SMART PROCESSES FOR SMART BUILDINGS: 'SUSTAINABLE PROCESSES', 'RECYCLABLE PROCESSES' AND 'BUILDING SEEDS' IN PARAMETRIC DESIGN

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Abstract

The rapid evolution of digital technologies and the resulting emergence of novel design methodologies are coinciding with climate change, population growth and increased pressure on global resources. This concurrence evokes opportunities to harness the new design methods to develop smart design solutions and processes that respond effectively to sustainability requirements. Meanwhile, parametric design is emerging as an ideal design methodology to support sustainably in design, whereby the associative parameters in parametric design systems enable automation and synchronicity in generating design forms and evaluating these forms against their environmental performance. This research explores the multifaceted way in which parametric design supports sustainability, and how this can lead to a more holistic understanding of sustainability by shifting the focus from sustainable buildings to sustainable processes. In addition, the work shows how the reusability of parametric definitions in parametric design applications can enable designers to recycle the design process, where a parametric definition acts as a building seed that can be 'planted' in different projects to automatically generate different forms. This may enable practitioners from all over the world to collectively develop a 'seed library' that has the potential for architects to empower, automate and enhance the environmental values of their processes. To achieve this, the main changes and shifts in computational design are reviewed, together with the impact of parametric design and its related applications on the architectural design process. In addition, a case study is conducted to explore how parametric design can significantly accelerate processes in real practice, and how the overlooked potential of reusing parametric definitions can make distinctive results in real architectural projects. Finally, the efficiency of the seed library is discussed as opposed to the apparent issues such as validity of seeds, motivation for sharing, and copyright.

Keywords: Architectural Design Process, Building Seeds, Parametric Design, Recyclable Processes, Seed Library, Sustainable Processes.

INTRODUCTION

In parallel to the rapid evolution of digital technologies, architectural practice is undergoing unprecedented and rapid transitional changes and shifts (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 the individual to collaborative (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).

This rapidly changing situation in the architectural domain coincides with an increase in natural disasters (Snell, 2018), growing limitations of global resources (Mueller, 2011), climate change (Kwok, Kwok, Grondzik, 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 being more and more associated to design innovation (Kocaturk, 2017). This simultaneity elicits a persistent necessity to dedicate the new design methodologies to support sustainability. Therefore, architectural practice is moving into performance-based practice (May, 2018; Tamke & Thomsen, 2018) , and hence, the observation of structural and environmental building behaviours are shifting into the early stages of the design process (Turrin, von Buelow, & Stouffs, 2011), and becoming the main criteria in evaluating building quality (Thomsen et al., 2015).

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 in automating the generation and evaluation of a large range of alternative design solutions (Barrios, 2005; Bernal, Haymaker, & Eastman, 2015; Chaszar & Joyce, 2016; Hudson, 2010; Mueller, 2011; Turrin et al., 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 (J. E. Harding & Shepherd, 2017). Thus, parametric systems are becoming cornerstones in the more complex performative digital environments (Oxman, 2006, p. 253).

The potential of parametric design in supporting 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 research will address three of these aspects: the potential of parametric design in accelerating the design process and hence to save energy and support sustainability within the design process, the distinction between the merits of the parametric design as a design methodology and the merits of the tools and applications that are used in parametric design, and the potential of the reusability of parametric design definitions across different projects.

The next section will explore the main developments in computational design. This includes how the focus is shifting to performance-based modelling and to enhanced collaboration and integration in the design process, in addition to the copyright issues that may emerge in collaborative environments (Figure 1). This is followed by a section in which the merits of parametric design are explored, which is split into two parts, the merits of parametric design and their impact on the flow of the design process, and the merits of the parametric design applications and their impact on the modality of the design process. These same aspects are investigated further in the real practice examples from real projects in the case study section. The discussion section addresses the different levels in which parametric design supports sustainability and how it can shift the focus from sustainable buildings to sustainable processes. In addition, the discussion section will explicate how the reusability of parametric design definitions enables designers to recycle the design process, and hence, will demonstrate how parametric design is the ideal design methodology that can support the implementation of building seeds (Carlile, 2014). The discussion will help in providing a more holistic understanding for sustainability by shifting the focus to accelerating and meta-accelerating the design process to save energy and support sustainability within the design process. The concluding section of the paper posits the development of the 'Seed Library' and the potential of sharing this library online to widen contribution and hence enrich the library content. This section will draw on the earlier discussions to show the real potential of sharing libraries and how architects could inspire innovative approaches and ideas from the software industry and web 2.0 development industry to enhance the validity of the seed library and to motivate highly intellectual computation design specialists to share their work for the general public (Figure 1).

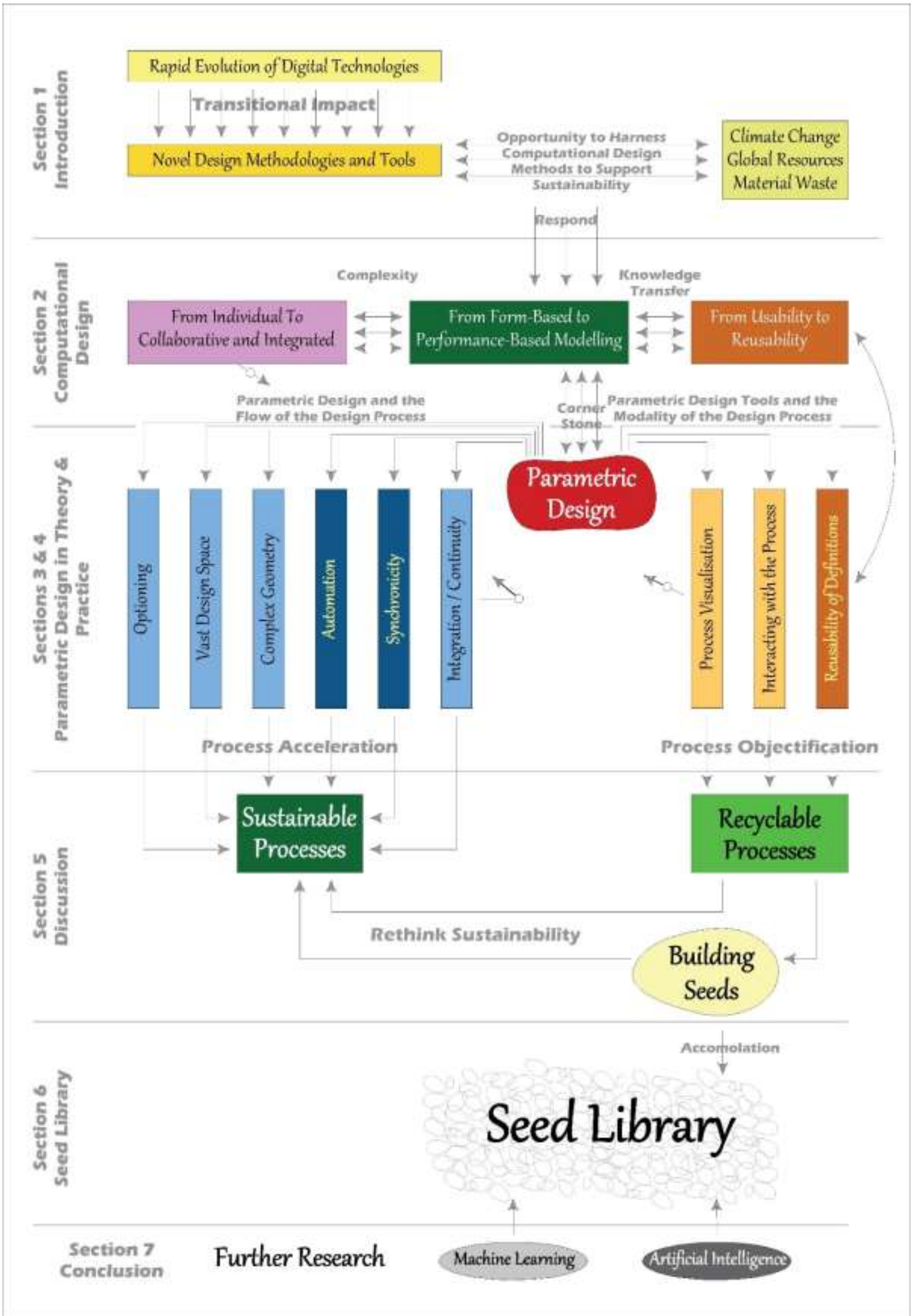

Figure 1: Paper Structure

CHANGES AND SHIFTS IN COMPUTATIONAL DESIGN

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 section discusses the main changes and shifts in the architectural design process offered by the different computational design methodologies, in order to form the context from which parametric design is emerging.

Evolution of Computational Design: From CAD to Algorithmic to Performative

Upon its ubiquity in the 1980s and 1990s (Penttilä, 2006), CAD proved its advantage over paper-based design due to its ability to speed up replications within the design process (Holzer, 2015). 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). New features were later added to CAD systems that allowed a certain degree of interactive and precise control over smooth, doubly-curved, and complex spaces and geometries (Bhooshan, 2017). This has enabled architects to start migrating from Euclidean spaces and Cartesian grids (Kolarevic, 2004), and hence to provide habitats similar to those of nature (Bhooshan, 2016).

This tendency towards expanding the level of geometric complexity tractable appears to be a main factor that instigated the development of new software and modelling techniques to enhance generation, presentation and evaluation of complex forms. For this reason, architects started to interact with their tools using scripting to expand the functionality of traditional CAD applications by adapting, customising or completely reconfiguring software around their own predictions and modes (Burry, 2013). The main issue with scripting that might restrict its effective use, is its cognitive barriers as it requires new computation skills for designers (Oxman, 2017b).

New design approaches started to emerge, replacing the traditional ‘direct manipulation’ of geometry (Aish & Hanna, 2017) in CAD applications with new methods, such as algorithmic design, which relies on developing a set of genetic rules and instructions in the form of an algorithm to generate design forms (Frazer, 1995; Oxman, 2017b). This is where the concept of computational design started to emerge, whereby the digital technologies and computational methods were not only used as representational mediums for design forms, but also as integrated parts of the design process itself. In fact, using algorithms to generate geometry enabled the generation of novel design solutions that would have been impossible to achieve with traditional methods (Liu, 2010).

From Form-Based to Performance-Based Modelling

In searching for new values, efficiency and environmental meanings for these emerging design forms, tools and approaches, architects started to explore new ways to respond effectively to the 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 rapid 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 (Thomsen et al., 2015), 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).

From Individual to Collaborative, Integrated, and Data-Driven Processes

Collaboration and Integration

The tendency towards increasing the level of complexity in design forms, and the increasing need to enhance the environmental performance of these forms, is resulting in a situation where, within a single project, a wide range of federated and coordinated models are being produced (Whitehead, de Kestelier, Gallou, & Kocatürk, 2011), and several software applications from different natures are being utilised (Michalatos, 2016). This situation is resulting in increasing complexity in the design process (Oxman, 2006; Thomsen et al., 2015), and is instigating indispensable need to enhance collaboration (Kocaturk & Codinhoto, 2009), which is becoming the main engine for innovation in architecture (Kocaturk, 2013).

From this necessity, the new digital technologies are allowing 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 case, different processes and decisions, such as choice of materials, structures and fabrication technologies are integrated into the inception stage of the design process (Oxman, 2017b).

Information and Data

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 and data at any time across disciplines and stages within the design process (Eastman, Eastman, Teicholz, & Sacks, 2011; Eynon, 2016; Kolarevic, 2004). According to Kocaturk (2017, p. 167), one of the problems in conventional design systems is the difficulty and high cost of collecting data, where data format and structure required 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). From this limitation, the new digital technologies, especially Building Information Modelling (BIM) applications 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, the new technologies are allowing data to act as a new material for designers (Oxman, 2006), and as the 'new oil' of the digital age (The Economist, 2017) 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).

Authorship, Ownership and Copyright

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 appears to be 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.

From Usability to Reusability: Knowledge Transfer, Digital Libraries and Building Seeds

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). Therefore, new methods are necessary to enable information transfer and knowledge, not only across disciplines within a project, but also across different projects.

Research and Knowledge Transfer

Many architectural practices are increasingly relying on research to enhance information and knowledge transfer, in order to deal effectively with the rapidness in the evolution of technologies. For example, the 'Specialist Modelling Group (SMG)' is an in-house research group at 'Foster + Partners' that carries out project-driven research and development (Whitehead et al., 2011). According to Hugh Whitehead (the Head of SMG), the tools and methods 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 this research is to excavate from practice and analyse historical precedents and methods in order to create cognitive models, information processing models and design methods, in addition to develop prototypes and software to inform later work. 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.

Digital Libraries

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 TensorFlow, Keras, CNTK, Accord.NET, Microsoft Azure, Amzon 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., 2017), where the knowledge and experiences can be transferred across the globe rather than being limited to enterprise borders.

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; Thomson, nd). The main feature of such a kind of interactive website 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 site development industry to achieve similar sensational results.

From Computational Design to Parametric Design

Among the limitations of CAD applications and algorithmic design, the cognitive barriers of scripting, the shift towards performative modelling to support sustainability, the increasing need for collaborative environments and integrated platforms, together with the need to find the appropriate tool to empower the building seed concept, parametric design is emerging as a unique design approach to push some of those limitations and eliminate those barriers. Parametric design applications can 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 methods (J. Harding, Joyce, Shepherd, & Williams, 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). The explicit nature in parametric design tools can offer a unique opportunity for external involvement within collaborative environments (Jabi et al., 2017). Finally, the ability to record history of form generation within a graph (J. E. 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.

PARAMETRIC DESIGN AND THEORY

Despite the fact that parametric design falls under the umbrella of computational design, the authors of this paper differentiate parametric design from other computational design methods due to its unique features (Oxman, 2017b). In this regard, Schumacher (2009) coins the term ‘parametricism’ to refer to the inflation of the concept 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. This section explores parametric design features and its related tools within the wider context of computational design and the rapidly evolving digitally driven methods in current architectural practice. While both Picon (2016) and Oxman (2006) emphasise the essentiality of investigating historical precedents to understand recent phenomena and current transformations, most of the parametric design features are investigated here in relation to traditional CAD methods.

Definition of Parametric Design

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 Recyclable Buildings to Recyclable Processes: Parametric Design Tools and the Modality of the Design Process

The vast array of 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 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 paper is termed 'recyclable processes'.

Parametric Design Tools

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 programs (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).

The most popular parametric modelling software applications that rely on visual programming are Bentley's GenerativeComponents™ (GC), McNeel's Grasshopper™, and Autodesk Dynamo™ (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).

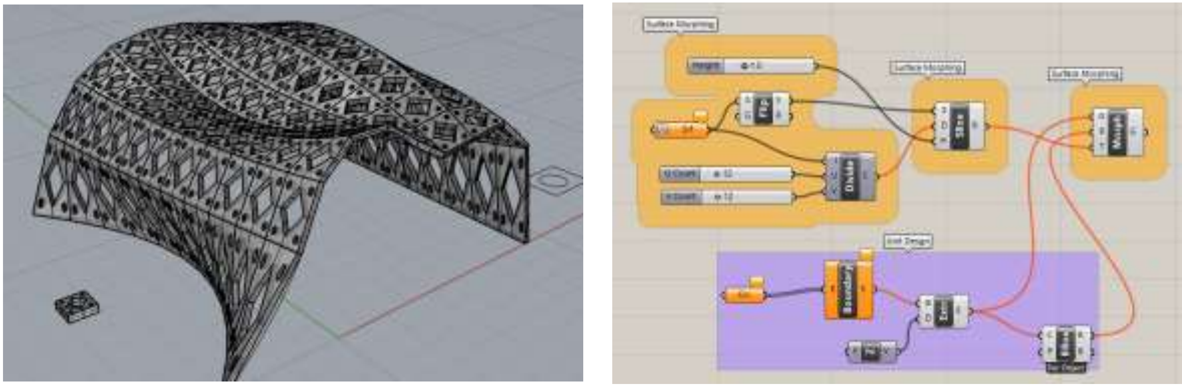

Figure 2: Simultaneous and interactive display of the graph and the design object

In a typical parametric design application, such as 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 2). Within this multiple representation, the building geometry is generated automatically while authoring the graph (J. Harding et al., 2012). The parametric graph 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 (J. 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).

Visualising the Design Process in Parametric Design Tools

Lawson (2011) highlights two design-related issues in architectural practice; 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, J. E. 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 (J. E. Harding & Shepherd, 2017; Jabi et al., 2017; Oxman, 2017b), rather than relying entirely on drawings (Lawson, 2011).

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 (J. 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 architectural practice transforms from a predefined fixed design to a process design (Anton & Tănase, 2016, p. 11). In other words, in parametric design applications, the design process can be designed in parallel to the design of a building, which is a new level in the design process.

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 (J. 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.

From Sustainable Buildings to Sustainable Processes: 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.

Capacity of the Design Space in Parametric Design

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, 2016). 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, generated and tested simply by manipulating parameters (Barrios, 2005; Bernal et al., 2015; Chaszar & Joyce, 2016; 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 (2016) refer to this phenomenon as ‘happy incidents’, whereby favoured design decisions are taken based on unintended results. 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. This shows how using a smart process such as parametric design can result in developing smart solutions.

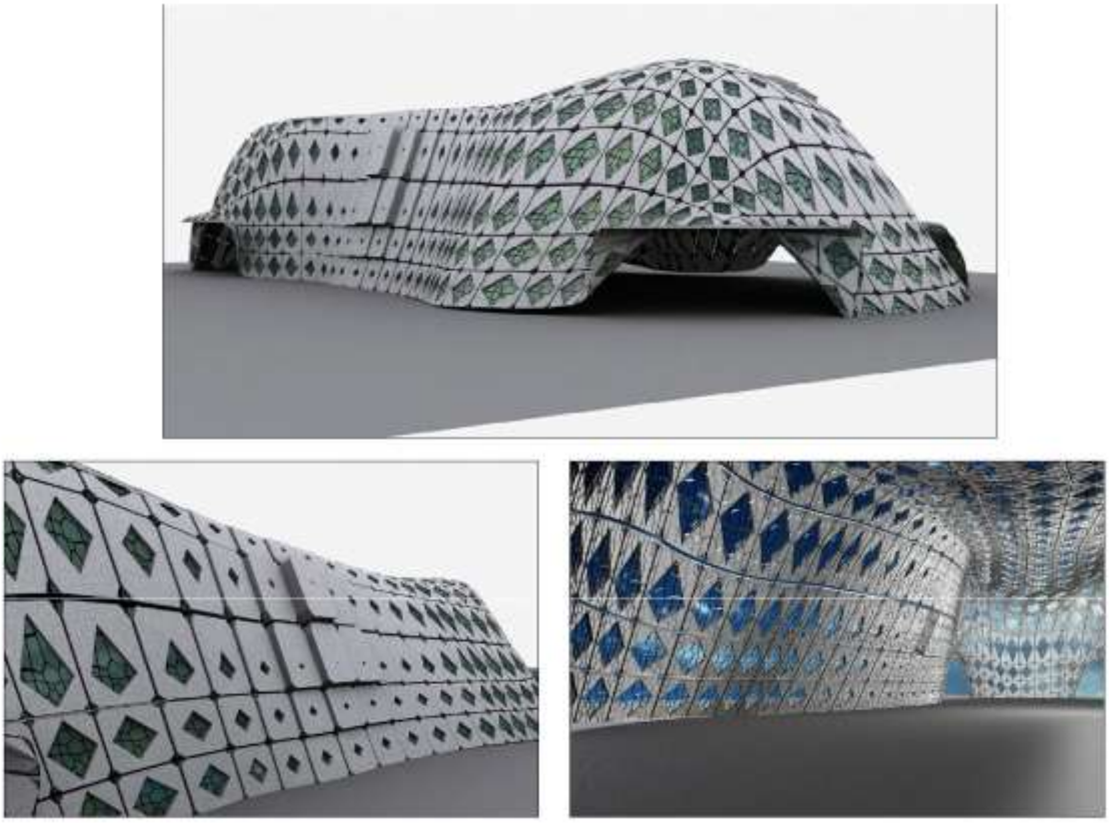

Figure 3: A doubly-curved surface consisting of environmentally-informed differential panels: Concept Design by Adonis Haidar, University of Salford (2009)

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 3) 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).

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 (J. Harding et al., 2012).

Flexibility and Modifiability in Parametric Design

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 (J. E. 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. J. E. Harding and 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, 2016).

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.

Parametric Design in Collaborative Environments

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. 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 results in digital continuity in the design process, from design to production (Kolarevic, 2004; Oxman, 2017b).

Parametric Design and Sustainability

As discussed earlier, 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. 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 stage 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 tools (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 obtained directly from 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 of flexibility, automation and synchronicity in generating 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.

CASE STUDY: PARAMETRIC DESIGN IN ARCHITECTURAL PRACTICE

The previous section discussed the potential benefits of parametric design in accelerating processes and so supporting sustainability within the design process, creating the necessity to explore this potential within real practice. In addition, the reusability of parametric definitions offered by parametric design tools, and its potential in enabling process recyclability, together with the disregard of this potential in the literature, all raise questions about the possibility, achievability, and efficiency of recycling parametric definitions in real practice and within real projects. Therefore, this section will investigate the benefits, impact and potential of using parametric design in architectural practice, and how parametric definitions can be re-used, recycled and hence, treated as building seeds in real architectural design projects.

Method

Case Study

Despite the large body of theory that is being produced to explain and document the significant potential of parametric design, this design methodology is still misunderstood (Jabi et al., 2017) and marginalised (Schumacher, 2016). This contradiction questions the maturity of the parametric design theory as it appears to be based on minimal practice. In fact, the novelty of parametric design and its rapidly evolving tools require continuous evaluation of its potential within research that relies heavily on practical and recent examples. While the case study research methodology involves the investigation of contemporary phenomenon in its real-world context (Yin, 2014, p. 16), this paper provides a different interpretation for parametric design features, through the presentation of the 'sustainable process' concept to enhance overall sustainability, as this needs further investigation in a practical context. A case study methodology is mainly used when the boundaries between phenomenon and context may not be clearly evident" (Yin, 2014, p. 16) as is the case here, through the disregard in the literature of the potential of reusing parametric designs across projects, together with the lack of practical context that can clarify how the seeding approach would work in real practice. Therefore, the case study methodology is appropriate for this research.

Parametric design is a design approach that represents the 'unit of analysis' and hence 'the case' in this case study. While the merits of parametric design will be explored within their practical context, they will be divided into the merits of parametric design as a design methodology and as a tool, which is the same way they were divided in the previous section.

The data were collected through semi-structured interviews to enable flexibility and depth in the investigation (Saunders, Lewis, & Thornhill, 2015). Interview questions were derived from the literature, and were narrowed down based on the specific objectives of the research to enable the investigation of the potential of parametric design in comparison to the arguments reviewed in the literature. The interviewees were asked about their views regarding the benefits of parametric design, and its role in supporting collaboration, together with the ability of reusing parametric definitions and the problems that may arise within practice.

The Participants

In an attempt to get the most valid and reliable results in the case study, the selection of participants focussed on establishing a high level and multi-faceted diversity amongst participants. Therefore, the participants were selected from different locations around the world. Moreover, they possessed different levels of experience and knowledge in parametric design, and so the participants are split into three groups: experts, competent users and researchers.

Group	Description	Participant code	Practice and position	Parametric Design Experience (in years)
Experts	Architects who have demonstrated efficiency and success in utilising parametric design in a wide range of architectural projects	E1	Digital Design Manager at different practices (USA)	9
		E2	Architect at architectural practice (Germany)	6
		E3	Architect and Mathematician at Architectural practice (UK)	5
Competent	Architects who have utilised parametric	C1	Architectural	2

Users	design successfully in a limited number of projects		Assistant at a leading practice, UK	
		C2	Senior Architect at a leading practice, UK	2
		C3	Architect at a construction company, Canada	3
Researchers	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	Senior Architect/ Researcher at architectural practice, Canada	-
		R2	Architect, Research Associate at a leading architectural practice, UK	-

Parametric Design and the Flow of the Design Process

According to the experts interviewed in this study, parametric design was heavily used in a wide range of architectural projects that ranged in scale from a chair to skyscrapers, and included an airport, a metro station and football stadium projects. In all these projects, parametric design demonstrated a higher level of efficiency in tackling design problems in comparison to conventional design methods. In general, there is a consensus amongst participants that tackling complex geometry problems is one of the main purposes for using parametric design, which demonstrates the potential of parametric design in giving access to a wider design space that cannot be explored using traditional methods.

Parametric Design and the Pace of the Design Process

E2 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, E2 emphasises the capability of parametric design in accelerating the design process, which is not the case in the reviewed literature, where the focus is on automation, flexibility, modifiability and all of the other aspects that appear to be progressive results, which lead to process acceleration.

According to E1, the most substantial contribution of parametric design is its ability to automate some activities within the design process by performing repetitive tasks. They argue that this function cannot replace the human, but allows the computer to be a repetitive machine, rather than the human, as was the case in conventional design methods. This is another argument that explains how parametric design enables the acceleration of the design process. Furthermore, automating repetitive tasks appears to have a significant impact on the design product, as it will save designers' time and effort, and hence, will give the opportunity to focus more on providing smart and highly performative buildings, rather than spending valuable-time on cumbersome and repetitive tasks.

The potential of parametric design in automating repetitive tasks and so accelerating the design process was demonstrated through an example given by E3. They stated that they used Dynamo to automatically provide the layout of seats in a large football stadium project in the

Middle East. Using Dynamo enabled them to embed the standards of a football stadium into the Dynamo script, and therefore, the height, location, and visual lines of all the seats were automatically set to comply with the standards in order to allow an appropriate view for all of the audience. E3 states that Dynamo was very effective in providing a high level of accuracy for the layout of the seats in a very short time. They also stated that using CAD for the same purpose could have resulted in the need to manipulate every single line of seats, and sometimes every single seat manually, which is extremely time consuming. This further demonstrates the capability of parametric design in automating repetitive tasks; the iterated process of dealing with each line of seats manually in CAD was replaced by a more smart process, whereby the layout was automatically generated from the Dynamo script. E3 noted that using Dynamo for this task resulted in a saving of at least 90% of the time needed to achieve the same results using CAD. The speed and accuracy of the seat layout demonstrates the capability of parametric design in accelerating the design process, while maintaining quality and compliance in the design product.

Parametric Design & Design Stages

While the literature shows a robust link between parametric design and the conceptual design stage, this case study 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 that participated in this study generally related parametric design to the early design stages only. For example, R2 stated 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. This is when developing algorithms becomes cumbersome and time consuming. In contrast C1, who used parametric design in several large-sized projects, claims that conceptual design can only be driven through freehand sketching and rough models, and therefore, parametric design is too complicated to be used in the early stages. To support their claim, C1 refers to their current work within a recent large project where parametric design was not used in the conceptual design stage, but in the construction stage for detailing, due to the accuracy it offers. In this regard, C3 supports the argument of C1 by stating that they effectively used Dynamo in construction projects for excavating site work, and for the process of refurbishing a building façade.

The experts that participated in this study were able to give detailed examples about how parametric design can be used in different stages throughout the design process. For instance, E2 reports using parametric design in the final stage of a metro station design project. In that project, Grasshopper was used for the rationalisation of the front façade of the metro station, where the façade was divided into differential panels, and another plug-in was used to enable automated generation of a schedule in Excel. The schedule included information about the shape, size, dimensions, coordinates, location and cost of each of the panels, in addition to providing number tagging for the panels to facilitate the installation of the panels on site. The schedule in Excel was automatically generated from the geometry created in Grasshopper, which was then sent to the fabricators at a late stage of the design process. In contrast, E3 states that they used Dynamo in the conceptual stage to generate site topography in Revit out of the point coordinates made in Dynamo. These various examples can be added to the previous stadium example discussed earlier where the layout of the seats was generated from a Dynamo script that appears to be at a late stage of the design process.

This conflict in explaining the potential of parametric design in relation to design stages highlights the difference in the level and nature of experiences amongst the participants. The theoretical experience of the researchers together with the lack of practical experience led them to link parametric design solely to conceptual design, while the practical experience of C1 and C3 enabled them to see its potential in later stages despite their limited experience. Meanwhile, the case study shows consensus amongst the experts that the potential of parametric design cannot be limited to a specific design stage, as it has demonstrated efficiency in different stages of the design and construction process.

The apparent reason for this conflict is that the mere theoretical knowledge of R2 and the lack of practical experience of C1 have led them to understand parametric design as a design method to be used as an alternative to traditional methods for the whole design process or for a whole stage within the design process. In contrast, the robust experience of the experts enabled them to reveal the potential of parametric design in relation to specific activities and specific tasks within the different design stages, such as driving a specific repetitive task, providing schedules for differential façade panels, or generating stadium seats within a CAD-driven design processes as in the previous examples. These examples show the flexibility of parametric design that enables it to be utilised to solve specific problems within the design process, rather than solely being used as an alternative to traditional methods. Parametric design is a flexible design methodology that can fit itself within a traditionally CAD-driven process without replacing or even disrupting the process.

Parametric Design and Integration in Collaborative Environments

In relation to the role of parametric design in supporting integration between architectural and engineering platforms, C2 states that parametric design was used in their practice for the documentation of both the design and construction processes. This is added to the efficiency of parametric design in the form finding and rationalisation processes by allowing the design to be seamlessly optimised against the structural and environmental performance of building. In this regard, E2 states 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 (Booshan, 2017; Hozler, 2015; Oxman, 2017).

In this regard, E2 explains how parametric design helped them in coordinating with the MEP external consultants in order to create circular bridges in one of the projects. Using Grasshopper allowed a high level of control over the complex and irregular form of the curved soffits that formed the bridge, while at the same time, being able to fit the ventilation ducts and mechanical systems into this complex geometry without affecting the functionality of the systems. To achieve this, the curved soffits and ducts were associated in Grasshopper, so that 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 flexibility of Grasshopper, together with the experience of the external consultants in using Grasshopper enabled the coordination required to address the problem. According to E2, using Revit for the same task would have been cumbersome, as it would have required feedback from the mechanical team for every single modification. This scenario shows another aspect of process acceleration that stems from the ability of parametric design tools in integrating 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 and file versioning.

Parametric Design and Digital Continuum

While Oxman (2017b) argues that using parametric design results in a digital continuity from design to production, this continuity stems from the integration of different design, structural and fabrication processes into the design process. As this continuity appears to be of a great potential in increasing the seamlessness and acceleration of the design process, it was thoroughly explored in this case study. R2 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, E1 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 E2, where several versions of the same 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.

The previous discussions show how using parametric design in architectural practice enables significant acceleration of the design processes by giving designers the capability to keep track of the design, automate repetitive tasks, and by offering flexibility that enables parametric design to be used for specific activities throughout the different stages of a CAD-driven design process. This acceleration is also established by facilitating integration with other disciplines, and by supporting continuity and interoperability between design and production. This acceleration will help architectural practice to reduce working hours, and hence to save energy and efforts within the design process.

PARAMETRIC DESIGN TOOLS AND THE MODALITY OF THE DESIGN PROCESSES

An important aspect of parametric design is the tools used to enable parametric reasoning to solve design problems. The capability to automate the generation of several design possibilities is enabled through scripting (Ceccato, 2010). However, the new parametric design tools that are currently emerging have a significant impact in their own right. This impact may, in some cases, exceed the scope of parametric design itself. This point is critical as revealed in the previous section, where the investigation needs to recognise the impact of parametric design as a concept from the impact of the tool itself.

Reusability and Recyclability of Parametric Design Definitions

With regard to the reusability of parametric definitions and the consequent capability of recycling the design process in parametric design, all of the participants indicate that parametric models can be saved and reused in different projects, and that this is essential when working in parametric design. In this respect, E3 states that the Dynamo script they developed for the stadium project was saved in order to be reused in similar future projects, which does not necessarily need to be a stadium. In fact, any project that requires seats to be distributed on several levels can benefit from this same algorithm developed for the stadium. On that point, E2 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 metro station 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 metro station building. In another project, the firm was involved in developing a design proposal of a football stadium project for an international architectural competition. Similarly to E3's stadium, one of the issues was the cumbersome and repetitive process needed to provide the layout of the seats. Considering the limited time available to provide the design, E2 searched online to find anything that was available to use. Within a short time, a pre-built Grasshopper definition for a football stadium was found, which had all 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, as in E3's case.

These are powerful examples that can blur the lines between the design object and the design process. In fact, in these examples, the design process is an object in its own right, and can be treated in the same way as a building. More precisely, the main focus of contemporary architecture is to provide intelligent and sustainable buildings, and to enable the different elements of a building to be recycled after the operational phase of the building ends. The design process in the design scenarios was treated the same way so that they were recycled. For example, the design of the staircase is a piece of process presented in the form of a parametric model. This same process (the parametric model) was taken forward for another building without the need to repeat the process again. In the stadium example, the parametric model of the seating area of the stadium project found online was taken, amended and reused in another stadium project. This same parametric model can continue to be reused in any stadium project. In this case, the parametric model represents one element of the design process that can be recycled for use in other similar projects, making the design process in parametric design truly recyclable. This may be another aspect that can be added to the discussion about saving time and energy within the design process. In fact, recycling processes can further accelerate the design process. For example, while E3 states that using parametric design for the stadium project enabled them to save 90% of the time, this process has the potential to probably save 90% of this remaining 10% of the time that is needed to build the algorithm from scratch.

Parametric Design and Building Seeds

With regard to the previous example about the reusability and the recyclability of parametric definitions, a 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 E2 found online represents a building seed that was taken from a previous project and 'planted' inside the environment of the new stadium project, whereby the associative parameters embedded in this definition enabled it to contextualise itself into the new project. In this regard, C2 provides an interesting example that shows a different approach of generating building seeds. While the previous examples show how the building seed can be generated in a project to be planted in another project, in C2's practice, they have some parametric design specialists from an in-house research group that dedicate some of their time to developing ready-to-use Grasshopper definitions for other designers in design teams to use in future projects. In other words, they spend time in generating seeds, but in this case, the seeds are not generated within the context of a real project, but separately and independently as part of their research.

Thus, following a few years of experience, designers can accumulate ‘building seeds’ developed either separately or within different projects to therefore establish a library of ‘seeds’ that can be consulted at the outset of any design project. In this context, R2 states that they are developing a ‘Script Bank’ to save scripts for use in later projects. In this case, each of the scripts represents a building seed. Similarly, C3 states that during their PhD research, they developed a similar library that contained parametric models. They call their library ‘LibraArchi’, and states that some of the contents of this library were used in projects within their practice. Within the same context, C2 states that parametric design tools will enable designers to create ‘Design Templates’ for the same purpose, where a designer only has to fill in parameters within these templates in order to develop a design project, rather than building the whole story from scratch for each and every single project.

PROBLEMS AND LIMITATIONS OF PARAMETRIC DESIGN IN PRACTICE

Based on the participants’ responses to the question about the problems of parametric design, problems were split into human-related and machine-related problems. The researchers mainly focused on the human-related problems. R1 attributes 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. In this sense, R1 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. Similarly, E2 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.

With regard to the machine-related problems, 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. For their part, E2 reports a set of technical problems in using Grasshopper; for them, parametric design applications are still not mature enough. They explored this immaturity on several occasions where they needed to use some complicated scripting to solve complex geometry problems such as trimming surfaces and recursion. They also complained about the contradiction between the graph space and the model space. In this regard, E2 states that many useful and essential commands in Rhino do not have counterparts in Grasshopper so that, on many occasions, they needed to build complicated Grasshopper definitions to achieve tasks that can be achieved with a few clicks in Rhino.

The results tend to suggest that despite the creative results that can be achieved with parametric design, this design methodology is still in its infancy. Thus, getting the most benefit from its potential is still subject to further maturation of the parametric design tools and wider adoption of this type of design in architectural practice.

DISCUSSION: SUSTAINABLE PROCESSES, RECYCLABLE PROCESSES AND BUILDING SEEDS IN PARAMETRIC DESIGN

While the potential of parametric design is limited to the maturity of its applications and the availability of the related experiences and knowledge in practice, the theory that underpins parametric design also requires continuous revaluation to respond to the rapidly evolving parametric design tools, and the general misunderstanding (Jabi et al., 2017) and marginalisation (Schumacher, 2016) of their potential. This section will focus on the potential of parametric design and its tools that are overlooked in the current literature. It will discuss the various levels in which parametric design supports sustainability in architectural design, and how the reusability of parametric definitions enables designers to recycle the design process and creating building seeds.

Sustainable Processes in Parametric Design

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 and 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 the case study, 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 the case study 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. Despite the fact that the paper focuses on the third level, all the previous three levels, in supporting sustainability, show that parametrically-driven design processes are truly sustainable processes.

Recyclable Processes in Parametric Design

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 deign 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 the case study through the consensus among participants about the reusability of parametric definitions across different projects. It was also exemplified in the case study 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 study, the designers developed a parametric definition to accelerate the design process, while in the second stadium project, 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.

Building Seeds in 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 the case study, the parametric definition that was developed to generate the staircase in a previous project was not only reused and hence recycled in the metro station 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 metro station. 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 project 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.

THE SEED LIBRARY: PRACTICAL IMPLEMENTATION AND FUTURE POTENTIAL

The case study shows 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 as discussed in the previous section. The second is to create seeds from scratch independently to feed future design processes, which was discussed in the case study 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 study, such as 'Script Bank' and 'LibraArchi' where designers develop a library that contains different scripts and parametric definitions for future reuse.

Online Seed Library

This seed library may be more effective if it is shared online and open to the general public to view, use and edit. Therefore, 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 is not new, it is, in fact, 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 earlier. 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 distributed intelligence in design (Kocatürk & Medjdoub, 2011) on a project or an enterprise level to achieve innovation, they can rely on global distributed intelligence.

Validation of seeds

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. In the case study, a designer 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. The other designer 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 and parametric definitions that need to be accessible by all architectural practices. This will enable other designers to develop the definitions further. For example, they can 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.

Motivation

Another important issue 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 the designer 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 the designer who downloaded the pre-built parametric definition 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 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 seeds 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 the potential.

CONCLUSION

The authors have investigated the potential of parametric design by focussing on the aspects that are largely overlooked in the literature. It showed four levels in which parametric design supports sustainability in architectural design. These levels stem from the ability of parametric design in spanning the design space, giving accessibility to more complex forms, accelerating the design process and recycling the design process. We have demonstrated how the reusability of parametric design definitions can ideally represent the building seed concept discussed in the literature, and that seeding can only be applied through using applications that support associative parameters. Furthermore we have suggested the creation of a seed library and discussed the potential of sharing the library online and making it available to the general public to widen contribution and enrich the library's content. In that sense, the work discussed how designers could inspire different innovative approaches and ideas applied in the software industry and web 2.0 development industry, to enhance the validity of the library content and to motivate highly intellectual computational design specialists to publish their algorithms, scripts and parametric definitions to the library for the general public to view and edit.

In general, the work shows how parametric design can help in developing sustainable processes, recyclable processes and building seeds, in the effort towards environmental sustainability. The concepts may help designers in rethinking sustainability in building projects, and may help to push towards a more holistic understanding of sustainability whereby thinking about environmental variables can start from the very initial stages of the design process, and continue seamlessly across the different design stages and across different projects. Understanding the building seeds concept could help designers in shifting the focus from creating sustainable design solutions for a specific building project, to creating a sustainable design strategy that works across different projects. This will not only enable designers to develop smart and intelligent processes, it will offer designers more availability of time and effort to focus more on the intelligence of the building itself, and help the flow of information, knowledge and processes from one project to another. Therefore, designers will be able to develop smart processes for smart buildings.

The seed library requires further research to support efficiency and enhance validity and motivation. For example, more focus might be required on the machine learning approach and its potential in gradually enhancing the capability and accuracy of search engines of the library. Furthermore, the seed library could benefit from artificial intelligence systems that might help users to automatically find the ideal seed that matches the current design situation. This will enable more automation and further acceleration of the design process. In addition, more focus could be placed on exploring precedents, whereby the existing libraries can be treated as case studies so that the development of the seed libraries could benefit from the potential and issues of those existing libraries.

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