed in one single example. It also shows the subtle link between ‘Complexity’ and ‘Tool Adaptation’ that should be represented in the framework (Figure 20).

### **7.9.2 Complexity for Simplicity**

The previous discussions identify the different aspects of complexity and reveal how those aspects relate to one another. In this case, a question can arise: what is the added value of complexity in design? This critical question can be answered through different readings of the previous scenarios. Cases 4 and 8 show that the purpose of increasing complexity in the technologies used, is to enhance effectiveness. This effectiveness is meant to simplify processes. In Case 8, the term ‘simplicity’ was introduced in order to raise the importance of concurrently investigating complexity and simplicity, where the complexity of technologies can result in simplifying processes, by offering a seamless flow of information across applications and disciplines in order to automate coordination.

As discussed earlier, the case studies reveal three aspects of complexity in architectural design; tool, process, and form complexity. The mutual effect of those different aspects on each other was investigated in the previous section, and resulted in the conclusion that simplicity is the main purpose for complexity. In fact, tools are growing in complexity in order to be more effective in simplifying the design process. For instance, parametric design applications are complex tools that are mainly utilised to simplify different aspects of the process by giving the capability to automate repetitive tasks as shown in the different project scenarios in the case studies. Similarly, BIM applications are very complex, however, this complexity enables the simplification of the intensive coordination required in a BIM process by enabling the automated and synchronised flow of information across disciplines and stages.

Within the design process, there are aspects that reveal complexity and other aspects that reveal simplicity. In general, the early design stages are becoming complex in order to simplify later stages. This relation is verified in all novel design approaches. For instance, in a performative design process, the main source of complexity is the intensive coordination needed in the early stages of the design process. According to Turrin et al (2011), within the conceptual design stage of a performative design process, designers need to coordinate work with different disciplines and to deal with a wide range of heterogeneous and conflicting

information to achieve early performative feedback. However, this complexity aims in simplifying later stages, where the early feedback will enable seamless workflows, with minimum amount of problems and interruptions as most of the problems are dealt with in the early stages. This same relation applies in any parametric design process. The Football Stadium seats in Case 4 shows that the complexity lies in the first stage, where the algorithm is built. This complexity results in simplifying the later stages, in which case, the simplicity lies in the automation and synchronicity in exploring different design possibilities and in achieving repetitive tasks.

### **7.9.3 Absorption Forces of Complexity**

The previous discussions show how complex processes are needed to deal with complex forms, and how complex digital tools are needed to deal with complex processes. This reveals the existence of absorption forces where complexity in one aspect of design is absorbed by another aspect, or where complexity in one design stage is absorbed by another stage. This results in increasing complexity in one design aspect or one design stage in favour of simplifying other aspects or other stages. For instance, in the different scenarios discussed in Case 2, form complexity was absorbed by process complexity, where additional activities and other teams were involved to rationalise, and hence, simplify the design form and make it buildable. In BIM-based design process, the complexity that stems from the increasing coordination required in design development and during the construction stages is absorbed by the conceptual design stage. Thus, the automated information flow in BIM applications enable architects and engineers to shift the coordination to the early stages, and hence, to eliminate most of the conflicts in later stages; as such, the later stages become more simple. Furthermore, in the Football Stadium seats scenario, the complex process of manually distributing seats and testing their compliance with standards and regulations in the later stages, in addition to considering the complexity of providing ticket prices based on the viewing quality at the operation stage, were absorbed in the early stage by providing a complex Dynamo script to automate, and hence, simplify the later stages. Therefore, understanding the aspects, the relationships, and the absorption forces of complexity are important at the outset as they affect the digital tools selection and the appropriate methods to deal more effectively with the different aspects of complexity.



### 7.9.4 Cure for Complexity

E5 explains how parametric design enables automation in the repetitive tasks within a design process. This is one way to reduce complexity, and in such cases, the designer will have more time to focus on their creative work as the machine takes care of the non-creative aspects, namely, repetitive tasks. The complexity in this case comes from a designer's lack of experience in spending most of their time experiencing the tool, rather than getting the use from it. In this regard, E5 argues that complexity is a matter of understanding, and that such challenges become simple when they are understood. This understanding, according to E4, can be gained when a designer has the right knowledge and experience to harness this novel design approach to produce creative work. Similarly, the designers in Case 7 attribute their struggle in dealing with the servers and network systems to the complexity of technologies, however, R7 is certain that when people understand how such technologies work, they will not seem that complex. These arguments suggest that the most effective way to reduce complexity is to increase knowledge and experience. This resonates with the previous discussion in Chapter 2 that discusses the ambiguity of design problem as one aspect of design complexity (Chaszar & Joyce, 2016; Jones, 1992). In this case, the ambiguity of these new technologies for the non-expert result in false feelings of complexity. More precisely, this feeling does not come from the complexity of technologies, but rather from the unfamiliarity of these technologies.

In general, the main cure for complexity is comprehension. Things remain complex until they are well absorbed and comprehended. This can be proved through many aspects in life. For instance, the alphabetical system is an extremely complex symbolical system. This system becomes simple when people understand it and experience it at an early age. The same could be applied for those new technologies. Similarly, R7 complains that designers in their firm find Revit complex; at the same time, they assure that designing a building is far more complex than mastering Revit. This again reveals that the issue is the familiarity of the digital technologies and not their complexity. Therefore, in architectural practice, simplification of processes and tools starts from the comprehension of different aspects of complexity. More precisely, practitioners need to determine the different aspects of complexity, and deal with these aspects by using the right tool and developing the right experience and knowledge. This requires developing strategies to improve experiences and knowledge in design teams. Such strategies will help in increasing the comprehension, and hence, making more effective use of digital technologies.

The previous discussion about having the right experience and knowledge to reduce complexity in digital technologies reveals the link between complexity and the 'DEK' node. Moreover, the strong relationship between complexity and coordination in collaborative and integrated work reveals the robust link between complexity and the 'CIA' node. Therefore, 'Complexity' is presented in the framework diagram as a dual-directional connect between the 'DEK' node and the 'CIA' node (figure 20).

## **7.10 Creativity**

Evaluating the impact of the 'digital' on the creative element of architecture is difficult. This is because the nature of this impact is subjective and unquantifiable, and thus open to a wide range of opinions from different people, including non-architects. This difficulty was revealed in Case 1, where R1 explained how they are undertaking research to develop scripts in order to enable automated structural and environmental optimisation. However, the visual and aesthetic optimisation remains unquantifiable, which supports the essential role of the human-designer who does not seem to be replaceable despite the availability of a wide range of technologies and experiences at the firm in Case 1. The literature reviewed in this research showed a high level of subjectivity when investigating the impact of the 'digital' on the creative aspect of design and the difficulty in identifying this impact. This same subjectivity was reflected in the case studies where contradicting and conflicting opinions were provided by the participants.

### **7.10.1 Creativity and Complexity**

The literature shows that the complexity in digitally driven processes represents a disadvantage for creativity (Bernal et al., 2015; Lawson, 2011). This is because designers in complex processes spend most of their time managing complexity, which shifts their focus away from their creative work. In this regard, C1 argues that the conceptual design can only be driven by providing freehand sketches and rough models. They also think that parametric design is too complicated for use in conceptual design where the main focus is on creativity. In this regard Bernal et al. (2015) appear to be supporting C1, in stating that sketching and freehand drawing offer freedom for designers in the early stages. In this context, freedom means eliminating the constraints caused by the reliance on complex digital technologies. In contrast, E3 ensures that parametric design enabled them to achieve creative work in the Facade Paneling System, by offering considerable ease and seamlessness in designing and manipulating differentiated and highly aesthetic panels. E5, in turn, states that parametric

design enables the automation of repetitive tasks, which can significantly reduce complexity, where the cumbersome and complex process of iterating same design activity is undertaken by the machine. This affords the designer more time and effort to focus on their creative work.

Therefore, the relationship between digital complexity and creativity in computational design can be seen from two different angles; from one angle, it can shift the designer's focus from creativity into managing complexity. From another angle, digital complexity can be used to eliminate complexity in the design process, such as automating repetitive and cumbersome tasks, which will enable designers to focus more on their creative work. In both cases, the discussion shows the strong relationship between complexity and creativity, which needs to be represented in the framework.

### **7.10.2 Creativity and the Compatibility between Digital Technologies and the Designer's Mind**

C1's emphasis on the importance of freeing up design from technology at the conceptual design stage and the unsuitability of parametric design at the early stages prompts a critical discussion on the compatibility between the specific technology used and the specific design activity, or design task, undertaken. This resonates the 'design as art vs design as science' debate (Plowright, 2014) highlighted in Chapter 2. It also echoes Jones's (1992) emphasis on recognising the difference between creative and technical activities in design. In this sense, C1 encourages the use of technologies in the late stage for rational activities, and emphasises the need to avoid disturbing concept design with technology, where most of the creative activities are conducted. C2 seems very aware of this compatibility, explaining that Maya is used in conceptual design due to its flexible and intuitive nature, and Rhino is used in the rationalisation due to its mathematical nature. In addition, the accuracy offered by AutoCAD makes it ideal for detailing and technical design.

While Lawson (2011) criticises the symbolic representations used in digital systems that cannot map with the symbolic representations in the designer's mind, this view is challenged in parametric design applications due to the ability of those tools to record the formation history of the design steps and to visualise this history in the form of a graph (Bernal et al., 2015; Harding & Shepherd, 2017). In this sense, C2 appears to agree with Lawson, stating that they were disappointed when working with parametric design applications as they expected novel design tools to be based on a design such application will support designers in

providing more creative work by allowing them to rely on their hands again, such as the case in sketching and freehand drawing. This means that C2 is urging technology developers to provide applications that are more compatible with the nature of creative activities in design. This issue can be attributed to the view raised by Lawson (2011) who argues that most software applications used by architects are not developed by architects.

This incompatibility appears to have an impact on the creative aspect and the aesthetic value of the design product. This was discussed by C2 who argued that relying heavily on computers results in a situation where designers become dictated by the tool, and hence, are limited to the software capabilities. They confirm that they can recognise a design form created, for example, in Maya from a form created by other software. They also think that the software application used dictates the choice of material. C2 claimed that, in many projects, they realised that the limited capability of Maya in tackling the tiling in brick material resulting in changes to the choice of material (namely, metals for cladding). This situation, according to C2, shows the negative impact of software on the creativity of design solutions where the software limitations in this situation prevented designers to benefit from the aesthetic value of brickwork.

This discussion highlights the significance of traditional design methods, especially in the early design stages where most of the creative activities are conducted. This importance stems from the limitations of current digital technologies. However, the importance of traditional methods vary based on the nature of the design project. For instance, the iconic nature of the Pavilion project required the use of algorithms to generate the complex form of the Pavilion. However, in other projects, the reliance on sketching and drawing is still essential, even in advanced firms.

### **7.10.3 Creativity and ‘Knowledge and Experience’**

While C2 argues that designers rely heavily on technology are limited to software capabilities, they appear to completely disagree with R7, who states that employees in their firm see the technological environment as a constraint because they are limited to their capabilities. With this statement, R7 places blame on the technology user, rather than on technology itself. They state that the lack of designer experience and knowledge restricts the effective use of these technologies to support creative work. Similarly, E4 asserts that creativity can be achieved in parametric processes when a designer has the right knowledge,

the right skills and the right techniques. This type of knowledge can enable a designer to harness novel approaches and tools to achieve creative design solutions.

The relationship between creativity and ‘experience and knowledge’ can be traced in the case studies through the conflicting arguments provided by the different participants who attempted to address this. The case studies show how this contradiction results from the variation of different participants’ knowledge and experience in parametric design. Researchers acknowledged that they were unable to see this relationship due to the limited use of parametric design in their firms. However, the Competent Users in cases 1 and 2 view parametric design as a tool that limits creativity in design, especially in its early stages, while the Experts in cases 3, 4 and 5 show different examples to demonstrate the potential of parametric design in supporting creativity, such as the Metro Station Facade and the Skyscraper project. According to E5, an architect’s creativity enables them to use any tool to support creativity in their designs. In general, the juxtaposition of these conflicting arguments and the difference in the experience and knowledge of the participants indicates that parametric design can constrain creativity when the designer does not have the right knowledge to use the related tool. In such cases, they can end up struggling to solve tool issues rather than the actual design problem. Therefore, it is necessary to have the right knowledge and sufficient experience for a designer to harness parametric design and support creativity.

#### **7.10.4 Creativity and Abstraction**

E5 states that in the design process a building does not begin as such, but instead starts as an idea, concept, sketch, or form. Later, as the design develops, these concepts and sketches start to evolve, and slowly change into a building. Subsequently, when the designers and other participants start to provide the details, the building changes into shapes, profiles and quantity take-offs, until eventually it starts to become a building again when construction starts. As the BIM software applications deal with a real building throughout the different stages of the design and construction processes, they do not respect the architect’s understanding of the building evolution throughout the design stages. In contrast, parametric modelling software tackles buildings in a way that is consistent with an architect’s concept; thus, in a parametric model the building starts as a concept, script, or graph, until it becomes a real building.

E5’s previous explanation can be linked to the abstraction reduction process noted in the literature. The literature shows a wide range of modelling techniques and methods that are

applied in the current architectural practice, while each type of model represents a specific level of abstraction (Kocaturk & Kevinimi, 2013; Whitehead et al, 2011). This link between model type and abstraction level inspires the definition of the design process as an abstraction reduction process. According to Whitehead et al. (2011, p. 244), a model is “a representation of an idea that externalises a thought process”, while Klassen, 2002 in Veliz, Kocaturk, Medjdoub, and Balbo (2012, p. 272) defines a model as “a representation of a conscious simplification of reality filtered and determined by cultural and individual backgrounds which necessarily conceives a systematic understanding of the reality and a set of reductional constrains”. These reductional constrains constitute the level of abstraction in design model. This level varies based on the design stage. In fact, the design process starts by providing models with a high level of abstraction, and then start to gradually reduce this level of abstraction when the problems, solutions and situations start to crystallise gradually. At the end of the design process, designers provide a final model or as-to-be-built model that have the lowest level of abstraction. In this regard, relying on BIM applications in the early design process changes this abstraction reduction process, as BIM imposes a low level of abstractions from the early stage of the design, where walls are walls and doors are doors, unlike sketching, where designer has the freedom to use any way they prefer to represent the different elements in the design object. According to Oxford Dictionaries (n.d), abstraction is the freedom from representational qualities in art. BIM forces a low level of abstraction and a high level of accuracy in the initial stages of the design process, whereby, in sketching, design has the freedom to play with the limits of abstraction and creates sketches from different levels of abstractions and accuracy, which seems to be essential in creative reasoning. This same issue can be viewed from another perspective. In a previous discussion, the compatibility between the nature of the technology used and the creative nature of design activities was criticised by Lawson (2011), and this was echoed by C1 and C2. This same incompatibility can be traced in E5’s previous argument where the use of BIM forces the image of a real building at the conceptual design stage, where the designer’s mind is generally more interested in recalling the images of events and abstract shapes from their memory or imagination. From this basis, the ‘graph’ in parametric design applications appears to be more compatible with the creative thinking of designers.

#### **7.10.5 False Feeling of Maturity**

Despite the ease, seamlessness and flexibility of the new computational design methods and the impact on design creativity reported by different authors in the literature and participants

in the case studies, a contrasting opinion is provided by Marion et al. (2012, cited in Kocaturk, 2013, p. 24) who identified a paradoxical problem caused by the fluidity offered by digital design throughout all phases of the design process. They claim that unless this fluidity is well-understood, managed and coordinated, the use of the digital tools may provide a ‘false sense of security’, which may result in a premature move to the next stage before sufficient maturity in the design solution is achieved. A lack of maturity in design solutions can refer to different aspects of the design, which may include creativity. This is a critical point that E5 would agree with; thus, BIM can offer an example of the case raised by Marion. Thus, the high level of accuracy that BIM offers in the early design stage may result in a false feeling of completion where the designer may shift the design to the following stage, while in reality the design needs more improvements and further maturation to achieve a creative design solution.

Therefore, when using highly-advanced digital technologies in architectural practice, practitioners need to observe the results on the creative aspect of the design object. This helps to identify the aspects and situations where traditional methods need to be maintained to avoid shifting the focus from creativity.

The previous discussion on how creativity can be achieved when designers have the right knowledge and experience to deal with technology, shows the strong relationship between creativity and the ‘DEK’ node. Meanwhile, the discussion concerning the limited creativity of BIM applications shows the link between creativity and the ‘CIA’ node. Consequently, ‘Creativity’ needs to be presented in the framework diagram as a connection between the ‘DEK’ node and the ‘CIA’ node.

## **7.11 Research in Architectural Practice**

The literature and the advanced and developing practice cases showed the significance of research in developing the tools and methods applied in practice. In fact, all the rapid changes and challenges that are discussed in the chapter can be addressed through research that can be undertaken within the practice. This type of research is referred to as practice-embedded research in Booshan (2017), while Still (2007, cited in Booshan, 2017) states that dealing with highly advanced digital technologies blurs the lines between research and practice.

### 7.11.1 Types of Research in Practice

Different types of 'practice-embedded research' (Booshan, 2017) are shown in the case studies, where a strong relationship was found between each research type and the advancement of 'digital' in each case. In the advanced firms, (Cases 1 and 2), large internal research groups exist that undertake research within the firms. The groups contain a number of members with an exceptional level of digital literacy. The main focus of these groups is to keep up-to-date with cutting-edge digital technologies in order to inform their design projects. In Case 1, the research group has a direct relationship with the design team as they act as supervisors to support designers with their digital experience and knowledge. Thus, the level of their involvement is determined by the nature of each project, mainly its complexity. This type of research appears to require a high budget as it requires the employment of different participants with exceptional skills.

In semi-advanced practices, some members of the design team occasionally join the research group to conduct research and employ the outcomes of the research in projects. The research can be focussed on a specific area, such as sustainability and green buildings. This type shows flexibility where designers are free to undertake research whenever needed; therefore, based on specific requirements, they can manage their time between research and design in accordance with the availability and commitment for different tasks.

In developing practice, research is critical and its value is highly appreciated where firms tend to rapidly develop the technologies they use and the methods they apply, which gives researchers the authority to undertake major decisions on behalf of the firm. In this regard, a very interesting model of research was explored in Case 6 where research relied on collaboration between practice-based and academic research groups. In this type of research, an internal research group is formed within the firm to conduct research under the supervision of an academic group. In this case, R6 acts as the leader of the internal group and at the same time as a member of the academic research group. This type of research is very cost-effective, as it relies on the mutual benefit for practice and academia, and avoids the need to hire a research group that can be expensive. More precisely, this research method relies on collaboration between academic and practical groups, where the practical group benefits from the broad knowledge offered by the academic group, and the academic group uses practice as a case study in order to explore the research context.



### 7.11.2 Purposes for Research

The case study participants outlined different purposes for which research is undertaken in practice. The first purpose can be referred to as ‘research for innovation’, where intensive research is conducted in an attempt to push the limits of possibility in terms of form and tool. This was found solely in the advanced firms (Cases 1 and 2). Both advanced firms are provided with in-house research groups that carry out independent and project-based research. The members of the research groups have exceptional digital experience and knowledge that operate on the organisation level by exploring cutting edge technology through internal research and by collaborating with other research groups, academic institutions and large software vendors. They also operate on the project level by directly supervising the design team and providing support for designers within different projects.

The second purpose for practical research can be identified as ‘research for development’, where research is undertaken to develop the experiences and knowledge of practitioners within firms. An ideal example for this research is shown in Case 6, where an internal research group is formed to lead the transition towards the BIM implementation at their firm. Another interesting example was discussed in Case 7, where R7 observed the design team and tried to capture the problems that recur within different design processes in order to search the different digital tools and methods to find a way to automate this recurrent problem. This was shown in the infrastructure project where the iterated process of cleaning up and copying plans, creating new sheets and placing plans on the sheets was automated in Dynamo script that was able to automatically iterate the same steps for 26 models. This can also be termed ‘research for acceleration’ as it aims to automate iterative task in order to save time. In fact, E4 stated that the main purpose of their research is to ensure future projects run faster. They gave an example where some specialists spend most of their time developing Revit families that, again, will help in accelerating future projects. Within the same case, E4 states that they have an architect in their firm who currently spends most of their time researching sustainability and green buildings. This research can also be classified under ‘research for development’ where the aim is to develop the energy efficiency of buildings designed by the firm.

In general, the main purpose of research is to allow ‘Knowledge Transfer’ across projects. This can occur on a project level, where knowledge are acquired from a project can inform later projects (Whitehead et al., 2011). Alternatively, it can occur on a practice level, where

research is undertaken to excavate from practice and analyse precedent projects in order to extract cognitive models that are communicable and applicable for different situations (Booshan, 2017). This is very similar to the situation in Case 4, where the research is undertaken on the organisation level and separated from project contexts. The research aims to treat previous projects as case studies in order to identify frequent problems and develop patterns or methods to solve those problems.

The previous discussions show how research in architectural practice relates to all aspects of design. For instance, the main purpose of research is to explore different technologies and to apply these technologies in design projects while at the same time developing knowledge and experiences amongst members of the design team. Furthermore, research in practice relies heavily on collaboration and, as shown in the previous discussion, it relates to all levels of collaboration. Therefore, it could be argued that all aspects of design in architectural practice can be developed and innovated through research, which is shown in the framework diagram (Figure 22).

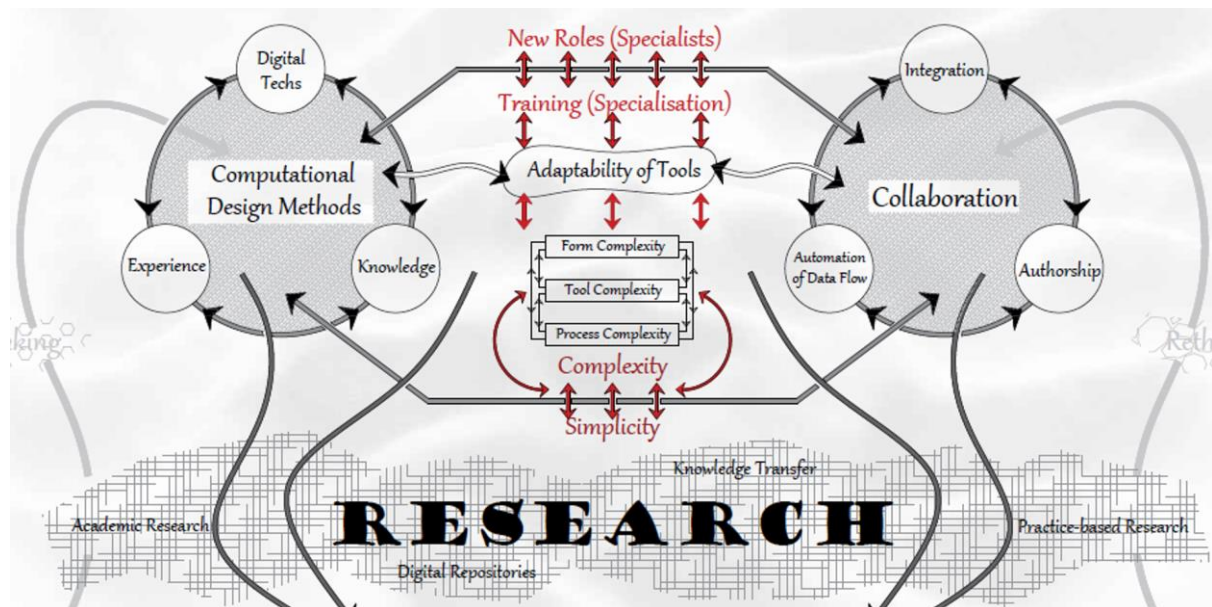


Figure 22: Research

## 7.12 Processes in Computational Design

The rapid evolution of digital technologies and computational design methods; the resulting shifts in design experience and knowledge; the shifts towards collaborative, integrated and data-rich design platforms; the increasing capability of tool adaptation; the emergence of new roles; challenges in design complexity and design creativity, and the increasing need for

practical research, are all aspects that are resulting in a series of paradigm shifts in the architectural design process. Therefore, the architectural theorists need to understand those paradigm shifts and how they challenge the definitions of conventional design in order to write a mature design theory capable of maturely and comprehensively describing the new phenomena in architectural design.

### **7.12.1 Paradigm Shifts in Computational Design Processes**

The paradigm shifts in the architectural design process were addressed in the literature review chapters and based on the juxtaposition of conventional design stages and methods and different computational design methods. These shifts were exemplified through various project scenarios in the case studies.

Therefore, the paradigm shift caused by scripting lies in the ability to tweak the design tool or to design the tool rather than use a traditional tool to support design activities. In other words, scripting enables a designer to adapt the tool to match the specific design activities rather than to shape the design activities to much the existing tools. This capability is seen as a new level in the design process (Mueller, 2011), where, prior to designing a building or in parallel to designing a building, designers can design the tool with which the building is designed. This was exemplified in different scenarios, such as the Pavilion and the Airport projects in Case 1 and the Football Stadium project scenario. In addition, it was exemplified in the Stadium project where the Dynamo script developed by E4 was seen as a tool that could be used for any project requiring seats to be located on different levels. In this case, Dynamo represents a meta-tool or a tool to design the design tools.

In algorithmic design, where the focus is on developing an algorithm from which the design form can be generated (Oxman, 2017b), the paradigm shift lies in using an algorithm that acts as a mediator between the designer and the design form. While Aish and Hanna (2017) use the term 'direct manipulation' to refer to the way in which design is conducted, using an algorithm to design forms can be referred to as 'indirect manipulation' where the design form is remotely manipulated by using algorithm. The impact of this paradigm shift can be traced to the Metro Station Facade scenario. E3 explained how designers using algorithms to design differential panels have to sacrifice control over each of the individual panels in favour of the capability to automate the generation, modification alternation and evaluation of the panels through the simple manipulation of the algorithm.

In performative design, where the focus is on shifting performative feedback into the conceptual design stage (Turrin et al., 2011), the paradigm shift lies in the migration of some activities (i.e. structural and environmental performance feedback) into the early stages of the design process. This is added to the inclusion of non-architectural activities in the core of the design process where the conceptual design stage becomes inundated with heterogeneous (Turrin et al., 2011) and conflicting information (Thomsen et al., 2015). This was shown in the Skyscraper example in Case 5 as well as in the Panelling System example in Case 3 where structural engineering information was integrated into the parametric model created by the designer.

When using BIM, different paradigm shifts in the design process can be identified. Firstly, using BIM applications enables the creation of a central model from which all 2D drawings (plans, sections, elevations, connection details, etc.) can be extracted automatically from the central model at any time throughout the design process,. This avoids the reliance on a wide range of drawings to describe design, as in conventional design. In this case, the paradigm shift lies in moving the main design activity (drawing) from the human designer to a machine. i.e. shifting from 'design by drawing' (Jones, 1992; Lawson, 2006) to 'design by intelligent modelling' (Kocaturk & Codinhoto, 2013).

Secondly, the central model that can be created with BIM can be associated with different types of information. This association enables the synchronisation between the building geometry and the information, where any change in the geometry results in an automated and real-time update of the associated information. While the design process relies on iterated loops of generation, synthesis and evaluation (Bernal et al., 2015; Lawson, 2006), the synthesis and evaluation are totally automated. Meanwhile, the synthesis is automated through the use of a central model where any change can result in the automated corrections of all views. Moreover, the evaluation is automated through the associated geometry and information where a designer can modify the geometry and directly evaluate the results by observing the resulting changes in the associated information.

The third paradigm shift is similar to that of performative design as it lies in incorporating the interdisciplinary into the core of the design process in addition to the migration of the affirmative feedback (evaluation) into the earlier stages of the design process.

### **7.12.2 Interactive and Designable Processes**

The digital technologies are enabling designers to interact with the very process (Oxman 2006). For instance, in a typical parametric design process, a designer develop an algorithm that can generate forms with various possibilities. This algorithm consists of specific steps, relations, and rules that can work in different design scenarios. Therefore, an algorithm represents an automated process created by the design, i.e. in parametric design, a designer can design the process itself in parallel to the design of the whole building, in which case, the activities, stages and sequences in the design process are becoming undefinable, as they are determined within the design process and may vary from one project to another.

Prior to the development of design concept in a conventional design project, designer looks at precedent buildings that are similar to the current project to gain inspiration in term of the possible form, structure and style. In parametric design, a designer may explore precedent processes in the form of algorithms or parametric definitions to gain inspiration about how current project will be approached. This situation was exemplified in the parametric design case in chapter 6, where the designer of the football stadium explored parametric definitions for the seating area of the stadium instead of just exploring precedent stadiums as complete projects. The same situation was exemplified in the cellular form design experiment, where the designer started to explore cellular shapes, extracted their components, and then started to explore parametric definitions that can enable the creatipn of such kind of forms. In this case, designer may start sketching the process itself rather than just sketching the building form as part of the thinking process in the conceptual design stage. In that, they might start sketching the parametric definitions and draw components and connections that represents the rules, which will later inform the parametric reasoning that will generate the design form. Therefore, rather than classifying styles in architecture, theorists may start identifying and classifying process styles.

### **7.12.3 Transparent Processes**

The literature shows how the parametric schema in parametric design applications make the processes explicit (Oxman, 2017; Jabi et al, 2017), which gives more opportunity for different participants in a design project to get involved in the process (Harding & Shepherd, 2017), and hence support collaborative work. In fact, this feature in parametric design applications can also be seen as a way to illustrate the process to allow internal dialogue inside designer's mind. The parametric schema is an illustration for the algorithm that

includes the logic and the rules that the generation of the design form is driven by. Therefore, this feature enables design to juxtapose their current state of mind to the whole history of the thinking process, which enables a mature evaluation of all the design decisions, while the associativity in parametric systems, gives the capability of changing any of those decisions and get the final result updated in the real time.

In order to capture the zeitgeist of the current digital age in developing innovative design strategies, the architectural practice needs to treat the design process as a creative piece of work in its own right. Just like the design object, the design process can be tweaked, designed, recycled, and explored as precedent work.

#### **7.12.4 Sustainable processes**

While supporting sustainability is currently becoming the main criterion in evaluating the quality of design (Thomsen et al., 2015), the literature and the case study reveal three levels in which parametric design supports sustainability in an architectural design project. The first level stems from the large capacity of the design space accessible with parametric design, and the resulting quantity of design solutions that can be obtained. In comparison to the limited number of design variations that can be generated and tracked in conventional methods (Chaszar & Joyce, 2016), and the late stage in which performative feedback is provided (Mueller, 2011) together with the resulting difficulty in using the feedback to inform changes in design form (Anton & Tănase, 2016), parametric design offers designers the ability to associate parameters to automate changes from the early stages of the design process. This enables designers to explore a much wider range of design variations in an automated manner, and to evaluate these variations against their environmental performance in the real time. Therefore, more sustainable and environmentally friendly design solutions can emerge out of this vastness of design solutions.

The second level stems from the level of form complexity tractable with parametric design, and the resulted environmental quality of design solutions that can be obtained. In comparison to the poor editing environments in CAD systems (Jabi et al., 2017), the fragile link between the genotype and the phenotype (Harding & Shepherd, 2017), and the resulting inflexibility in form generation (Aish & Hanna, 2017), parametric design enables a direct link between the design form and its formation history where any change in the initial steps results in direct update of the final form. This offers designers ease and seamlessness in exploring, generating and evaluating more complex forms and differentiated geometries, to

then harness this complexity and differentiation in improving the environmental performance of the resulted building.

The third level stems from the associativity, automation and synchronicity offered by parametric design and the resulting acceleration in the design process that can be gained. In comparison to the inflexibility in CAD systems (Aish & Hanna, 2017) that often results in a complete re-run of the form generation process in order to manage changes (Harding & Shepherd, 2017), the associative parameters in parametric design enable automated generation and evaluation of design form, where the final form and the initial steps of the form generation are synchronised. This enables a substantial acceleration in the design process as shown in Case 4, where Dynamo enabled automated layout of the seats in the football stadium together with the automated evaluation of the compliance of the layout to the existing standards while maintaining accuracy and efficiency. The layout was configured in a very short time in comparison to the cumbersome and time consuming process needed to provide the same layout and evaluation manually in CAD. This acceleration can be enhanced by the ability of parametric design applications together with the new existing plug-ins in integrating structural analysis, environmental performance, fabrication information and other criteria into parametric definitions. This was exemplified in Case 3 where using Grasshopper and other plug-ins enabled automated generation of differentiated panels for the metro station façade together with the schedule in Excel that contained information about dimensions and shape of each panel for the fabrication team and prices for quantity surveyors. This shows the substantial time saving resulting from using parametric design to automate the coordination of information among disciplines. Therefore, parametric design not only offers access to a wider design space and more complex and differentiated geometries to facilitate the production of sustainable and energy-efficient design solutions, but also enables a significant acceleration of the design process. This could potentially give designers the opportunity to reduce working hours and save time and effort, and hence save energy within the design process.

All three levels explain how parametric design is becoming the cornerstone in performative modelling systems (Oxman, 2006) prioritising the environmental performance of buildings when making design decisions. All the previous three aspects show that parametrically-driven design processes are truly sustainable processes.

### 7.12.5 Recyclable processes

The recyclability of the design process enabled by parametric design applications originates from three points. The first point stems from the fact that the development of the graph/parametric definition is an integral part of the design process (Harding et al., 2012; Oxman, 2017b), where designers add, remove and associate nodes to form a parametric definition within the graph space in order to generate, edit and evaluate geometry in the modelling space (Jabi et al., 2017).

The second point stems from the ability of parametric design applications to objectify the design process, where the design process represented in a graph becomes an object that can be visualised, designed, edited and interacted with. The graph in this case acts as a record for the history of design development (Harding & Shepherd, 2017), which allows designers to juxtapose their current state of mind to the whole history of the thinking process, whereby, mature evaluation of the design decisions can be obtained throughout the design process.

The third level stems from the ability to reuse the parametric graph across projects. This possibility was demonstrated in all the case studies through the consensus among participants about the reusability of parametric definitions across different projects. It was also exemplified in Case 3 through the stadium project, where the designer used a pre-created parametric definition and successfully embedded it into their current stadium project.

The previous three points show how parametrically-driven design processes are recyclable processes that can be reused in different projects with no limitations. This will enable architects to rethink recyclability in building design. Rather than recycling elements of building structures after the demolition of buildings to reduce waste, with parametric design applications, architects can recycle elements in the design process for the same purpose. The difference is that, in the second case, the design process can be recycled an infinite number of times, which is physically impossible in the first case.

With regard to knowledge transfer and the ability to reuse knowledge, experiences and methods across projects, the recyclable processes appears to be a more efficient method to support this tendency. It enables the transfer of whole processes in the form of a parametric graph that hosts different sorts of knowledge and experiences, in addition to the algorithmic logic that underpins the design concept and development in previous projects. Therefore, at the outset of a design process, where designers explore previous projects to gain inspiration



about how the building could look, with parametric design tools, designers can explore precedent processes encapsulated in parametric definitions to gain inspiration about how a current project can be approached, and how the form can be generated.

Since recyclability of materials and elements is one of the essential elements of sustainability, recyclable processes are important aspects of sustainable processes, and can, therefore, represent the fourth level in which parametric design supports sustainability. This can be seen as a way to further accelerate the design process; in the first stadium project discussed in the Case 4, the designers developed a parametric definition to accelerate the design process, while in Case 3, the designer reused a pre-built parametric definition and embedded it into the current project. Thereby, the designer in the second case has accelerated the process that is already accelerated, resulting in ‘meta-acceleration’ of the design process.

As the paradigm shifts in the design processes are the result of all the previous phenomena in computational design, these paradigm shifts and the resulting processes are placed at the bottom of the framework diagram with arrows that show those results (Figure 23).

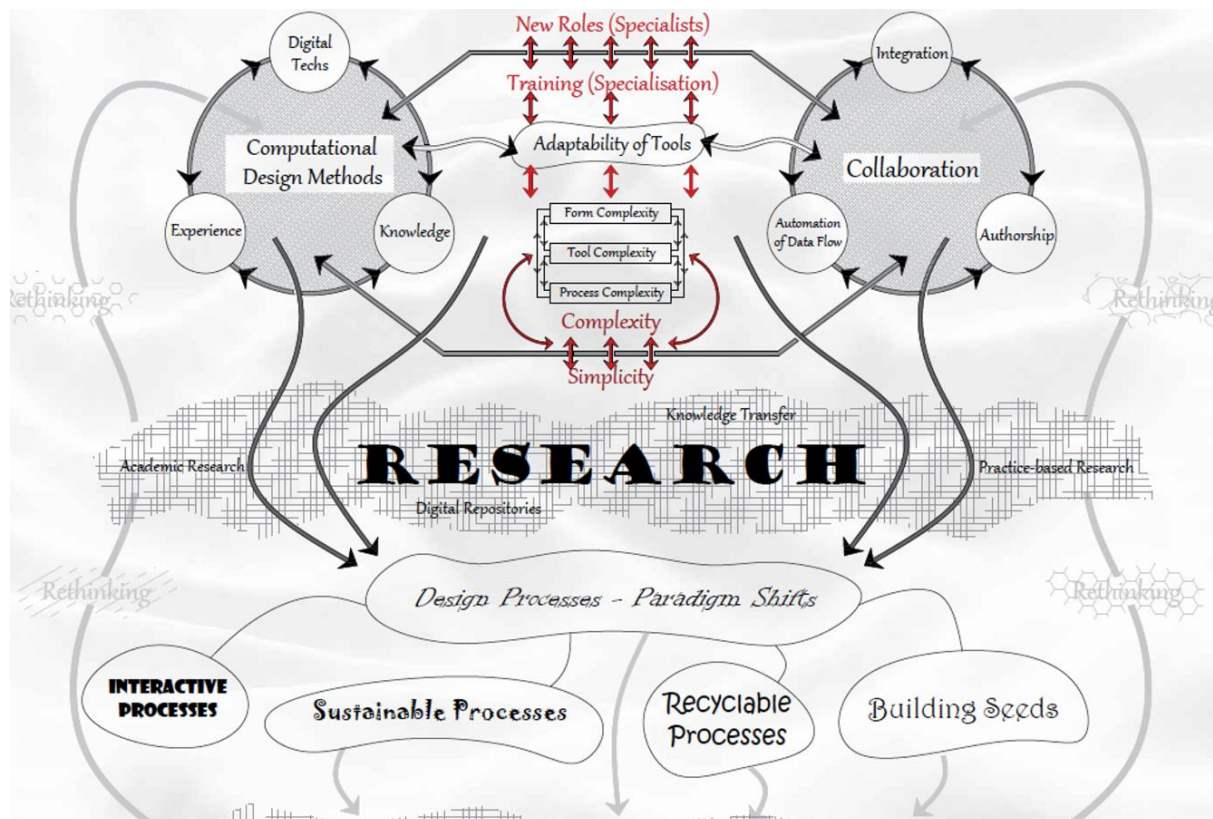


Figure 23: Processes in Computational Design

## **7.13 Building Seeds**

The building seeds were discussed in the literature based on Calile's (2014) speech in KeenCon2014, when she argued that architects needed to learn from the software industry, as software developers build software on top of each other's work rather than starting every project from scratch, as is the case in architectural practice. From this basis, she urges architects to shift their focus to design building seeds that are able to generate different buildings rather than designing single building.

### **7.13.1 Methods to Generate Building Seeds**

The building seeds were exemplified through different examples from real projects shown in the case studies, which shows three different ways in which building seeds are designed; the first is based on extracting the seed in the form of Dynamo script from a current project for use in a later project, as shown in the Football Stadium Seats project in Case 4. The second is based on extracting the seed from a project developed by others, as shown in the Football Stadium Competition project in Case 3, where the seed was found online and incorporated into the current stadium project to automatically generate the seats. The third takes place on the organisation level by designing building seeds separately from the project context. This was shown in Case 2, where parametric design specialists provide a Grasshopper definition to automate particular functions in later projects.

### **7.13.2 Building Seeds and Parametric Design**

At first glance, the concept of building seeds appears very similar to the concept of recyclable processes as they both relate, in this paper, to the reusability of parametric definitions across projects. However, there is an essential difference that gives 'seeding' significant merits over 'recycling'. In the staircase example, discussed in Case 3, the parametric definition that was developed to generate the staircase in a previous project was not only reused and hence recycled in the stadium project, it has, in fact, automatically adapted its height and number of steps to match the heights in the new project. Even the shape of the staircase was automatically changed to enable the stairs to go around the curved skin of the stadium. The result was a totally different staircase that was generated out of the same parametric definition. Therefore, similarly to the way the same seed can generate different trees based on the site it is planted in (Carlile, 2014), the same parametric definition can generate different design forms based on the project they are embedded in.

The recyclable processes are not limited to parametric design environments. Any algorithm or script that can be reused in different projects is an example of the recyclable process even if it does not support parametric functions. Nonetheless, when it comes to building seeds that can adapt for new projects, it is only the power of associative parameters that can permit this adaptation as demonstrated in the staircase example. Therefore, the seeding approach is enabled solely by parametric design.

### **7.14 Rethinking Innovation**

The building seed concept urges the promotion of the mindset towards strategic thinking that can be based on the development of innovative strategies in architectural design. Emmitt (2014) divides the design manager's task into two levels; the operational level and the strategic level while emphasising the need to operate between these two levels by acquiring knowledge from design projects on the operational level to use knowledge in different projects on the strategic level. Similarly, Cuff (1992) separates the tasks of different individuals in an architectural practice into the project and organisation level, while Weisz (2018) urges architects to adopt a 'system thinking' rather than a 'project thinking' approach to support sustainability in building design and thus respond to climatic challenges (Snell, 2018). Therefore, innovation emerges from the harmonious development of the current design problem and the design strategy or design system. In this case, designers can first explore the system already developed through the accumulation of knowledge and experiences in previous works in order to extract patterns that can be used to solve current design problems. It is then possible to embed these patterns into a current project, and later on, the final results can be fed back into the system in order to inform later projects. While this strategy is already shown in the different case studies, the value of the building seeds lies in the way in which knowledge and experiences are encapsulated in building seeds. Therefore, rather than relying on memory to recall previous experiences, or relying on precedent narrative knowledge or precedent models, the seeds exist in the form of algorithms and parametric definitions that represent pieces of processes that can be embedded into the current design process to automate some specific tasks and activities.

In such cases, the design process emerges from a combination of the various seeds used to automate some design tasks, and the traditional tasks that are driven manually using traditional methods. This capability is enabled through the associative parameters in the building seeds that enable them to automatically adapt and contextualise themselves within

different projects, as revealed in the previous section. Consequently, in the case of the building seeds, the design process can be outlined in three stages; in the first stage, architects navigate different sources including precedent projects, different algorithms and parametric definitions. These are provided locally or by others in order to find the potential seeds that can support a specific design project by facilitating, automating or accelerating specific tasks. In the second stage, designers embed the different seeds into existing project to inform the design process, while in the third stage, the new seeds that were generated in an existing project or that were adopted from previous projects and further developed in existing projects are saved for re-use in later projects.

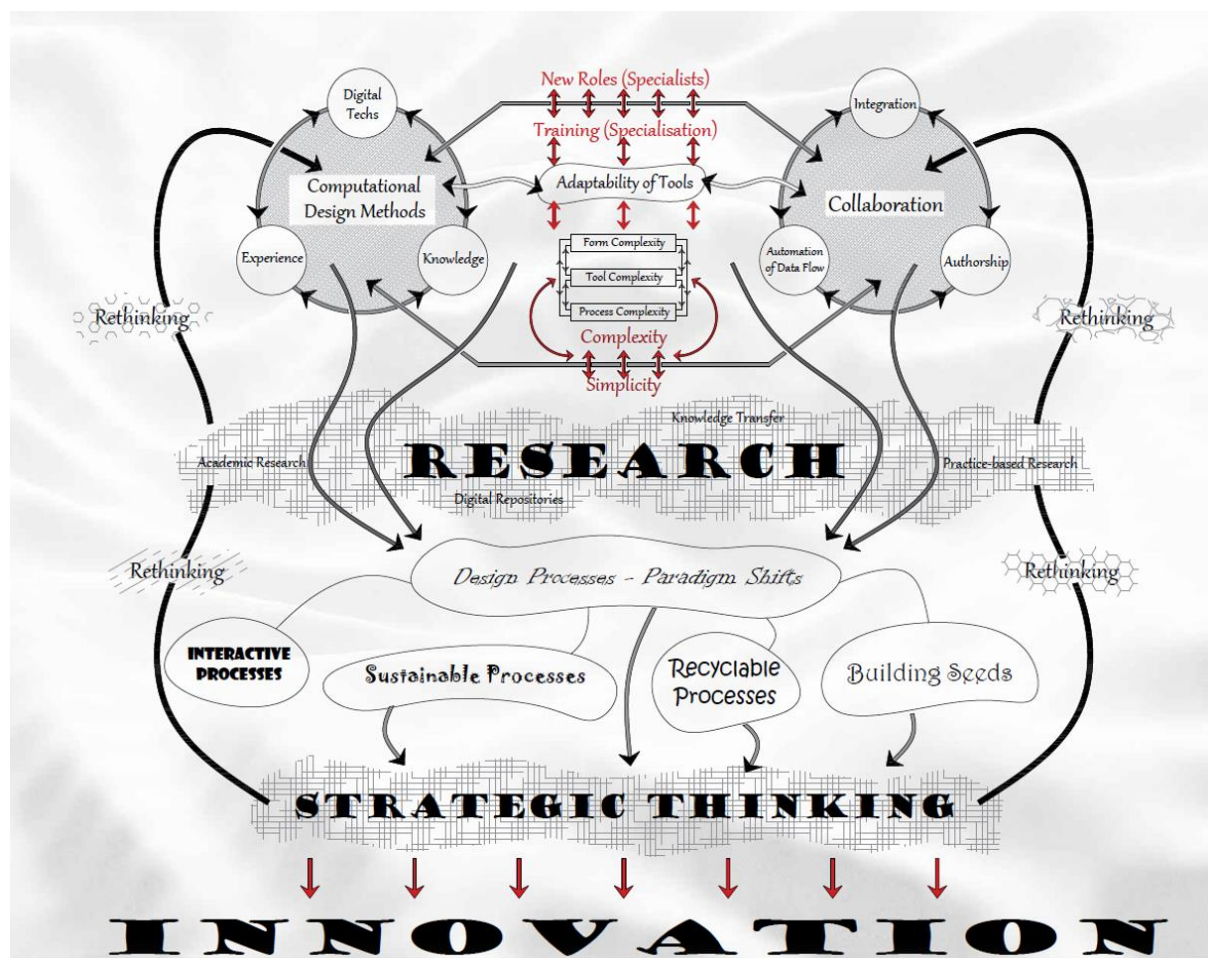


Figure 24: A Theoretical Framework for Innovative Design Strategies

This allows for more flexibility and automation in developing new design strategies by offering a robust link between the project level and the strategic level. This link prompts the strategic thinking of architects. Thus, in each design activity and task, they can rethink the technologies and design methods needed, the knowledge and experiences and collaborative methods required, the limits of form complexity tractable, and the type of research required to

developing more mature, flexible and digitally-driven innovative strategies in architectural design. This method of thinking is represented as recursion arrows as shown in the final framework diagram (figure 24).

### **7.15 Chapter Summary**

This chapter relied on the cross-section analysis to discuss the final findings from all the cases in relation to the literature review. At the same time, the chapter shows how the final theoretical framework is developed. The framework identified the criteria for selecting the right digital technology for the right purpose. These criteria are based on the nature of this technology and its consistency with the project nature and the design stage in which it is used, in addition to its maturity and compatibility with other technologies used. Moreover, the framework showed how the selection of technology can be affected by the budget of the firm and the general environment in the firm's area, and highlighted the essentiality of the traditional methods and the ability to use those traditional methods in tandem with the advanced technologies available.

The framework revealed the robust link between the digital technologies and the experience and knowledge available and highlighted the problems in integrated work caused by the contradiction in mindsets and the imbalance in experiences and knowledge. Furthermore, through different examples from the case studies, the framework explained how the experience and knowledge of architects in practice can help them to gain power, and how this power can be affected by the general environment of the firm in addition to explaining different methods in which the digital experience and knowledge can be developed.

The framework explained different problems in collaborative work and analysed different project scenarios in the case studies to reveal the potential of parametric design in supporting collaboration. Therefore, the framework identified four levels of collaboration, highlighted the importance of the global level of collaboration, and revealed the potential of this level in enabling innovation and enhancing the efficiency of the 'digital' in design. Furthermore, the framework showed how the traditional methods of sharing files and information are still widely applied in all cases and identified several problems that architects encounter in integrated work in addition to analysing different project scenarios to show the role of parametric design in supporting integration and the difficulty of achieving digital continuity in the design process especially in large and complex projects. In addition, the way in which data can act as a raw material was thoroughly explained through different parametric design

scenarios. Those scenarios demonstrated that parametric design applications can be considered highly effective BIM tools that can go beyond the capability of the popular BIM applications by integrating new types of information.

The framework also showed different purposes for which software applications are adopted and the context in which this adoption is needed in addition to the role of parametric design in adapting digital tools by acting as a meta-tool. Furthermore, the framework discussed the emergent roles in practice based on the firm advancement and project context. It showed verities in allocating those emergent roles and expected the changes and shifts in those roles in the future.

Based on arguments from both the case studies and the literature review, the framework identified three aspects of complexity (form, process and tool complexity) and relied on projects scenarios from the case studies to reveal the relation among those aspects and identify the absorption forces of complexity in the design process. Additionally, the framework investigated the impact of the ‘digital’ on design creativity and how this creativity is affected by different aspects of complexity, the architects’ experience and knowledge and compatibility between the nature of the technology and designer’s mind. Besides, the framework analysed and differentiated the potential impact of BIM and parametric design on design creativity in relation to the levels of abstraction in the different design stages.

Furthermore, different types of practical research derived from the case studies were explained together with the purpose for each type of research. The framework then summarises the paradigm shifts in the architectural design process caused by the different computational design methods, and explained how the design process can be accelerated in different ways. Therefore, it revealed new understanding for sustainability by introducing the terms ‘sustainable processes’ and ‘recycling processes’ and investigating the role of parametric design in supporting this type of processes. In addition, the appropriateness of parametric design in enabling the implementation of the ‘building seed’ concept was demonstrated and exemplified from various project scenarios from the case studies.

The framework concludes by urging architects to adopt the strategic thinking and shift their mindset towards simultaneous development of design projects and design systems where architects consult the system, develop their design projects and use the results of the current project to feed the system.

# CHAPTER EIGHT

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## 8 Introduction of the Wiki Seed Library as an Innovative Design Strategy

### 8.1 Introduction

The availability of a wide range of digital technologies and computational design methods in architecture together with the minimal use of those technologies and methods in practice highlights the need to reflect on the theoretical framework developed in the previous chapter by placing it within a potential practical context. Therefore, this chapter shifts from the development of a theoretical framework for innovative design strategies, to developing an innovative design strategy. This will give the opportunity to test the theoretical framework by using it to evaluate the potential impact of this innovative strategy.

For this reason, the chapter will introduce the Wiki Seed Library (WSL), which represents an example of an innovative strategy. Therefore, the chapter will discuss different approaches to enhance the efficiency of this seed library, and demonstrate the applicability of the theoretical framework through the potential impact of the Wiki Seed Library to practice and theory through the framework.

### 8.2 The seed library

Before introducing the Wiki Seed Library and evaluating its potential based on the theoretical framework, it is necessary to discuss the ability to develop a local seed library on an organisational level. In this respect, the case studies showed two different ways in which building seeds can be generated in practice, the first way is to extract seeds from previous projects, just like the way the parametric definition of the staircase was extracted from a previous project in Case 4, and the way the parametric definition of the football stadium seats was imported from the internet in the same Case. The second is to create seeds from scratch independently to feed future design processes, which was discussed in the Case 2 where specialists in parametric design develop parametric definitions outside of any project context for possible future use. In both cases, the focus on developing seeds will enable an architectural practice to accumulate building seeds gained from different projects. Therefore,

this practice will be able to develop a ‘seed library’, that can be an essential source at the outset of every design project, where designers start to explore precedent seeds that can be reused to accelerate and automate different aspects of the design process of new projects. In this regard, different examples were discussed in the case studies, such as ‘Script Bank’ in Case 7 where designers develop a library that contains different scripts and parametric definitions for future reuse.

### **8.3 Introduction to the Wiki Seed Library (WSL)**

This seed library may be more effective if it is shared online and open to the general public to view, use, and edit. This is where the Wiki Seed Library can be established, so that, instead of developing the seed library based on a handful of members in internal teams, a much wider range of participants from all over the world would contribute to the development of building seeds. They might develop their own seeds on top of existing seeds and share them again for other designers to develop them further, and hence they will come up with smarter and more efficient seeds. This development strategy does not represent a new way of thinking, in fact, it is very similar to the way in which interactive websites in Web 2.0, such as Wikipedia and YouTube, develop their content based on contribution from the whole world resulting in much larger and more reliable content as discussed in Chapter 4. Similarly, enhancing this tendency in architectural practice will result in smarter and more intelligent design methods and solutions. A building seed that is generated from a specific project will not only be reused in other projects, it will be tweaked, edited, and developed further and therefore, it will grow smarter every time it is reused. Similar to the machine learning approach, the seed will keep learning from the knowledge contained in every project, while sharing the library online, will enable the seed to learn from a much wider range of knowledge generated from all over the world. This will enable practitioners to rethink collaboration, and therefore, to go beyond the limits of their practice and collaborate with a wider range of practitioners. Rather than relying on distributed intelligence in design (Kocatürk & Medjdoub, 2011) on a project or an enterprise level to achieve innovation, they can rely on global distributed intelligence.

#### **8.3.1 Validation of seeds in WSL**

An important issue may arise at this point concerning the validity of seeds contained in the library. The same problem can be found in social websites. In Wikipedia, for example, the information and articles are often provided by non-specialists, which requires a critical validation before the information is put into use in research or any other work. Similarly, the



seeds in the library might not be trusted especially when the developers of the seeds are anonymous. In fact, a variety of algorithms and parametric definitions are available on different websites including the Grasshopper website. Most of these libraries are random and contain defragmented and non-validated content. E3 stated that before using the pre-built parametric definition for the stadium project they needed to validate that the rules created in this definition were consistent with the standards and regulations of a football stadium. E4 created a Dynamo script from scratch that included the rules and regulations of a football stadium and used this definition in the stadium project. Such a validated script, together with other scripts and parametric definitions represent validated seeds that are needed to be shared online, and hence, to be available for all practices. Therefore, rather than providing standards and regulations in the form of texts and tables of numeric values, standards can be provided in the form of scripts or parametric definitions that need to be accessible by all architectural practices. This will enable other designers to develop the definitions further. For example, they may enhance the flexibility of the stadium definition so that a user can click on the country that corresponds to the location of the project, and the equations in the definition will be adapted automatically to match the standards and regulations of that particular country. As a result, the cumbersome process of testing manually the compliance of the different structures and materials with the local building codes and standards, can be replaced by an automated process that is based on using validated parametric definitions and scripts to achieve the same test.

In general, the building seeds that are scattered everywhere on the web need to be organised, categorised, and validated, and then included within central libraries that need to be provided with smart search engines. Similarly to the way in which online search engines have considerably facilitated research, the same type of search engine will facilitate the design process by automating different design activities and accelerating the pace of the work. In addition, it will allow architectural practices to develop their design projects on top of the work of other practices, rather than reinventing the wheel for each and every single project.

### **8.3.2 Motivation for Participation in the Development of WSL**

Another important question that may arise is how to motivate highly professional specialists in computational design to share their parametric definitions, algorithms and scripts online for public use? More precisely, how does one convince E4 who developed the Dynamo definition for the stadium to share this valuable and validated seed online for others to use

and edit? Similarly, how to convince E3 who downloaded the pre-built parametric definition of the football stadium and validated it, to upload this validated definition back for others to develop further? This is where the complicated and problematic issues of authorship, ownership and copyright arise (Fok & Picon, 2016).

One of the main methods that can motivate a wider contribution to the seed library is to allow participants to sell their seeds, which will require a reliable evaluation, and hence, fair pricing. For this purpose, the library should benefit from the way some commercial, academic and social media websites operate, thereby it should allow interactivity, where participants can comment, reply and provide star rating. They can also report on the effective use of a specific seed and upload images or videos to show how this particular seed worked. In addition, the system can allow the seeds to be peer-reviewed by giving more value to the feedback provided by highly-specialist users. This will enable the system of the library to evaluate the value of this seed based on the collective rating, number of interactions and number of downloads. Even when the seed is offered for free, the author of the seed would gain points based on those same statistics. This would help this author to build a reputation that can help investment in building seeds in the long term. This point system appears to be similar to the impact factor that some websites provide to evaluate academic journals. Therefore, the smart seeds that gain popularity among library users can give credits not only to their authors, but to the author's enterprise or institution. In addition to motivating authors, different ideas can help in motivating feedback and interactivity. For example, a user can gain points based on the intensiveness of their interactivity. Those points might give those users a premium account that will give accessibility to a wider range of seeds that might not be accessible with a basic account. The system can also benefit from the 'granular data structure' (Michalatos, 2016) that will enable the system to capture every single contribution when an algorithm is collectively built by several authors, and therefore, will be able to save versions of each seed while reserving the authorship of each contributor. Furthermore, similarly to Turnitin, the system can be provided with a function that can capture plagiarism or to evaluate the level of similarity with other scripts or other parametric definitions. It can also enable auto-referencing to be embedded into parametric definitions as a note component. This kind of system will motivate a wider contribution to the building seed library to increase its richness and efficiency. This is also how designers can start thinking of selling design methodologies, rather than traditional architectural services (Bernstein, 2016). In general,

selling methodologies and design processes, rather than buildings is a wide cultural shift that requires some time for practitioners to absorb and appreciate its potential.

## **8.4 The Wiki Seed Library and the Theoretical Framework**

Having introduced the Wiki Seed Library (WSL), explored different approaches and ideas to enhance the validity of the library seeds, and examined the motivation to contribute amongst expert computation design specialists, this section will investigate the future potential of the WSL based on the theoretical framework developed in the previous chapter.

### **8.4.1 WSL and DEK: Digital Technologies and Methods, Experience, and Knowledge**

The seed library will enable architects to see successful and failed scenarios that will enlighten their design decisions in different design projects, such as enabling greater maturity by selecting technologies that are more suitable to the specific design project nature and that match the existing experiences and knowledge available within design team members operating in the process.

The WSL will provide a rich source of algorithms, scripts, and parametric definitions that will host a vast amount of knowledge and experience encapsulated in seeds. These seeds will enable a shift of knowledge and the development of the skillset required to deal with new technologies and methods. In fact, the development of the WSL represents a collective creation of knowledge and development of experiences on a global level that will help the users of the WSL to develop their own knowledge and experiences. This is enhanced through the nature of the parametric definition that not only can be contextualised into different design situations, but can also illustrate the history of the development of a parametric definition (Aish & Hanna, 2017). This will enable the designer to understand the algorithmic logic behind the parametric definition and to develop the capability to manually edit this algorithm to match the aesthetic and performative requirement of the current design project using the library.

The case studies showed the significant difficulty in providing training and developing skills in practice due to the continuous commitment of architects in practice to different project tasks and deadlines. The WSL, in this case, will offer architects the opportunity to learn scripting, algorithmic design and parametric design through the context of a real project. This is also enabled through the transparency and editability of parametric definitions.

The possible increased reliance on the WSL in architectural design will result in the increasing popularity of computational design. In fact, the library will help a wider range of architects to recognise the true potential of new computational design methods. For instance, they will start to understand the real scope of parametric design and its potential in automating, synchronising, and accelerating different tasks in the design process.

The increasing reliance on seeds will have a significant impact on digital technologies in general. A lot of scrips and parametric definitions will be developed on top of existing software. This could add to the iterated regeneration and re-evaluation process of other seeds on top of the existing seeds, and will not only result in the emergence of highly mature and effective seeds, but also enable a radical grow of software applications when designers and scripters from all over the world augment the functionality of such applications. It could also enhance the interoperability between the different software applications. Therefore, the few existing software developers who develop software solutions, as in Case 2, could be replaced by a wide range of participants from different cultures, backgrounds and views who can work from a distance to help developing more effective, more efficient and smarter technologies to enhance the efficiency of digital technologies in architectural design.

#### **8.4.2 WSL and CIA (Collaboration, Integration, and Automation of Data Flow)**

The development of seeds in WSL could be based on collaboration from all over the world. In that sense, it is an ideal example of the global level of collaboration discussed in the previous chapter. Furthermore, the WSL itself can represent a global, integrated platform for designers to share, transfer and exchange information, comments, and replies. They can offer opinions, give feedback and conduct assessments. This is added to the collective development of designs and system solutions. In fact, the WSL could support collaboration on all levels, as identified in the previous chapter; on the design team level, the WSL can contain algorithms and parametric definitions for the different members of a design team to collectively exchange and develop seeds until a design solution starts to develop. This could be challenged by the current limitations of parametric design applications that, until now, do not allow for different users to simultaneously manipulate a parametric definition. However, the global contribution of specialist users to the development of the seeds in a WSL would offer an opportunity to resolve this problem over time.

On the organisational and industry levels of collaboration (identified in the previous chapter), where the focus is on collaborating with internal or external engineering or MEP consultants,

the WSL could be open to non-architects, where, for example, engineers can develop their seeds on top of existing architectural seeds. This gives an opportunity to develop interdisciplinary seeds to support integration and facilitate coordination amongst participants from different disciplines.

In addition, the WSL will disseminate the understanding of the real potential of data amongst architects on a global level. The WSL is an ideal example to show the potential for data to act as a raw material. While the data was changed into geometry in the Site Topography scenario, and translated from Geometry in Grasshopper into a table of panels in the Metro Station Facade scenario, the data in WSL can generate dynamic systems with associative, parametric principles that enable systems to automatically adapt, fit and contextualise data into different situations.

The nature of the WSL platform and its similarity to the social media website, will enable architects to apply the granular model concept (Michalatos, 2016) so that each single contribution to the development of seeds can be saved in order to fully secure their copyright, authorship and ownership. This could be added to the potential to automatically capture plagiarism and provide a report of similarity, such as the case in Turnitin system.

#### **8.4.3 WSL and Tool Adaptation**

As discussed in the previous chapter, a node-based parametric design application, such as Grasshopper, is not only a tool to generate algorithms that, in turn, can generate design forms. In fact, each of these algorithms can be seen as a tool in its own right; this tool can automate a specific sort of task within different projects. This makes Grasshopper a meta-tool that can be used to design different tools. From this basis, a WSL could disseminate the skills required to ‘design a design tool’ on a global scale, by offering a vast array of tools, with feedback and assessment opportunities from a large number of participants. Alongside the ability to view, explore, and locally adapt the tools, this will result in the development of smarter and more mature tools to promote the continuous development of more efficient design tools in architecture.

#### **8.4.4 WSL and Roles**

The WSL might result in the emergence of new roles in architectural practice. For instance, a ‘seed miner’ may be required whose task is to dive into the WSL by exploring, searching, and chatting and interacting with others in order to find suitable seeds that represent potential

design solutions. Therefore, a seed miner needs to be part of the design team that understands the design solutions as well as the practice policy. Just like a design manager (Emmitt, 2014), the seed miner can operate on a project or on an organisational level. On a project level they need to understand the project requirements in order to search for precedent solutions, precedent systems or precedent processes that can be encapsulated in building seeds to inform design decisions in projects. On the organisational level, the seed miner can work on developing a local seed library that can be derived, extracted from, connected to or associated with the WSL. Therefore, the WSL can be reduced to a local seed library that is synchronised to WSL, so that only the seeds that correspond to the nature of the practice or the nature of the projects will be contained in the local library. In this case, the same question regarding the permanence or the temporality of the new roles, can be asked of the ‘seed minor’ role. Thus, the role can be temporary; for example, they may fertilise experience by dealing with the WSL within design team until the members of the design team themselves have the relative experience that enables them to efficiently navigate the WSL unaided.

#### **8.4.5 WSL and Complexity**

The WSL could potentially reduce complexity in different ways. Chapter 2 and the different case studies showed different aspects from which complexity stems. Thus, where complexity in design stems from the ambiguity of a design problem (Chaszar & Joyce, 2016), the ambiguity of the knowledge and experiences needed to design (Lawson, 2011; Plowright, 2014), and the lack of information in the early stages alongside the resulting difficulty in predicting future design (Jones, 1992), the WSL will offer a vast array of pre-made and automated design solutions. On the one hand, these could reduce ambiguity in the design process due the ease and seamlessness in exploring a large number of similar problems alongside their solutions over a short period of time. The library could also reduce ambiguity in knowledge and experiences by offering seeds that represent blocks of knowledge whilst also providing the ability to gain particular knowledge from chatting and interacting with other library users in order to gain insight into how a problem can be solved and what specific seeds are more appropriate for adoption. With regard to the lack of information and the difficulty of predicting future, the library could naturally inherit parametric design features so that the associated seed parametrics could enable the testing of possibilities within the seeds and the direct observation of future results.

The case studies showed how tool complexity stems from the knowledge and experiences needed to leverage technologies and to change them into efficient design tools. This is enabled by a variety of parametric design definitions that, by nature, show the seed and its formation history. It could also enable ‘chatting’ so that any question or issue that may arise can be solved by posting a question and sharing a designer seed. It would then be possible to wait for someone with the relevant experience to offer an appropriate answer or to take the algorithm or parametric definition, in order to update it, and re-post it. Alternatively, they could even post their own algorithm or definition that could be generated from previous design projects or experiments. All of these cases are happening already on the Grasshopper website; however, with seeds validated, categorised and arranged in a WSL, alongside a smart search engine and experts who are motivated in diverse ways, the collaboration required to resolve complexity in a WSL could be more efficient.

#### **8.4.6 WSL and Creativity**

The potential for a WSL to support design creativity lies in the vastness of the library and the inclusion of an infinite number of seeds combined with a smart search engine that makes it easy to find appropriate solutions. This would enable designers to reduce the time needed for incubation (Jones, 1992), while the large number of solutions that could be reviewed would increase the opportunities to generate design ideas, and hence, accelerate the ‘leap of insight’ (Jones, 1992). This would result in a radical increase in the comprehension of the problem, which would naturally change complex design problems into simple ones (Jones, 1992). In addition, while parametric design offers designer the capability to automate cumbersome and complex tasks, the WSL could inflate this capability by providing the opportunity to explore different scenarios made by the library users where a range of repetitive tasks are automated in different contexts.

#### **8.4.7 WSL and Research**

The literature review showed the significance of research in practice, which is motivated by the novelty of the digital technologies available and a minimal reliance on these technologies despite their potential. Nonetheless, the case studies showed the high cost of professional research groups comprised of expert and knowledgeable researchers. From this basis, the WSL appears to be an affordable solution for highly effective research. This affordability was discussed in the context of motivating professional computational design experts to contribute to the development of seeds within the library,. Therefore, rather than only relying

on pricing and offering the ability to sell seeds, different approaches were suggested to motivate contributions to the WSL, such as a feedback and star ratings, a points system, and authorship protection. All these systems and approaches were inspired by different industries, such as commercial online websites, social media websites, and academic journals.

The case studies showed that research could rely on the conduct of design experiments based on scripting and parametric modelling. In this case, the WSL would offer a wide range of algorithms and parametric design definitions that are based on experiments made by other users worldwide. In this case, rather than building scripts and parametric definitions from scratch, a researcher would have the choice to partially or entirely adopt an experiment encapsulated in a seed and build on top of it for greater efficiency.

Furthermore, the case studies illustrated how research could be conducted by studying precedent projects where each project or each design situation is treated as a case study to inform potential similar situations in future projects. The WSL would also offer this potential where the seeds could be developed either through a separate design experiment or within the context of a real project. Therefore, each of these seeds represents a case study for a precedent design experiment or a precedent project, which is enhanced by the nature of the parametric definitions, where the seed development process can be read and interacted with through the parametric graph.

The case studies demonstrated that all of the firms use digital repositories where precedent projects are saved on a server for design members to use either as projects or as different elements. In addition, participants in the case studies have already developing libraries for parametric definitions and algorithms for potential future use. The WSL, in this case, represents a valuable and affordable source of knowledge encapsulated in a plethora of seeds, where the variety and vastness of these seeds is beyond the limits of any local server.

#### **8.4.8 WSL and Processes**

In the stadium project in Case 4, the process of manually creating the seats was accelerated through the development of an algorithm to automatically generate the seats. In the Stadium project in Case 3, adopting a pre-created algorithm and embedding it into the project accelerated the process of manually creating the algorithm. From the perspective of the first scenario (manually generating seats), this can be seen as a meta-acceleration of the process. From this basis, the availability of a plethora of reliable and validated algorithms and



parametric definitions alongside a smart search engine, could accelerate the identification of an algorithm, which adds an additional level of acceleration to the design process. This acceleration could further reduce the working hours required, and hence, save energy by enabling more sustainable processes.

The WSL could enhance the process objectification concept, where each seed could be seen as part of a process of achieving a task, such as generating a stair or seat distribution. In this case the design process could emerge through the accumulation of contextualised and harmonious seeds, where the seeds can either be downloaded and embedded into the current process, or connected to other seeds so that the connected seeds can be read directly from their original sources. This would enhance the recyclability of the design process (discussed in the previous chapter) so that it relies on recycling different pieces of a process and embeds them into a current process.

#### **8.4.9 WSL and Innovation**

The previous chapter showed how the building seed concept promotes a strategic thinking mindset that is based on in the development of innovative strategies in architectural design. It also discusses how innovation emerges from the harmonious development of a current design project and a design strategy or design system. The WSL urges the promotion of strategic thinking at a higher level, namely the meta-strategic level. In this case, innovation in architectural design emerges from the harmonious development of an existing design project, a local firm's design strategy, and a global meta-strategy. This relationship can be traced to the potential seed miner tasks, which (on the strategic level) can enable the development of a local library that could be extracted and reduced from a global library (WSL). In this case, innovation could be achieved from the collective development of innovative strategies within different architectural firms around the world. Thus, the WSL would act as a meta-system that could be used to develop local systems, which in turn, could be used to inform design projects. In return, the seeds generated or developed within a project would be fed back to the local firm's system, which would be made available and trackable by the search engine in the WSL. Hence, this would be incorporated into the WSL and result in the development of innovative meta-strategies to further enhance the efficiency of digital tools in architectural design.

## 8.5 Chapter Summary

This chapter has introduced the concept of the ‘Wiki Seed Library’ as an example of an innovative design strategy that could enhance ‘digital’ efficiency in architectural design. The potential efficiency was evaluated on the theoretical framework that was developed in the previous chapter, showing how the WSL could motivate architects to develop their experience and knowledge in order to ensure benefit from the WSL. It also explained that the WSL could incite a global level of collaboration by offering a globally integrated platform for designers, and scripting and parametric design specialists from around the world to share and exchange work, experience and knowledge. In addition, the chapter showed how the WSL could unearth the true potential of data which, in this case, could act as raw material to generate dynamic systems. The chapter also discussed the potential value of the WSL in supporting research, and the potential impact of this new strategy on the design process. Finally, the chapter showed how a WSL could potentially shift the mindset of architects towards a meta-strategic level, where designers could develop their designs on a project level, while at the same time contributing to both the local system on the strategic level, and the global system at the meta-strategic level.

# CHAPTER NINE

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## 9 Conclusion

### 9.1 Introduction

This chapter will summarise the overall work by explaining how the research objectives were met, outlining the main findings, and providing a series of recommendations for architects in practice based on the findings of this study. In addition, the chapter will discuss the contribution to knowledge, and the limitations of the research. Finally, the chapter will conclude by suggesting different research strategies and topics that can be adopted in future research based on the outcomes of this study and its limitations.

### 9.2 Reflection on Research Objectives

*Objective 1: To determine how digital technologies and computational design methods are reshaping the architectural design process and resulting in radical changes to architectural practice*

This objective was met throughout the whole study, where the impact of digital technologies on architectural practice was divided into aspects; each aspect was presented as a new phenomenon in computational design, and each phenomenon was discussed individually, and was investigated within its real practical context within the different case studies. Those phenomena were re-articulated in the discussion chapter based on the findings from the literature and the cases studies to represent the real impact of digital technologies on architectural practice, and how they are reshaping the design process, by giving the ability to interact or totally design the process, and how they are resulting in the emergence of new types of processes, such as recyclable, sustainable, and transparent processes.

*Objective 2: To identify the factors that restrict efficient use of digital technologies in the architectural practice.*

A wide range of barriers that are restricting effective use of technologies were explored through different examples from the current practice. For instance, the case studies show difficulty in dealing with new technologies that require different types of experience and knowledge that are hard to be learnt within practice, especially when it comes to old

practitioners that used to use traditional methods over a long time. The case studies also showed a dilemma in collaborative work, where the lack of experience in one team or one individual result in pushing all other teams down to using traditional methods. The problem of misunderstanding parametric design was thoroughly discussed to show the sources of this misunderstanding, and the challenges that practitioners encounter when trying to implement parametric design in practice.

*Objective 3: To demonstrate the centrality of parametric design in developing innovative strategies in architectural design.*

The centrality of parametric design was demonstrated throughout the research. The comparison between the features of parametric design and those of other computational design methods showed how parametric design can enhance the benefits of all other methods. This can include expanding the functionality of CAD applications and replacing the singularity of design solutions in algorithmic design with a multiplicity of automatically generated and evaluated design solutions. In addition, the research demonstrated the capability of parametric design applications in acting as BIM tools and to go beyond the capability of BIM applications.

Furthermore, the research showed four levels in which parametric design can support sustainability which result in the emergence of new terms in this research, such as ‘sustainable process’ and ‘recyclable process’. In addition, through different examples from the case studies the research demonstrated that the building seed concept can only be implemented through parametric design applications. From this basis, developing seed libraries in architectural firms was suggested and the ‘Wiki Seed Library’ was introduced as an innovative design strategy

*Objective 4: To develop a theoretical framework for innovative design strategies through the establishment of new links between design theory, architectural practice, and digital technologies.*

The abductive approach adopted in this research enabled the achievement of this objective. The computational design phenomena were classified and discussed in the literature review, and from this basis, the first data analysis stage enabled the exploration of the phenomena in their real practical contexts within different case studies. The second data analysis stage enabled the juxtaposition of evidence from different case studies with regard to each

phenomenon. This approach enabled a thorough explanation of each phenomenon that helped to enrich the theory.

*Objective 5: To demonstrate the applicability and reliability of the theoretical framework by suggesting an innovative design strategy and evaluating it based on the theoretical framework*

This objective was met by introducing the Wiki Seed Library as an innovative design strategy and using the theoretical framework to evaluate the potential impact of this library.

### **9.3 Summary of the Research Findings**

The research provided a detailed and comprehensive theoretical framework based on a thorough review of the literature and a range of examples from current architectural practice. The framework provides a way to consider the dynamism of the current situation caused by the rapid evolution of an array of digital technologies and computational design methods. Thus, the theoretical framework could be used as a guide or a ‘road map’ for future research that might investigate the impact and the potential of future digital technologies and methods on architectural design. This will help architectural theorists provide a more mature and coherent design theory, and it helps architects in practice to develop innovative design strategies in order to enhance the efficiency of the ‘digital’ in architectural design. The research, therefore, contributes to the simultaneous development of design theory and architectural practice.

The literature review juxtaposed the different features of conventional design and those of computational design. This enabled the identification of paradigm shifts in the design process, caused by the utilisation of each computational design method. In addition, the research highlighted the centrality of parametric design by showing how this inherits the paradigm shifts of all other methods, and how it can result in a series of other paradigm shifts that are solely enabled within parametric design. Furthermore, the literature review highlighted the strict difference between the impact of parametric design and the impact of the node-based applications used in parametric design, where each type of impact was discussed separately.

The literature reviewed in Chapter 3 explored different computational design methods and identified the paradigm shifts caused by these methods. The outcome of this chapter was used to further identify the digital impact on design (in Chapter 4). Thus, rather than describing

the impact of the digital technologies and methods, the research enabled the specification of a particular technology and a particular method that could result in such an impact.

The case studies demonstrated the significance of the traditional methods, and the ability to use new computational design methods to complement rather than replace traditional methods. This was revealed in the different project scenarios that showed how parametric design can be used to facilitate, automate and accelerate some specific tasks within a traditionally-driven design process without disturbing the whole process.

The research also showed different methods of developing experiences and knowledge in practice, and the importance of achieving balance in experience and knowledge amongst different participants in collaborative work. This helps to avoid pushing expert teams back to traditional methods when dealing with less expert internal or external teams.

The case studies exemplified the power associated with digital experience and knowledge, the relationship between this power and the general ambience of the firm, and with the nature of the project. Furthermore, the research investigated the permanence and temporality of the emergent roles in architectural practice and explained how those new roles can help in fertilising experience and knowledge in design teams.

In order to enhance the efficiency of the digital in architectural design, the discussion chapter examined the criteria of selecting the right technology and the right method that match the nature of the project, considering the nature of the design stage at which the technology is used, and ensuring interoperability among the different technologies used. In addition, the discussion showed how the selection of technology can be affected by the maturity of this technology and by the general atmosphere in the geographical area of the firm. Furthermore, the discussion showed the importance of having the right experience and knowledge to leverage technology towards greater efficiency.

The research identified four levels of collaboration and specified the purpose of each of those levels. In addition, the research emphasised the need to focus on a global level of collaboration and its potential to achieve innovation in architecture. Furthermore, through a critical review of the literature and various examples from projects in the case studies, the research revealed the capability of data to act as a raw material, and how this raw material can benefit from parametric systems that change into different types of geometry and

information, alongside its ability to generate dynamic systems that can automatically generate design solutions.

The analysis of the case studies showed the ability of parametric design applications to support integration in architectural design, and hence to demonstrate the ability of these applications to act as highly effective BIM tools. Furthermore, some project scenarios showed how parametric design applications can go beyond the capability of current BIM applications by enabling the integration of new types of information into parametric definitions, such as building codes and standards.

The research filled the gap in the literature with regard to complexity in computational design. The outcomes of Chapter 3 showed how different computational design methods can simplify some aspects of the design process. This aspect was explored in the case studies and discussed in Chapter 7, resulting in the identification of three aspects of complexity, which are form complexity, process complexity, and tool complexity. In addition, three zones of form complexity were identified, which are simple zone, complex zone and impossible zone. Therefore, based on examples from the case studies, the discussions revealed how digital technologies have shifted design forms from the impossible to the complex zone. Furthermore, the discussion clarified the relationship among the three aspects of complexity and how form complexity can be simplified through process complexity, which in turn can be simplified through tool complexity. This led to the identification of the absorption forces of complexity in the design process. Consequently, based on the arguments provided by different case study participants, understanding new technologies and having the right experience and knowledge were identified as the cure to resolve complexity.

The research discussed the impact of the 'digital' on design creativity, and explored different aspects that affect design creativity in computational design. This included, complexity, compatibility between digital technologies and the designer's mind, and the designer's knowledge and experience. In addition, the discussion chapter showed different ways in which to rely on BIM applications that can affect creativity. This was addressed in relation to the levels of abstraction in the design stages and the false feeling of completion that can result from the use of BIM applications in the early design stages.

With regard to the design process, the discussion chapter introduced new terms, such as 'sustainable processes', and 'recyclable processes'. The ability to develop such processes was demonstrated within different project scenarios in the case studies. These new concepts can

result in a new understanding of sustainability in design where designers can accelerate processes and recycle different parts of precedent processes in order to reduce effort and costs and save energy within the design process.

The building seed concept, that was discussed in the literature, was exemplified through four examples from the case studies. The discussion chapter demonstrated that the building seeds can solely be enabled within parametric design applications. Therefore, the research demonstrated that, with the available digital technologies, it is possible for architects to shift from designing single buildings to designing buildings seeds that can generate buildings in different contexts.

Moreover, Chapter 8 introduced the concept of the ‘Wiki Seed Library’ as an innovative design strategy, and investigated different methods to enhance the validity of the seed library. This included the motivation of highly expert computational design specialists to share their processes on a global scale. In addition, the potential impact of the ‘Wiki Seed Library’ was evaluated based on the theoretical framework.

The research has provided several examples that show how architects have the opportunity to inspire innovative strategies from other disciplines and other industries and apply similar strategies in architectural practice. For instance, the idea of the Wiki Seed Library was inspired from Wikipedia, as discussed in Chapter 8. Moreover, in order to enable practitioners to rethink innovation in computational design, the research urged practitioners to shift their mindsets towards strategic and meta-strategic thinking in order to enhance connectivity among current design tasks on a project level, the local system on a strategic level, and the global system on a meta-strategic level.

Finally, the research provided a range of detailed recommendations, ideas and inspiration for architects in firms who are involved in developing their practice. The recommendations were derived from the cross-case analysis in relation to the literature. They were organised, structured and categorised based on the theoretical framework which enabled breadth, depth and detail to generate and articulate the recommendations.

#### **9.4 Recommendations for Architects in Practice**

The following are recommendations for architects and other stakeholders in architectural firms. These recommendations are attempts to answer one major question; how can the efficiency of digital technologies and computational design methods be enhanced in



architectural design? This question suggests that technologies already exist and are mature; however, enhancing the efficiency lies in changing the way in which technologies are utilised rather than changing technologies themselves.

#### **9.4.1 Criteria for Selecting Tools**

A wide range of heterogeneous digital technologies and computational design methods are currently being utilised in architectural practice. These technologies represent the tools that architects rely on to facilitate design. Within this multiplicity and heterogeneity, the main question that may arise is how to select the most appropriate tool that meets the specific requirements of a practice and its project needs, and the specific situation in which the different technologies can be used more effectively and efficiently. This is the most critical question within practice as the selection of the wrong application may result in significant and unnecessary expenditure, when applications might remain unused after the purchase of licences. Therefore, enhancing the efficiency of the 'digital' starts from selecting the right tool for the right purpose at the right time.

The first aspect that architects in practice need to consider when selecting a digital tool for design projects is the compatibility between the nature of the tool and the nature of the specific project at hand. For instance, the desire to design complex buildings that have complex, fluid and irregular shapes requires the use of specific software applications, or specific computational design methods, such as scripting, algorithmic design or parametric design. These tools give designers the ability to tackle the increasing complexity of form by simplifying the cumbersome process of manually manipulating the forms into a simple and seamless process that requires the manipulation of a simple script, simple algorithm or an architect-friendly parametric definition. In addition, when a project is complex and large in size, the main challenge is to manage and achieve efficiency in the extensive coordination required. In this case, architects need to consider relying on BIM and using BIM applications in order to enable automation and seamlessness in the share and exchange of information.

The selection of the tool can be affected by the budget of the architectural firm. Therefore architects need to not only consider the cost of the licence of software applications, but also the cost of the related hardware needed for the software applications to work effectively. For instance, BIM applications are mainly used to support integration in building projects which require information on various geometric elements and the integration of a wide range of interdisciplinary information into single models. This is added to the potential extra expenses

required to develop skills and experiences in design teams that are essential to achieve efficiency in BIM.

When using multiple software applications, the main problem is the interoperability among the various applications, where different types of information might be lost when files are transferred from one application to another. Therefore, prior to selecting and utilising different applications, architects need to know in advance how those applications are going to work together. In other words, each software application has its own language; however, in order to ensure its effective and efficient use, architects need to have the capability to translate information among a range of applications.

The selection of the tool can be affected by the general atmosphere, either globally or within the specific geographical area of the firm. For instance, BIM has already started to gain wide recognition on a global scale. It is also becoming mandatory in some countries, which is added to the fact that, in many current projects, a BIM model is becoming an essential part of the client's requirements. This is due to the ease and seamlessness that BIM offers in facility management during the operational phase of building projects.

Another aspect that can be considered is the maturity of the tool in use. Therefore, architects need to avoid over-expecting the results when a new tool used in design projects. For instance, various aspects of immaturity in parametric design applications were reported by different authors and practitioners. Therefore, using parametric design can be limited to the automation of specific tasks, which depends on the nature of the project. In contrast, BIM applications appear to be far more mature and capable and, therefore, are more popular.

In addition, the tool selected should be compatible with the nature of the design stage in which it would be used. For instance, using BIM might be disturbing in the early design stages, where architects need to work more freely and with minimum constraints to achieve creative and highly aesthetic design solutions. In this case, using intuitive and friendly editable tools can be more appropriate, such as SketchUp, Maya or Grasshopper. BIM could be more appropriate in the design development and technical design stages due to the need to benefit from the capability of BIM applications to automate coordination at these stages. In general, the planning of the project and its stages must be conducted in tandem with a critical specification of the tools that will be used in each design stage and for each design activity.

Furthermore, an important aspect that architects in practice need to consider is the significance of traditional tools and methods. They need to understand that new technologies and methods are not being used to replace traditional methods, but rather to complete them. In fact, even in advanced firms where highly advanced digital technologies are used, some traditional methods, such as sketching, free-hand drawing and CAD, are still essential.

#### **9.4.2 Experience and Knowledge**

Experience and knowledge are highly related to the selection of technologies; in fact, each technology and computational design method requires a specific type of knowledge and experience benefit from the technology or method. Without this knowledge and experience, the new technology will act as a cognitive barrier that may threaten its efficiency. Therefore, architects in practice need to consider digital technologies, experience and knowledge as one single entity, where the efficiency of digital technology can be achieved when the user has the right experience and the right type of knowledge to deal with the technology in the right situation.

Having experience and knowledge in digital technologies may also bring power; for example, an individual who is highly expert in dealing with a specific digital technology might have the power to adopt a major role in some projects or take major decisions on behalf of the firm. This might be affected by the nature of the project. For instance, the power of a parametric design or scripting specialist might inflate when a project has a complex form that requires this type of knowledge. The same rule applies for BIM specialists in large and complex projects that require the extensive coordination with internal or external consultants. The power can also be affected by the general ambience in the firm, where the power gained from having specific knowledge or experience can be based on the existence of similar knowledge and experience amongst other individuals within the firm. In general, architects in practice should be aware of the exaggerated power that might be gained from individual digital knowledge and experience, as it could result in the authority to take major decisions without the right professional experience and strategic view.

Nevertheless, architectural firms need to continuously develop the experience and knowledge of their staff in order to ensure the most benefit from digital technologies. Thus, they should be aware of the efficiency and effectiveness of providing training within the practice. This efficiency might be threatened as, in many cases, architects would prefer to deal with their

work pressure in order to meet their deadlines. In such cases, allowing sufficient time for training is recommended in order to achieve the intended results.

Furthermore, another effective way to develop experiences can be considered in architectural firms. An architectural firm can appoint a number of highly expert members with exceptional digital literacies. These members can supervise the design team by providing the knowledge and experience to help architects utilise digital technologies effectively in relation to the project requirements. While this method can be expensive, it can result in significant cost savings in the long term. In fact, working under the supervision of highly expert members will result in a situation where the experience and knowledge of the experts will naturally be fertilised amongst design team members. In this case, the design team will be able to undertake such tasks unaided. This method appears to be more effective than training, as it helps architects to learn how to use digital technologies and how to apply the computational design methods within the context of real projects.

When using parametric design applications, developing the relevant experience and knowledge become easier. When these applications are used, a design form can be generated by developing a parametric definition that is represented as a graph. This graph not only shows the final form, but also the history of the whole formation process. Therefore, these parametric graphs represent knowledge encapsulated in a parametric definition, where designers can read the graph, analyse it and learn from it. Therefore, architects with parametric design experience are advised to use online libraries and to explore different parametric definitions to test their applicability on current projects. Moreover, the social networking enabled on the Grasshopper website and other similar websites offer exceptional opportunities for architects to develop their experience and knowledge from online interactions with other specialists.

### **9.4.3 Collaboration and Integration**

An architectural firm has to promote the potential for collaboration and has to push the mindset towards collaborative and integrated work. The importance of collaboration and integration stems from the plethora of complex digital technologies and methods available for architects; therefore, dealing with these technologies is beyond the capacity of any individual in architectural firms. Consequently, collaboration and integration should be understood as the key to leverage technology towards greater efficiency in computational design.

Collaboration and integration are highly related to experience and knowledge. Architectural firms need to be aware of this critical relationship when developing experience and knowledge to support collaborative work. In this case, an architectural firm should ensure a balance in experience and knowledge among its individuals and teams. This balance is essential for successful collaboration; without it, some expert individuals and teams might find themselves obliged to revert to traditional methods due to the lack of similar experience in the collaborating team. For instance, within a BIM-based project, where data can be automated and shared within integrated models, the lack of experience in one of the teams may result in a situation where all other teams will have to use CAD or pdf rather than BIM in order to share and exchange information with that particular team. This results in significant inefficiencies as the whole integration will be broken. Similarly when architects use parametric design to share work with engineering consultants, the successful integration is subject to the existence of the same experience and knowledge within that consultant. Otherwise, architects need to change their parametrically generated models into CAD models, which means breaking the seamlessness and continuity that parametric design offers.

Even when an architectural firm is capable of securing a balance in the experience and knowledge among individuals and teams, the same problem may emerge when working with a smaller firm with a less knowledge and experience. In this case, a firm needs to ensure that the smaller (or the less advanced) firm does not dictate the way in which information is shared. For instance, if an architectural firm has an advanced server and network system, and has already developed the experience amongst its members to effectively deal with this network system and the CDEs, they need to ensure that they are not to be obliged to return to traditional methods of sharing, such as using email or WeTransfer. Instead, they have to encourage the less advanced firm to use the server by employing an expert who can deal with these advanced technologies.

Another way to support collaboration and integration is to explore different technologies that can be used for support in practice. Apart from the popular software applications that support collaboration and integration, other smaller applications can be explored and used to enhance efficiency in integrated platforms, such as Slack, BCF (BIM Collaborative Format), and Bluebeam. In addition, some online platforms that exist online which support collaboration, contain a wide range of simple and small sized application. Those applications offer a seamless and automated flow of information across different applications without the need to share whole files.

Furthermore, an architectural firm needs to consider going beyond the borders of practice when seeking effective collaboration. For instance collaboration with software vendors proves fruitful when genuine and realistic feedback is provided by architectural firms; this is highly appreciated by software vendors who rely on such feedback to develop software based on the specific needs of current architectural practice.

Individual architects within practice can also consider collaboration on a global level, where they can use some interactive or social media websites to interact with other architects around the world, for instance Grasshopper's website contains an interactive platform where an account can be created. In such cases, a member can post a question or share a parametric definition and ask for support. In this case, a wide range of members might respond by providing an answer, or by directly developing the parametric definition, or uploading a similar parametric definition to solve the problem.

In general, architectural firms need to push the mindsets in their team towards more collaborative and integrated work. They have to explore different ways to solve the issues of copyright, authorship and ownership in order to enhance security when data is shared within integrated platforms. Furthermore, the different mindsets among individuals from different generations with diverse types and levels of experience can have positive impacts; this can be encouraged by considering both the technological experience of younger and the professional experience of older employees.

#### **9.4.4 Complexity**

In order to deal with complexity, architects need to know that it is important to have appropriate and sufficient experience and knowledge. In other words, the complexity of digital technologies can be eliminated by understanding them; thus, the user can benefit from these technologies rather than struggle to solve their complexity.

Understanding the value of complexity and the purpose for its increasing is important. In fact, technologies and processes are becoming more complex in order to be more effective. Designing complex forms require complex processes; these complex processes, in turn, require complex technologies to deal with them. For instance, designing a complex and large project requires a complex process by increasing the coordination and shifting the provision of feedback to the early stages. Consequently, a complex technology, such as BIM, is required to automate this coordination and hence simplify the process.

Complexity can be problematic as it could cause frustration for architects, as it might shift the focus away from creative work. In this case, understanding the absorption forces of complexity might help to reduce this frustration; for instance, when BIM is implemented, the increasing coordination required in the early design stages helps to reduce, and hence simplify, the later stages. Similarly, when using parametric design, the complexity of algorithms and parametric definitions can result in the automation of later stages for more ease, seamlessness and synchronicity when exploring design alternatives. In both of the previous examples, the early stages absorb and simplify the complexity of the later stages. Understanding this equation might reduce the frustration as efforts made in the early stages can be later invested when the generation, evaluation of forms and coordination with other participants are automated.

#### **9.4.5 Creativity**

Creativity is highly affected by complexity, and hence is highly related to knowledge and understanding. More precisely, the complexity of technology has two contradictory aspects; On one hand, it can shift a designer away from creativity towards the struggle to solve complexity. On the other hand, it can automate some cumbersome and repetitive tasks in order to allow more time and effort availability to focus on creative work. In between these two extremes, experience and knowledge enable a designer to move from struggling to solve tool complexity to efficiently using the tool.

However, when using digital tools, architects should be aware of some aspects that can threaten design creativity. First, when relying heavily on a digital tool, designers need to be aware not to end up being dictated by the tool, or being limited in their design decisions to the tool capability. If this is the case, it could be argued that architects are not using the right tool, or that the tool does not match the nature of the project, or the nature of the design stage in which the tool is being utilised. At this case, designers might decide either to use a more suitable tool or to revert to traditional methods, such as sketching, drawing or CAD.

When using BIM applications in the early design stages, creativity can be risked in two different ways. First, BIM forces the image of a building at a stage where the designer is usually more interested in recalling events, ideas, thoughts, diagrams or abstract images. In this case, using traditional methods can be preferable as they can free the designer's mind from the physical constraints of a real building. Second, the image of a completed building that BIM applications provide early in the design process might result in a false feeling of

completion that might cause architects to shift to the later design stage before the required range of creativity is achieved.

#### **9.4.6 Research**

The rapidity in which the digital technologies are emerging and the novelty of these technologies should motivate architectural firms to conduct research within their practice in order to determine the potential of these technologies and how they can be employed to achieve positive results. In this case, a design project can be treated as a research project and hence develop different approaches to acquire knowledge in order to use this to inform later projects.

Research in practice can be conducted by employing a research team that can continuously explore the state-of-the-art digital technologies available and to harness these technologies to facilitate design in the firm. If the budget of the firm does not allow for the establishment of such a research team, a more flexible approach could be applied by allowing architects to conduct research when needed.

Another highly recommended approach in conducting research is to develop partnerships with academic research groups. This can be an almost cost-free approach to research as it is based on mutual benefits. Thus, the academic group offers the knowledge for the development of the technologies and methods applied in the firm while in return, the firm acts as a case study in order to help the academic group explore the practical context of its research. Therefore, while the implementation of BIM is gradually becoming mandatory, architectural firms should be prepared for the time in which their contribution to research might become mandatory.

#### **9.4.7 Sustainable Processes**

While sustainability is becoming a greater concern in temporary architecture, a more holistic understanding of the concept is recommended. Sustainability is not only about designing energy efficient buildings; in fact, sustainability starts from the first step in the design process. Architects need to think of developing sustainable processes where time and cost savings and a reduction to energy consumption stems from the acceleration of the design process, which can be achieved by facilitating and automating repetitive tasks and synchronising changes and coordination. In this case, parametric design and BIM offer useful methods to achieve this acceleration.



Another aspect of sustainable processes is the ability to recycle processes, which is enabled through parametric design. Thus, the same parametric definitions can generate different forms within different contexts and across different projects. This is where a parametric definition can act as a building seed that can be planted in different projects to grow into different design solutions. Therefore, architects should think of developing seed libraries within their firms. The seed library can be made of algorithms or parametric definitions, whilst the seeds can be generated from previous projects, or created separately as part of a research initiative. Moreover, they can even be borrowed from others' work on the Internet. However, architects could continuously accumulate seeds so that over time, they will have rich and large libraries that can be consulted at the outset of each project to facilitate and automate some design tasks.

#### **9.4.8 Strategic Thinking**

In general, architectural firms need to push the mindset of their teams towards strategic thinking, where architects operate on dual level - a project level and a strategic or system level. Therefore, in each design task they can consult the system (the library) and find methods to facilitate or accelerate the task in hand, and then use the outcomes of the task to feed the system. This will allow the system to grow in maturity and richness over time to greater enhance the efficiency of the digital in architectural design.

### **9.5 Contribution to Knowledge**

One of the contributions of this research lies in demonstrating the applicability of the building seed concept in architectural design. The research shows different examples from real projects in which parametric design definitions act as building seeds. This is possible due to the associative parameters in those definitions that enable one single parametric definition to generate different and automatically contextualise forms in different projects. Therefore, the research authenticates the shift from designing building forms to designing building seeds that can generate different forms as an applicable design approach and can be achieved with existing technologies.

The research introduced the 'Wiki Seed Library' (WSL) as an innovative design strategy where architects and designers from all over the world can share seeds in the form of algorithms, scripts and parametric definitions so that architects can collectively develop seeds for other users to apply and develop further. This idea was inspired from Wikipedia where,

similarly, authors from all over the world collectively develop articles and continuously develop those articles to keep them up-to-date. With this example, the contribution lies in adopting an innovative model from the Web 2.0 development industry and apply it to an architectural context to enable similar rapid growth in architectural practice.

Another aspect of the contribution to knowledge in this research lies in expanding the scope of existing concepts, such as collaboration, integration, parametric design and sustainability. With regard to collaboration, the research identified four levels of collaboration and introduced a new level which is 'global collaboration'. The potential of this level of collaboration was demonstrated by showing examples from real life projects where architects went beyond the borders of their organisations by using social media websites to interact with designers across the world in order to inform their design decisions within current projects. With regard to integration, the research introduced the 'Wiki Seed Library' as a global integrated platform that can be used in tandem with local, integrated platforms within architectural firms. In terms of parametric design and sustainability, the research contributed to a more holistic understanding of sustainability by introducing the terms 'sustainable processes' and 'recyclable processes'. Moreover, the research identified four levels in which parametric design can accelerate the design process and hence reduce effort and save energy (sustainable processes). It also demonstrated the overlooked potential of recycling parametric definitions across different projects (recyclable processes).

The research demonstrated the ability of parametric design applications to act as BIM tools. Meanwhile, the research emphasised the parametric principles that underpin the automated flow of information in BIM applications. The contribution in this case lies in combining two concepts (BIM applications and parametric design applications) so that BIM is understood as a method and BIM applications and parametric applications are two different types of technologies that support the same method. The usefulness of this combination stems from the ability of parametric design applications to go beyond the capability of BIM applications, such as integrating information about building standards and regulations into parametrically generated models, which is currently not possible within existing BIM applications.

Another aspect of this research contribution lies in contrasting existing theory, which suggests that adopting the 'digital' in design results in increasing complexity in the design process. The research relied on examples from the case studies to identify three aspects of complexity (form, process and technology complexity) and explained the relationship among

these aspects. In addition, the research revealed the absorption forces of complexity in design by showing how increasing complexity in the early design stage result in simplicity in the later stages. With this example, the research exemplifies the term 'simplicity' which has already been adopted in one of the software development firm's website.

In general, the flexibility of the theoretical framework and its reusability and modifiability means it can respond to the dynamics of the current situation where a vast array of digital technologies and a variety of computational design methods are evolving, and awaiting efficient and widespread use in architectural projects. From this basis, the theoretical framework offers the foundation/roadmap/guide for future research involved in the continuous evaluation of design theory and hence the continuous contribution to knowledge. In addition, the framework can be adopted by practitioners in architectural firms in order to develop innovative strategies to enhance the efficiency of the 'digital' in architectural design. The applicability of the theoretical framework was demonstrated by using it to evaluate the WSL strategy and predict of its potential. In addition, the framework was used to derive the recommendations for architects in practice that was discussed in the previous section.

## **9.6 Limitations**

The research starts from the understanding that the majority of architectural practices are still relying heavily on traditional methods despite the positive results that are emerging from the application of digital technologies in a minority of firms. Therefore, it could be worthwhile to consider the collection of quantitative data, such as using surveys and questionnaires, in order to measure the level of reliance on digital technologies in a wider range of architectural practices, and to quantitatively investigate the efficiency and feasibility achieved by their utilisation. This could have enlightened areas of further investigation in the case studies as well as further research. However, the difficulty in making effective use of digital technologies was already demonstrated from the literature, and it was demonstrated further from the case studies, which showed that most practices are still relying on traditional ways of sharing information, and that BIM technology is still in its initial stages. Furthermore, the case studies revealed the rare use of scripting and parametric design in most of the practices. The design scenarios showed that, even in advanced practices, practitioners are still relying heavily on traditional approaches to communicate design ideas and information. Amongst these difficulties, it could be argued that it is currently too early to apply such methodologies; digital technologies within architectural design are still in their infancy and require time for

the real impact of these technologies to be fully realised. However, the rapid growth of those technologies, their mandatory use in some countries and the growth in client demand will result in their rapid adoption by a wider range of architectural practices. In such a case the lack of such methodologies might pose a limitation to future research.

Another methodology that could have been used in this research is the ‘experiment’ strategy. In fact, within this research some design experiments were attempted in order to explore the potential of algorithmic and parametric design. The experiments failed to meet their intended results due to the abstract nature of the experiments and the lack of context in which the experiments could be used. Furthermore, a vast array of similar or more advanced design experiments exist on the Web that attempt to show the potential of these new design methods. However, only a minority of architectural practices are able to make efficient use of these novel design methods. This contradiction between the existence of large numbers of abstract parametric design experiments and the rare use of parametric design in practice reveals that the context is missing. This required the sole focus on case studies in order to enable greater depth when investigating the practical context in which these design methods can be used efficiently. Again, a wider adoption of parametric design in the future will enrich this context, and in which case the experiment research strategy would enable an examination of their further potential where the wider or unlimited scope of parametric design could be explored.

The data in this research were collected from large architectural firms that have several branches in different locations. In this case, dealing with smaller sized firms could enable a greater understanding of the roots of the problem by investigating this issue from a different perspective. The focus on large firms can, again, be attributed to the difficulty in adopting digital technologies in smaller firms and the high costs associated with these technologies. Therefore, rather than considering a variety of firm sizes when selecting the sample, the reliance was on the variety of advancement levels in the adoption of digital technologies. This decision was based on the nature of the research that does not tend to generalise the state of the practice but rather the efficient use of digital technologies within practices. Therefore, the firms selected offered a reliable context that cannot be offered by firms with small sizes and low budgets.

In general, all the limitations explained above are affected by the time in which this research is being conducted. The architectural practice is not only passing through a transitional era, it is in the very early stages of this transition era. Therefore, the changes and shifts in

architectural design caused by the rapid evolution of technologies, should be associated with changes in the way design theory is approached and the methodologies applied in related research.

## 9.7 Future Research

The limitations discussed in the previous section can be addressed in various ways in future research; for instance, a survey strategy can be used, and a questionnaire can be conducted to measure the extent of reliance on parametric design and scripting, and the purpose of using these novel design approaches in relation to the nature of the project in which parametric design was used, which includes the function of the building, and its size and complexity. In addition, a questionnaire could address a representative portion of parametric design experts from the overall members in design teams, and the importance of these experiences in real projects in addition to the efficiency and feasibility achieved by adopting these new methods. Additionally, the questionnaire could include lists of different hardware and software technologies with checklists and levels that show which of those technologies are being used, and to what extent they are considered effective. The ease and automated manner in which data can be collected and analysed in this methodology will help to expand the sample used so that computational design phenomena can be investigated based on the income from a large number of architectural firms from various locations, sizes, and budgets. This will also enable the further testing and development of the theoretical framework developed in this research. Nonetheless, as discussed earlier, a much wider adoption of digital technologies in architectural design is required for this research methodology to be effective.

The theoretical framework can be adopted to develop mature theory in future research and to develop innovative strategies. In terms of theory development, the theoretical framework offers the foundation for future research that is involved in developing a more mature theory. For instance, future research can focus on one of the components of the theoretical framework, and use the framework to further investigate the impact of this component on the other components within the framework. In other words, future research could investigate the impact of the 'digital' on one of the computational design phenomena, in which case the theoretical framework will offer a road map to explore how this particular phenomenon is affecting and being affected by the other phenomena. For instance, one of the PhD Theses that the author reviewed investigates the potential impact of Big Data on architectural design. Future research in this area could benefit from the theoretical framework by exploring the

impact of using Big Data in design on the complexity/simplicity of the design process. Furthermore, applying the framework could help to pose essential questions, such as what new roles may emerge when Big Data is utilised in design? What are the shifts in experience, knowledge and skill sets that may result from this adoption? In addition, what sort of paradigm shift in the design process might result?

In terms of developing innovative strategies in practice the research has already introduced the WSL as an innovative design strategy and used the theoretical framework in order to evaluate the effect of this strategy and predict its potential. Similarly, the ideas and concepts that develop and enhance the efficiency of digital technologies can be introduced as innovative design strategies. In this case, the framework will not only act as a guide to evaluate the potential impact of the new strategy. The strategy itself will inspire further areas of development in the framework by exemplifying and testing it within the process of developing and evaluating the strategy.

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## **Appendix A Participant Information Sheet**

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### **About the research**

The research explores different computational design methods and approaches that are being applied and developed in the current architectural practice. Those approaches and methods will be linked to the related design theory, and based on this link, the research will develop a framework for innovative strategies in architectural design practice. To achieve this, a case-study research methodology is adopted where a series of semi-structured interviews will be conducted with practitioners from leading architectural practices that have proved success and efficiency in utilising and developing highly-advanced digital tools and methods in real architectural projects.

### **About the participation**

The participant will be interviewed by the researcher either face-to-face, via Skype or by telephone, which depends on the participant's availability and location. The interview will be semi-structured where the researcher will ask some questions about the practice. The interview questions can be provided prior to the interview upon the participant request. However, the questions might be slightly changed or modified during the interview based on the flow of information. The estimated time of the interview is 60 minutes.

### **Participant rights**

The participant (interviewee) will have the right to skip answering specific questions or even withdraw from participating at any time without providing any explanation. In this case, any data that might be already collected will be destroyed and will never be used neither for this research nor for any future research.

### **Confidentiality and Anonymity: Procedures for saving, archiving, using and accessibility of data**

The data collected from the interview will be used in the research to exemplify different theoretical aspects and to form part of the theoretical framework as explained in the Research Brief. Prior to that, the data will be saved on a password-protected computer which is only accessible by the researcher. Besides, any copies of the data on CDs, memory sticks or any printed versions of the data will be stored on a locked file cabinet in a locked room, and that

will also be accessible only by the researcher. Furthermore, the data will be kept anonymous and it will be given a code which is only known by the researcher. The data will be seen by very limited people, such as the supervisor and the examination board.

### **Contacts**

For any further inquiry about the research or any other issue, please contact me or any of my supervisors

Researcher : Adonis Haidar : [A.Haidar@edu.salford.ac.uk](mailto:A.Haidar@edu.salford.ac.uk)

Supervisor : Professor Jason Underwood : [J.Underwood@salford.ac.uk](mailto:J.Underwood@salford.ac.uk)

Co-supervisor : Dr. Paul Coates : [S.P.Coates@salford.ac.uk](mailto:S.P.Coates@salford.ac.uk)

## Appendix B: Consent Form

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*(please edit as appropriate)*

**Title of Project: Parametric Design in Collaborative, Integrated and Adaptation in Architectural Design Process**

**Name of Researcher: Adonis Haidar**

*(Delete as appropriate)*

- I confirm that I have read and understood the information sheet for the above study (version x- date) and what my contribution will be.

Yes	No
-----	----

- I have been given the opportunity to ask questions (face to face, via telephone/Skype and e-mail)

Yes	No
-----	----

- I agree to take part in the interview

Yes	No	NA
-----	----	----

- I agree to the interview being digitally recorded

Yes	No	NA
-----	----	----

- I understand that my participation is voluntary and that I can withdraw from the research at any time without giving any reason in which case the data collected will be destroyed

Yes	No
-----	----

- I agree to take part in the above study

Yes	No
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Name of participant :

Signature :

Date :

Name of researcher taking consent: Adonis Haidar

Researcher's e-mail address: a.haidar@edu.salford.ac.uk

**If you have any concerns about this research that have not been addressed by the researcher, please contact the researcher's supervisor via the contact details below:**

Supervisor's name Professor Jason Underwood

Supervisor's email address: J.Underwood@salford.ac.uk

## Appendix C: Interview Schedule

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### About you and about your practice

- 1. How many years of experience in architectural practice and in ---? Can you give a briefed description about your role at ---?**
  - Things that you do (in general, within a design project, in each design stage)
  - Your responsibilities
- 2. How do you describe the difference between your work at --- and your experience in other architectural practices?**
  - Nature of practice
  - More reliance on digital technologies and software
  - Unfamiliar roles in the design team (software developers, geometry specialist...)
  - Early coordination with other disciplines
  - Higher level of complexity
  - Other

### Technologies and Roles

- 3. What are the technologies that you use in the design process at your practice?**
  - Software (Modelling, BIM, Parametric Modelling, Scripting...)
  - Hardware (3D printers, laser cutters, CNC, virtual reality...)
- 4. Which areas of specialisation do you normally have within your design team and within the project team as a whole?**
  - Programmers/scripting specialist/software developers
  - architects
  - Structural engineers
  - Geometry specialist/mathematicians...
- 5. What sort of skills you think everyone at --- design teams should have?**

### Collaboration and Multidisciplinarity

- 6. How do you (as individuals in a design team) collaborate with each other?**
  - Sharing ideas
  - Sharing information and knowledge



- Providing feedback...

**7. How do you (as a design team) collaborate with other disciplines?**

- In what design stage
- In some specific times or continuously throughout the design process
- Using what tools/software or techniques...

**Research and Development**

**8. Do you have any group specialised in research or developing tools?**

- The role of the research group(s)
- How do they interface with the design team?

**9. Can you describe some situations within building projects from your work at --- where the design process required developing a piece of software to fit some specific needs of the project?**

**10. Who is involved in developing tools/software?**

- Architects with advanced digital literacies
- Software developers (non-architects)
- Research group
- External teams...

**11. In which context do you normally develop your tools/Software?**

- Independent research
- Within a project (parallel to the development of a design solution)
- Based on external teams

**12. Bryan Lawson (A professor in architecture at the University of Sheffield) argues that one of the problems is that many architects and authors in architecture underestimate the role of verbal words in the design process. How do you address this problem?**

- Recording discussions to inform later design decisions
- Providing a report for each meeting
- Using specific software that can record or save discussions or briefed reports...

**13. Do you have any central data base or intranet to save scripts, codes, parametric models or other data to be used in later projects?**

**14. Based on the projects you worked on at ---, did you rely on any sort of information, data or knowledge gained from earlier projects?**

- Piece of software developed in previous project
- Script
- Parametric model
- Database...

### **Problems**

**15. What sort of problems do you encounter when these digital technologies are applied?**

- Lack of interoperability (Information loss when changing file format)
- Lack of experiences
- Increasing complexity in the design process
- More constrains or less design freedom/more design freedom
- Shifting the focus away from creativity
- Other...

**16. Within this rapid evolution of digital technologies, how do you see the future of the architectural practice in ten years from now?**

### **Parametric Design**

**17. What are the different purposes for which parametric design is used in building projects at your practice?**

- Aesthetical perception
- Form finding
- Ideation and conceptualisation in the initial stages
- Coordinating design and structural processes
- Modelling of building performance (environmental or structural performance)
- All of the above or any other...

**18. How do you use parametric modelling in your projects?**

- Individually
- Collaboratively or by multidisciplinary team...

**19. Who is involved in developing parametric models**

- Architects or designers with the relevant skills
- Individuals which are specialist just in parametric modelling
- Geometry specialists
- Non architects...

**20. To which of the following purposes is parametric design being used at your practice?**

- Modelling of standards and regulations
- Automated extraction of tables of costs
- Automated extraction of construction time schedules and link to 4D simulation
- Clash detection
- Interoperability between different applications

**21. Would you agree that parametric modelling software is changing into a highly-effective BIM tool?**

**22. What does this rapidly-evoluted parametric software have over usual BIM software (ArchiCAD, Revit...)?**

- More interactive
- More flexible
- Simpler than popular BIM software

**23. To what extent do you think parametric design software can be an alternative to programming and scripting?**

**24. Which parametric modelling software applications and plug-ins do you use in your design team?**

**25. Is there any way to give different eligibilities in modifying parametric models (such as locking some components in Grasshopper)?**

**26. How do you describe the relation between parametric modellers and the rest of the design team within a building project?**

**27. How do you describe the impact of parametric design on the resulted building**

- More creative or less creative design solutions comparing with buildings designed based on traditional methods...

**28. What are the problems that you encounter when utilising parametric design?**

**How do you address those problems?**

- Lack of experiences
- Time consuming
- Increasing complexity

- Cost
- Lack of interoperability...

**29. In what design stage do you think parametric design is more effective?**

- Ideation
- Conceptual design stage
- Design development
- Detailing
- Communication with construction team
- All of the above

**30. Do you provide different parametric models for each design stage or is it one continuous parametric model?**

**31. Is there any possibility of using the same parametric model for more than one design project? i.e. parametric model as a seed to grow different buildings.**

**32. What are the limitations of parametric design? Which design cases/stages cannot be based on parametric design?**

**33. Do you think parametric modelling enhances the role of young designers?**

**34. Do you think that parametric design can result in a shift in the way a designer think?**

**35. Within this rapid evolution of digital technologies, how do you see the state of the architectural practice in the future?**

**36. How do you see the role of parametric design within the architectural practice in the future?**

## Appendix A Participant Information Sheet

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