Developing an IFC interoperability specification for integrated and energy efficient building design

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Abbreviations

AEC: Architecture, Engineering and Construction

BEP: BIM Execution Plan

BIM: Building Information Modelling

BPMN: Business Process Modelling Notation

BPS: Building Performance Simulation

BREEAM: Building Research Establishment Environmental Assessment Method

CBP: Cross-organizational Process Business Processes

CO_2: Carbon Dioxide

DOE: US Department of Energy

EPBD: Energy Building Performance Directive

GHG: Greenhouse Gases

IFC: Industrial Foundation Classes

IPCC: Intergovernmental Panel on Climate Change

LEED: Leadership in Energy and Environmental Design

MIDP: Master Information Delivery Plan

NASA: National Aeronautics and Space Administration

PIP: Project Implementation Plan

PIM: Project Information Model

PPM: Parts Per Million

SD: Sustainable Development

STEP: STandard for the Exchange of Product

TIDP: Task Information Delivery Plan

UKCIP: United Kingdom Climate Impacts' Programme

UML: Unified Modelling Language

UN: United Nations

UNCHE: United Nations Conference on the Human Environment

UNFCCC: United Nations Framework Convention on Climate Change

USGBC: U.S. Green Building Council

WCED: World Commission on Environment and Development

ZEB: nearly Zero-Energy Building

Abstract

Human activities release greenhouse gases (GHG) that are warming and changing the climate and putting at risk the life on the planet. Among these activities, the building sector has an important position as it consumes 30-40% of global energy. The primary use of energy is domestic heating, and it contributes 12% of GHGs. More efficient housing design should mean a reduction in the carbon emissions generated by the building sector.

Unfortunately, current energy design tools are not sufficient enough to deal with this problem. Energy rating and standards are able to evaluate energy performance and reduce energy consumption respectively, but they are not able to represent the complexity of the multiple variables involved in energy performance. Recent methodologies such as Building Information Modelling (BIM) and Building Performance Simulation (BPS) have been able to handle the complexity of energy simulation. Nonetheless, the current interoperability issues need to be improved to allow the collaboration of both disciplines.

This research proposes to develop an interoperability specification for integrated and energy efficient building design. This standard will allow any user to integrate BIM and BPS tools in order to facilitate the workflows between both disciplines and to promote an early collaboration with the energy designer to achieve a better energy performance and, consequently, lower consumption and fewer carbon emissions.

Acknowledgement

Before starting with the acknowledgements I would like to express what this dissertation has meant for me. From an academic point of view, it has become a challenging task pushing me to go deeply into topics that I have tried to avoid before such as actually understanding how the IFC structure works or how to execute an energy simulation. From a personal point of view, it has made me aware as to how real the environmental problem is. At the time of writing these acknowledgements, it has been identified that one of the biggest ecosystems in the world, the Great Barrier Reef, has an irrecoverable damage of 30%. Fortunately, there is good news too, in that last April Portugal was able to work for four days entirely utilising only renewable energy, becoming clear proof that countries can work using these kinds of energies.

Now to proceed to the acknowledgements. Firstly, I would like to thank my tutor, Yusuf Arayici, for his patience and for giving me this opportunity with this new degree. It was something unexpected for me, and I really appreciate what he has done for me. I did my best, and I hope not disappoint him. Secondly, I would like to thank the Director of the THINKlab, Terrence Fernando, for allowing me to be involved in this research and allowing me to keep growing professionally and as a person. Thirdly, thanks to Hanneke van Dijk for her valuable help in suggesting changes and proofreading this dissertation. Thanks, Hanneke! Finally, but not least importantly, thanks to my parents: gracias papas por el apoyo y animo que me han brindado a la distancia. Espero haber sido digno de su ejemplo, y espero poder abrazarlos y besarlos luego, los quiero.

In this world there is room for everyone. And the good earth is rich and can provide for everyone. The way of life can be free and beautiful, but we have lost the way.

Charles Chaplin, The Great Dictator (1940)

Chapter 1. Introduction

1.1. Motivation

For years there has been discussion about the veracity of climate change and the role of human activities as the main instigators of it. Some sectors have denied this situation stating that global warming is a natural cycle of the weather on the planet. Nonetheless, there is enough data to set human activities as the primary cause for this issue. The change in the climate will affect the environment and living beings across the planet in multiple ways.

The climate issue has been discussed in several conferences attended by multiple governments. These conferences have focused on reaching agreements and setting goals to control the warming problem. The most recent conference (held in December 2015) brought about the Paris Agreement. This agreement came to an understanding regarding keeping global warming below 2°C but with an urgent call to limit it to 1.5°C above pre-industrial levels. Thus, to meet this goal, each country will be required to adjust their economic activities in order to reduce their carbon emissions. The building sector is a major carbon producer. This sector consumes 30-40% of the global energy with around 25% of it being utilised in heating and cooling buildings. Thus, improving energy design, would mean a reduction in energy consumption and, consequently, fewer carbon emissions.

Currently, energy design is a very backwards field that is based on the use of rating systems to evaluate performance or standards to reduce energy consumption. Unfortunately, these tools are not able to represent all the variables involved in a project, and their results will present a possible solution but not necessarily the best option that maximises the beneficial factors involved in a project. Indeed, the right procedure should be an iterative simulation until a suitable solution is found for the project's requirements.

In recent years Building Information Modelling (BIM) has advanced as a promissory method in designing and coordinating multiple strands of information throughout the whole lifecycle of a project. Indeed, this discipline is understood as a natural complement to Building Performance Simulation (BPS).

However, both disciplines are not integrated yet. As a consequence, energy simulation is undertaken as late as possible within the architectural design (i.e., when the design has been mostly defined) to avoid losing time in adding missed data in the model. A late energy analysis makes it impossible to introduce significant changes in the project because any change at this stage will mean a low-performance impact but a high financial cost.

Keeping in mind this problem, this research proposes to develop an interoperability standard to integrate BIM and BPS tools. This specification will be vital for the project Design4Energy (D4E) which aims to predict the current and future energy efficiency of a project both at the individual and neighbourhood level. The design data will be created for different stakeholders at various stages; then the appropriate interoperability will allow for the sharing and reusing of the output from multiple designers.

1.2. Research Question

How can BIM/BPS tools work collaboratively to enhance energy efficient design during the design stage?

1.3. Aim

To define an interoperability specification to allow a collaborative energy efficient design via BIM-BPS tools

1.4. Objectives

- To conceptualise a BIM-based collaborative platform using a range of models such as IDM and MVD.
- To identify the core challenges, including process, technology, and people related issues within energy efficient design.
- To explore the state–of-the-art for interoperability to build up a contextual understanding of integrated design.
- To explore the sustainable development concept and how such a concept can be implemented to understand the importance of energy efficient design.

1.5. Research contribution

This research will build up knowledge around the interoperability between BIM and BPS tools. This knowledge will be fundamental to the success of the D4E project, thus allowing for the information exchange of data generated by different stakeholders using different tools at different stages of the project lifecycle.

1.6. Dissertation structure

This dissertation is divided into seven chapters plus an Appendix. Chapter 1 presents the motivation, the research question, aim and objectives, and the contribution of this study. Chapter 2 introduces the concept of sustainable development, the consequences of climate change, and the energy ratings and standards currently used in sustainable design. Chapter 3 presents the BIM and BPS concepts, their features and challenges, and the state-of-the-art within the field of interoperability. Chapter 4 introduces the research methodology used in this study (the onion methodology has been selected) and then each component of this method is presented with the objective of explaining how this research will be undertaken. Chapter 5 introduces the first part of the research. It focuses on describing the interoperability from a non-technical point of view using IDM methodology.

Chapter 6 uses the outputs from chapter 5 to develop the interoperability from a technical point of view using MVD methodology. Finally, the Appendix presents the results from chapters 5 and 6.

Chapter 2 Sustainable development and the AEC industry

This chapter, as its objective, wishes to note the importance of the concept of sustainable development and the negative impact that a lack of it has on the environment. Climate change is the most important consequence of economic growth that does not take into consideration environmental and social factors. Once the chapter has introduced the concept of sustainable development and the implications of climate change, the protocols to address carbon emissions will be presented. Finally, there is a discussion of the design methods that architecture, engineering and construction (AEC) are using to reduce carbon emissions from within their projects.

2.1. Towards sustainable development

Sustainable development (SD) is a relatively new concept. Indeed, it was only in the early 1960s when different environmentalist organisations warned about the threats caused by issues such as population growth, pollution, natural resource depletion and what these would mean for the environment and, consequently, for humankind (Peura, 2013).

Defining SD has been challenging because of the need to integrate issues and interests from different areas. Mebratu (1998) identifies three distinct stages that define what SD has gone through in order to reach what can be regarded as the current concept:

- Pre Stockholm Conference

This stage covers the period before the Stockholm Conference on the Human Environment (1972), and it is characterised by a total unawareness of the impact of human activities on the environment and a complete absence of the SD concept. However, several experts had described how a lack of natural resources had affected their areas, e.g. Georg Agricola, a German mining engineer, described the negative impact of woodcutting and mining on wildlife in the 16th century; Marchand and Wilhelm Gottfried Moser, forestry experts, criticised the overconsumption of wood in the 18th century, and they put forward recommendations to conserve the forests (Du Pisani, 2006). The most famous essay from this stage is “An essay on the principle of population” written in 1798 by the demographer and political economist, Thomas Robert Malthus. In this document, Malthus recognised a possible lack of resources when food production could not keep pace with the growth of population (Paul, 2008).

- From Stockholm Conference to the UN World Commission on Environment and Development (WCED)

This stage is between the Stockholm Conference on the Human Environment (1972) and the UN World Commission on Environment and Development in 1987. This period is distinguished for the awareness of the risks that environmental issues such as population growth, pollution, and natural resource depletion would mean for the whole of life on the planet (Du Pisani, 2006; Peura, 2013). An increase in concern about environmental problems was due mainly to the book “The Limits to Growth” published in 1972 by a group of eminent economists and scientists, known as the Club of Rome. This document had a great impact because it used computer simulations to show the limited supply of natural resources that the planet has and, consequently, how overexploitation could endanger humankind (Du Pisani, 2006).

This publication was criticised because of its extreme environmentally-centred view leading to proposals for drastic schemes such as limiting or banning economic growth to protect natural resources (Kidd 1992; Hill and Bowen, 1997). The opponents to such an approach argued that any commercial restrictions would increase inequalities between countries (Du Pisani, 2006; Paul, 2008) especially in developing countries that need a higher economic growth to reduce poverty (Mitcham, 1995). Another problem with this approach is the assumption that there will be an exponential growth of population and industrial capital; as a result, pollution and the demand for resources would grow in the same way until depletion (Paul, 2008).

Additionally, in 1972, the United Nations Conference on the Human Environment (UNCHE) was held in Stockholm to discuss for the first time the environmental problem as a political issue of international importance (DTI, 2004). This conference was critical to changing world opinion about economic development and its consequences on environmental degradation and the well-being of the world's population (Kidd, 1992) but it was unable to integrate fully the environmental approach with the need for economic development. The partially integrated approach was particularly rejected by developing countries who viewed this approach as an excuse by developed economies to put a brake on developing countries' growing economies (Mebratu, 1998).

In 1987, the UN World Commission on Environment and Development (WCED) tried to integrate both environmental and economic approaches by publishing the Brundtland Report. This publication was focused on the social and economic goals of society and on ensuring a global equity for future generations by redistributing resources towards poorer nations to promote their economic growth (Du Pisani, 2006; Hill & Bowen, 1997).

SD is defined by WCED (WCED, 1987, pp 43) as the development ***"…that meets the needs of the present without compromising the ability of future generations to meet their own needs…".*** This definition has two key ideas: firstly, the concept of 'needs' considers economic and social needs in a generic way because these needs can be different for developed and developing countries. Secondly, this statement contains the idea of soft limitations imposed by the current state of the technology and social organisations on the environment´s ability to meet present and future needs (Kidd, 1992).

Even though this definition has been able to balance social, economic and environmental needs (Du Pisani, 2006), this balance does not mean a call for any transformation in economic growth (Carter, 2007). Indeed, the ambiguity in this meaning of SD (Bartlett, 2006) has made possible new interpretations of the concept according to the needs of any economic sector. As a result of these multiple interpretations, many organisations see the term SD as a form to perpetuate corporate interests but giving the impression of adherence to SD (Euractiv, cited by Du Pisani, 2006; Johnston et al., 2007).

- Post WCED

Previous stages focused on recognising and identifying sustainable development issues. In this stage, there is a call for action through multiple meetings to reach agreements that allow for a reduction in the impact of human activities on the environment.

In 1992, the UN Commission on Sustainable Development (UNCED) held an Earth Summit in Rio de Janeiro. This meeting gathered together 114 heads of state, 10,000 representatives from 178 countries and 1,400 non-governmental organisations to discuss how to achieve SD (Paul, 2008). The key outcomes of the conference were the Rio Declaration on Environment and Development and Agenda 21 (Nef, 2009). The Rio Declaration acknowledged the responsibility that developed countries have in global environmental degradation and, as a consequence, the fact that these countries need to pursue sustainable development because of the impact that their population has had on the environment and on the technologies and financial resources that they have. Agenda 21 is a set of practices and recommendations to be implemented by each country to develop their sustainable development strategy. Also via Agenda 21, developed countries reaffirmed contributing 0.7 percent of their annual gross national product (GNP) for development assistance and the transfer of environmental technologies to developing countries (Murphy & Drexhage, 2012).

2.1.1. Triple Bottom Line paradigm

As pointed out above, the WCED´s definition for SD became the starting point for new interpretations. Indeed since 1987 almost 400 new definitions have been developed (Johnston et al., 2007; Woodhouse, Howlett, & Rigby, 2000). Even though this number is large, all these definitions have been developed in terms of the three dimensions proposed in the WCED definition: environment, economy and society (Kuhlman & Farrington, 2010; Harris, 2003).

The most important of these interpretations was made by Elkington in his book ´Cannibals with Forks´ published in 1997. The central idea of Elkington was to recognise the business paradigm that SD will play in the 21st century, highlighting the need for the adaptation of economic systems to new requirements from governments and business leaders as a solution for a broad range of problems on the international agenda (Elkington, 1997). Using the elements introduced by the Brundtland Report, Elkington challenged the traditional ´bottom line´ which focuses on economic performance, to create an accounting and report tool called Triple Bottom Line (TBL). This tool puts together economic, environmental and society needs as indicators of the success of a company (Curtis, Davidson & Mitchell, 2007; Jonker & Harmsen, 2012; Kuhlman & Farrington, 2010).

Figure 2.1 shows each dimension and their interaction under the TBL paradigm (Elkington, 1997; Harris, 2003):

- Environmental: this aspect is concerned with how natural resources are affected by current and future operations, ensuring a stable base of natural resources, avoiding over-exploitation of renewable resources and proposing mitigation activities for the exploitation of non-renewable resources.

- Social: this dimension promotes fairness in distribution, opportunities and access to social services. Equality in access to resources will lead to trust between different groups making working together easier for a common purpose such as sustainability.

- Economic: this dimension produces goods and services that are constant in time, creating profitable growth for stakeholders under controlled risks and avoiding imbalances which could damage industrial production.

Jointly alongside these three dimensions, TBL introduces multiple interactions or ´shear zones´ between each dimension; thus to achieve the goals will require the fulfilling of the requirements of these new sub-dimensions. The intersection of any bottom line defines the zones shown below (Elkington, 1997):

- Eco-economy: the delivery of competitively-priced goods and services satisfying human needs and quality of life. It implies reducing ecological impact through the efficient use of resources and energy.

- Socio-environmental: deals with natural resources to ensure they will remain available in the short and long term for future generations.

- Socio-economic: changes the traditional relationship between companies-employers-communities, creating companies which are socially responsible and which are concerned about their actions and the impact that they have on different actors.

Finally, figure 2.1 shows an overlap between the three bottom lines. The intersection of these dimensions defines SD as an attempt to achieve economic growth while also protecting the environment without any trade-off and links social equity to the environment (Carter, 2007). For Elkington, SD is not a matter of business ethics, it is a strong metric based on financial performance, impact on the economy, the environment and the society in which it operates (Savitz & Weber, 2006). The success of any company will depend on how well the three bottom lines are balanced (Harris, 2003).

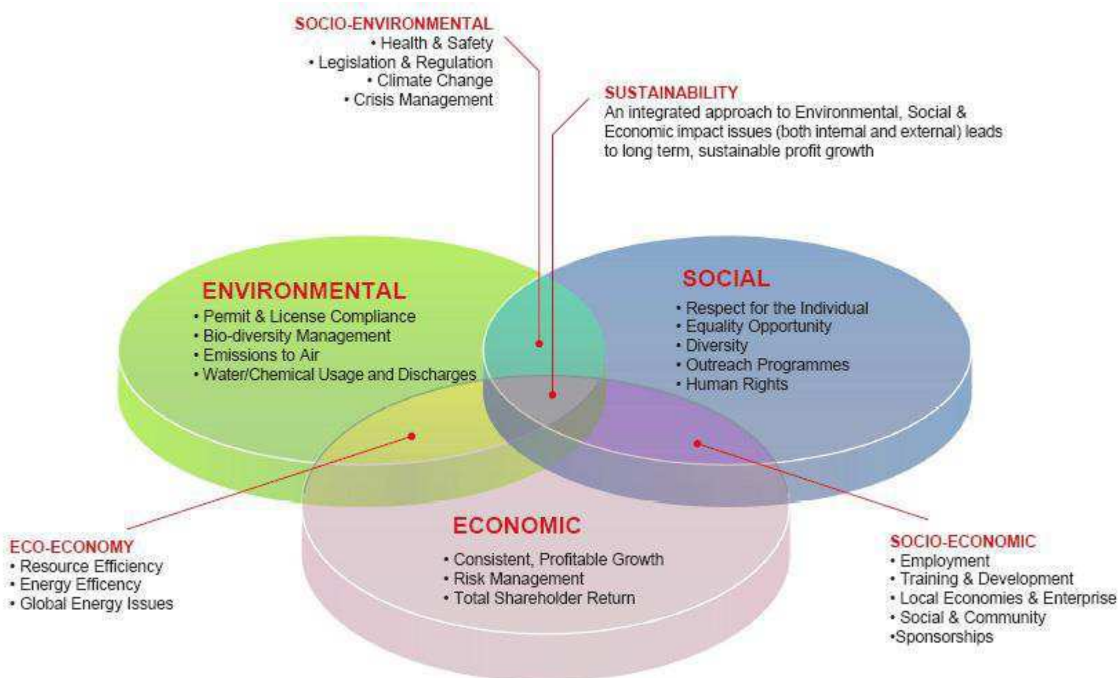

Figure 2.1. Triple Bottom Line (Mann, 2009)

2.1.2. Criticizing TBL

The TBL paradigm was widely accepted and distributed by companies such as AT&T, Dow Chemical, Shell and British Telecom which saw in this approach a chance to balance environmental, social and economic needs (Curtis-Davidson & Mitchell, 2007; Jonker & Harmsen, 2012; Norman & MacDonald, 2004). Multiple governments adopted the TBL approach because of the enthusiastic reception given it by industry. Finally, TBL was adopted in the United Nations World Conference on Sustainable Development in 1992 (Jonker & Harmsen, 2012).

Despite the broad acceptation of Elkington´s definition, the literature shows some drawbacks in the TBL paradigm:

- A lack of Key Performance Indicators (KPIs): the absence of a clear set of indicators to measure organisational performance (Jackson, Boswell & Davis, 2011; Sridhar, 2011) makes it difficult for any organisation to check their strategic objectives

(Curtis-Davidson & Mitchell, 2007). As a result, a company will not be able to compare outputs over goals and, consequently, it will not be able to take appropriate actions to grow sustainably. Thus any goal and objective will just be a declaration of good intentions (Mitchell, Curtis & Davidson, 2008).

- Difficulty in accounting for the social dimension: social impacts cannot be precisely defined since impacts in a community and on individuals are varied, e.g. metrics such as loyalty and charitable donations are complex to determine because they regularly change (Sridhar, 2011). Norman and MacDonald (2004) state that it is impossible to find a universal scale to weigh the ´good´ and ´bad´ impacts caused by a firm, thus to create a methodology to measure this dimension is not possible.

2.2. What is climate change?

Climate change has been a matter of discussion for years. During the first half of the twentieth century, it was thought as a natural phenomenon caused by volcanic activity or by a change in the amount of energy emitted by the sun (Emmanuel & Baker, 2012). Nonetheless, there is substantial evidence to suggest that natural factors on their own cannot influence or change the climate to the levels observed in the latter half of the last century. Thus it is clearly seen that this change is driven by external factors (Lockwood & Fröhlich, 2007; Somerville & Jouzel, 2008; Terpstra & Russow, 2011).

In 1989 the United Nations (UN) asked the Intergovernmental Panel on Climate Change (IPCC) to develop a series of assessments to understand the climate issue and its importance for public policy (Somerville & Jouzel, 2008). These reports recognised climate change as a real problem that could represent a threat to life on the planet. In the Third Assessment Report (TAR) published in 2001, the IPCC concluded: ´there is new and stronger evidence that most of the observed warming observed over the last 50 years is attributable to human activities´ (IPCC, 2001, pp5). This conclusion was reinforced in 2007 with the Fourth Assessment Report (AS4). It stated that: ´it is very likely (>90% probability) that anthropogenic greenhouse gas increases have caused most of the observed increase in global average temperatures since the mid-20th century´ (Jenkins, Perry & Prior, 2008).

For the UN (UN, 1992, pp 7) climate change is *"…a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods…".* Whereas for the IPCC (IPCC, 2007, pp 30) climate change means *"...a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity …"*

2.2.1. Evidence of changes in global climate

The indicators used to measure changes in the environment are multiple, and they differ from one organisation to another. For example, the United Kingdom Climate Impacts' Programme (UKCIP) uses temperature in Scotland and Northern Ireland, precipitation over the UK, North Atlantic oscillation, storminess, coastal sea-surface temperature, and the sea level around the UK. On the other hand, the IPCC uses GHG' emission levels, atmospheric GHG concentration levels, changes in global mean temperature and a rise in sea-level, changes in regional climate variables and modifications in the intensity or frequency of extreme events. Independent of any organisation, the most important parameter is the global average surface temperature (UKCIP02, 2002), because it is a parameter that is easy to identify, and there are a large number of observations dating from the mid-19th century. Thus it establishes a solid database to understand recent changes (IPCC, 2013).

In this dissertation, the IPCC´s parameters will be used because of their universal character. Also, the facts shown by IPCC are more consistent, having developed reports in 1990, 1995, 2001, 2007 and 2014. In each of them, the data is compared with the previous report and a projection for the coming report is also undertaken (Somerville & Jouzel, 2008).

- **Changes in global mean temperature and a rise in sea-level**: The atmosphere and the oceans have increased in warmth by 0.85°C during the twentieth century (IPCC, 2013; Jenkins, Perry & Prior, 2008) with most of this rise occurring in the last 25 years (IPCC, 2007).

  Figure 2.2 shows information on temperatures from three different sources. It is clear that the combined temperature of the land-ocean has been rising since the 1950s. Indeed, the period 1983-2012 was the warmest 30 year period in the last 1,400 years in the Northern Hemisphere (IPCC, 2014a). Additionally, the National Aeronautics and Space Administration (NASA) has pointed out that 2015 has been the warmest year since modern temperature records started in 1880 (Norton, 2016).

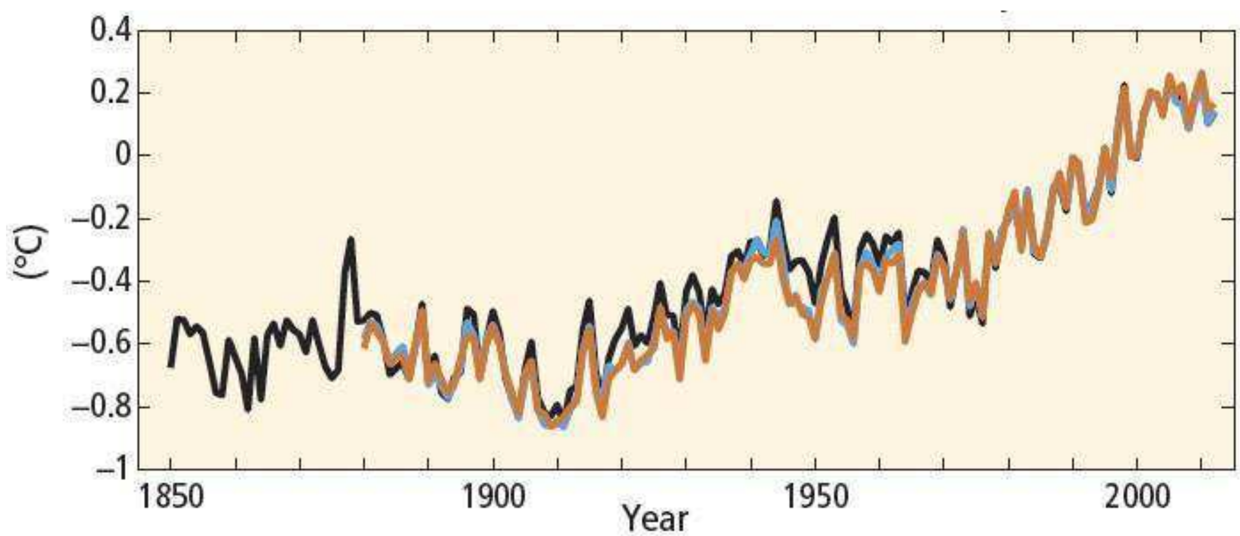

Figure 2.2. Globally averaged combined land and ocean surface temperature (IPCC, 2014a)

The oceans have absorbed around 80% of this warming in the atmosphere (Somerville and Jouzel, 2008). As a consequence, the temperature in the oceans has increased at a rate of 0.11°C per decade between 1971 and 2010 (IPCC, 2014). The polar masses have been affected by this overheat. The Arctic ice is losing mass at a rate of 3.5-4.1% per year while the Antarctic ice is gaining 1.2-1.8% of mass per year (IPCC, 2007). Figure 2.3 shows an increase in the sea level as a result of the melting icecaps. The rate has been rising at 1.7 mm per year during the last century (Terpstra & Russow, 2011).

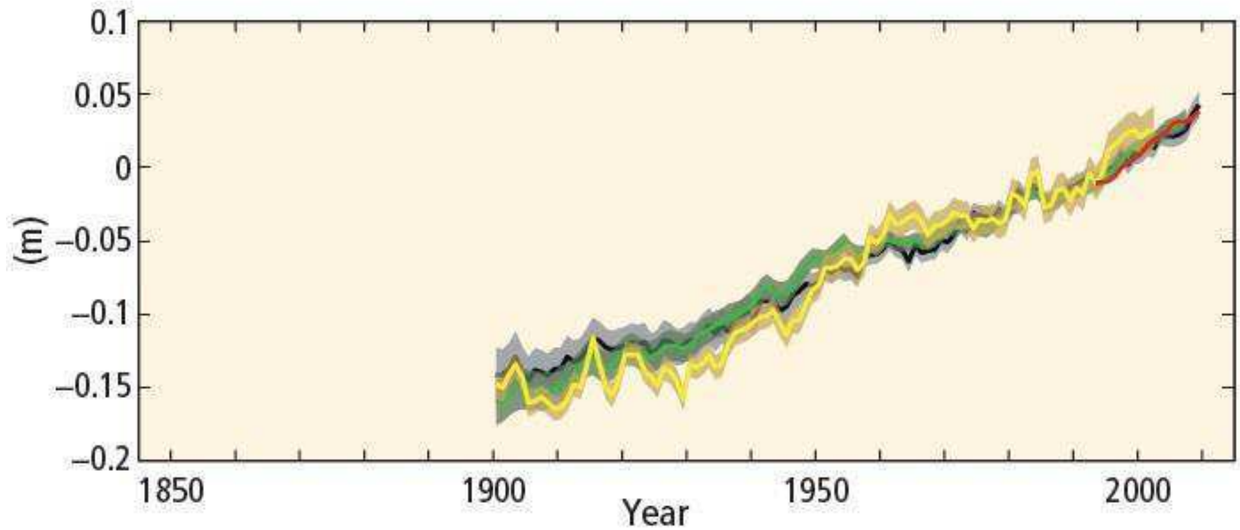

Figure 2.3. Globally averaged sea level change (IPCC, 2014a)

- **GHG emission levels**: Undoubtedly, human activities are responsible for increasing GHG emissions (carbon dioxide, methane and nitrous oxide) (Marland & Boden 2002). Figure 2.4 shows that half of GHG emissions have happened between 1970 to 2010, with CO_2 being the main contributor with 78% of the emissions (IPCC, 2014a).

  Each GHG has a different lifetime in the atmosphere (50 to 200 years) before being absorbed by the ocean, vegetation or by a chemical reaction (Gautier & Le Treut, 2008). Nonetheless, the atmosphere is not capable of absorbing an overload of emissions and around 40% of GHGs stay in the atmosphere (IPCC, 2014a).

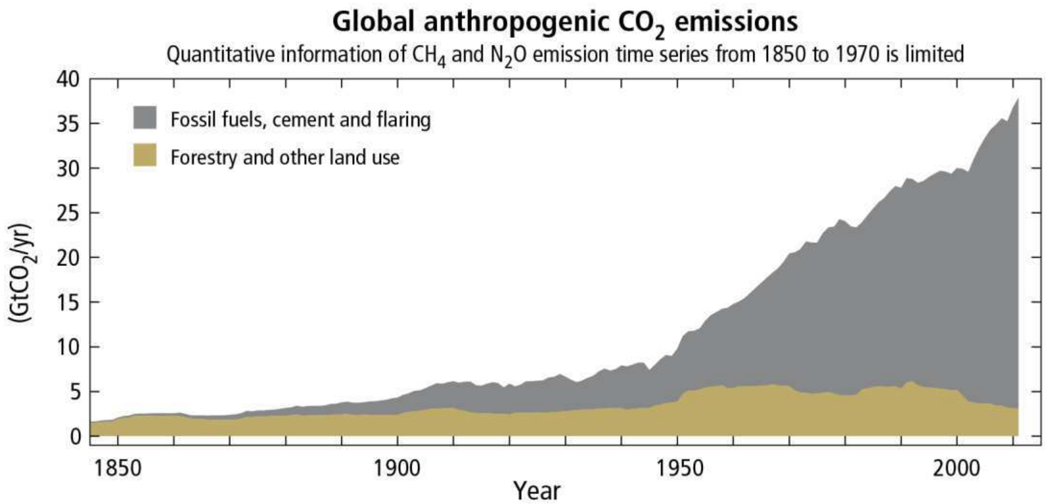

Figure 2.4. Global anthropogenic CO_2 emissions (IPCC, 2014a)

- **Atmospheric GHG concentration levels**: along with the increase in emissions, the concentration of GHGs is rising too. GHG concentration has grown faster since the 1950s to reach levels not recorded in 800,000 years (IPCC, 2014a).

  As shown in figure 2.5, the concentration of CO_2 (shown by the green line) reached a worrying level of 350 parts per million (PPM) early in the 1990s. Concentrations over that level will make it difficult to keep the global temperature going up by below 2°C by the end of the 21st century (Terpstra & Russow, 2011). Even worse, the concentration levels have kept growing in recent years with a CO_2 concentration of 403.19 ppm in 2016 (Tenenbaum, 2016). According to Barnola et al. (1999), the last time that the GHG concentration exceeded 300 ppm was 420,000 years ago.

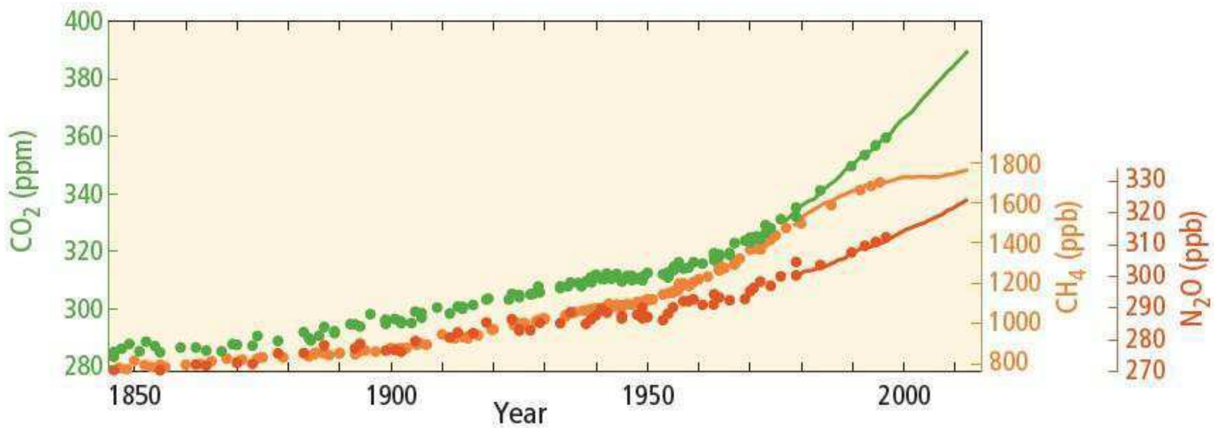

Figure 2.5. Globally averaged greenhouse gas concentrations (IPCC, 2014a)

- **Changes in regional climate variables:** there is substantial evidence on how climate change is affecting natural and human systems. These changes are altering the availability and quality of water because of altered precipitation patterns and altered amounts of snow and ice (IPCC, 2014a).

Figure 2.6 summarises where the main effects of climate change can be seen across the world:

- Rivers, lakes, floods and/or drought across North, Central and South America, Africa, Asia and Australasia.
- Glaciers, snow, ice and/or permafrost in all continents and the Polar Regions.
- Terrestrial ecosystems in North America, Europe, Asia, Africa and Australasia.
- Marine ecosystems in North, Central and South America, Europe, Africa, Asia and Australasia.
- Food production in Central and South America, Africa and Australasia.
- Livelihoods, health and/or economics in all continents.

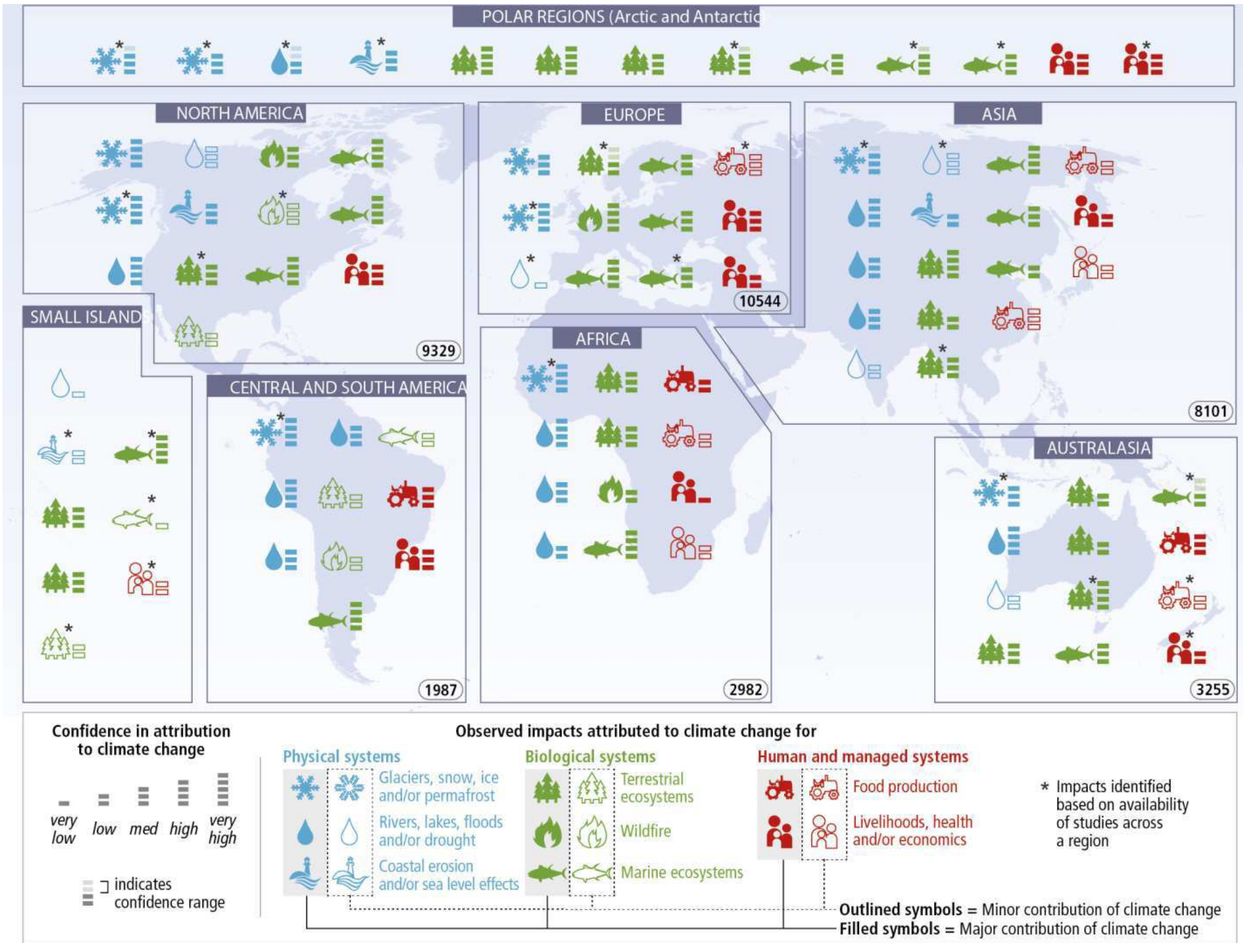

Figure 2.6. Widespread impacts attributed to climate change (IPCC, 2014a)

- **Variations in the intensity or frequency of extreme events:** the number of extreme events which have been observed has increased since 1950. The main events include a decrease in cold temperature extremes, an increase in warm temperature extremes, an increase in the extreme high sea levels, an increase in the number of heavy precipitation in some regions, and an increase in the frequency of heat waves in large parts of Europe, Asia and Australia (IPCC, 2014a).

2.2.2. Greenhouse effect

The sun emits energy in the form of infra-red radiation. This energy passes through the atmosphere and is absorbed by elements on the surface of the planet such as water, air, soil and vegetation. The GHGs reflect the portion of energy not absorbed by the atmosphere (see figure 2.7). Because of this, the temperature of the planet has increased from -18°C to 15°C (Gautier & Le Treut, 2008; Mitchell, 1989) making possible the climate conditions to support life (Krause, Bach & Kooney, 1995).

While the "greenhouse effect" can be beneficial, human activities such as burning fossil fuels, deforestation, altered land uses and wetland changes, and the use of CFCs in refrigeration systems are increasing the amount of GHGs in the atmosphere (Emmanuel & Baker, 2012). A large concentration of GHGs will boost the greenhouse effect of the atmosphere not allowing the escape of heat and thus sending it back to the surface and increasing the temperature on the planet (IPCC, 2007).

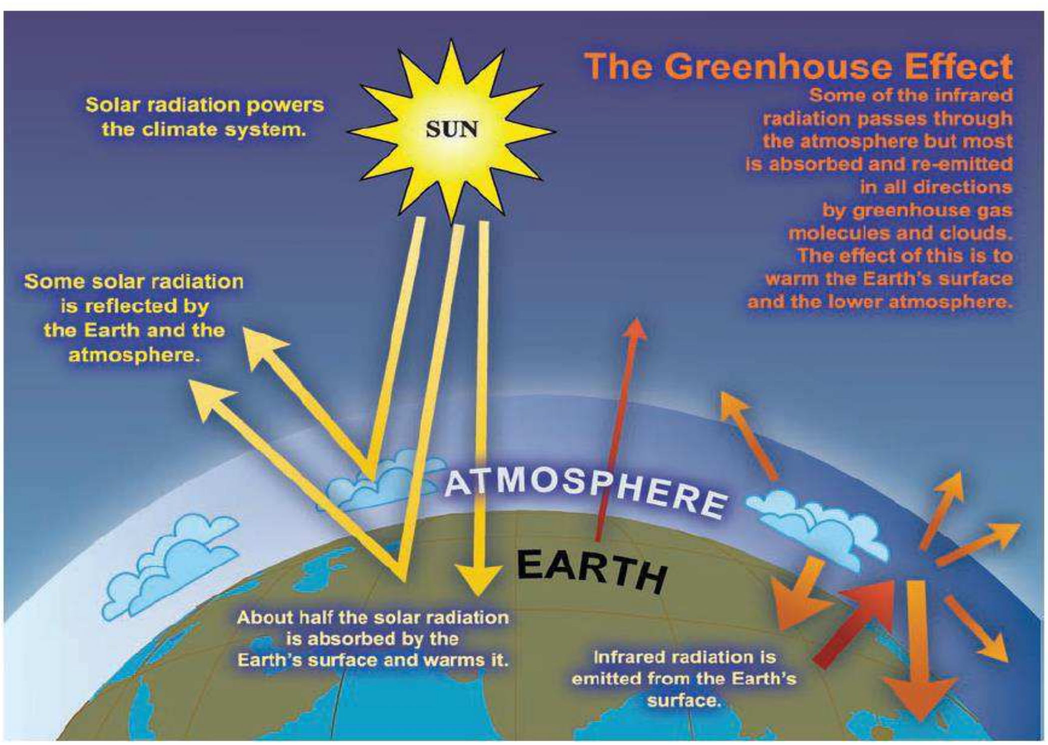

Figure 2.7. Greenhouse effect (IPCC, 2007)

The effect of each GHG will differ because of their different lifetimes in the atmosphere. Water vapour evaporates in a few weeks, and its concentration is not affected by human activities. By contrast, the other three gases have a long lifetime (50-200 years). Thus the gases are concentrated in the atmosphere for a long before being absorbed by the oceans, vegetation or chemical reactions (Gautier & Le Treut, 2008).

2.2.3. Source of GHGs

As mentioned above, climate change is caused by an increase of GHGs as a consequence of human activities. Thus, there is a need to identify the different economic activities that are generating emissions to find suitable methods to deal with them. Because of the need to find such methods this research is focused on energy consideration within building designs and this analysis is focused on this sector. Even though GHGs' emissions might seem to be a problem that is related to other industries rather than to the built environment industry, the literature is clear in pointing out that the AEC industry can be a key driver in reducing GHGs (Riley, 2013; Emmanuel & Baker, 2012).

In 2010, the building sector consumed approximately 30-40% of global energy (Emmanuel & Baker, 2012; IPCC, 2014a), mainly coming from oil. This amount of energy consumption released 49 $GtCO_2eq$ into the atmosphere (IPCC, 2014a). These emissions are broken down as follows in figure 2.8: industry (21%); transport (14%); buildings (6.4%); agriculture, forestry and other land use (AFOLU, 24%); electricity and heat production (25%), and other energy (9.6%). Looking only at the emissions that come from electricity and heat production it shows that buildings contribute 12% in the generation of GHGs.

Usually, a building uses 30-40% of energy for heating and cooling (Ward, 2009). IPCC (2014a) differentiates between residential and commercial consumption (see figure 2.9). According to this separation, the consumption for residential is 36% while for commercial it is 49% (including both heating and cooling). Furthermore, the demand is likely to grow to 79% and 84% respectively over the period 2010-2050.

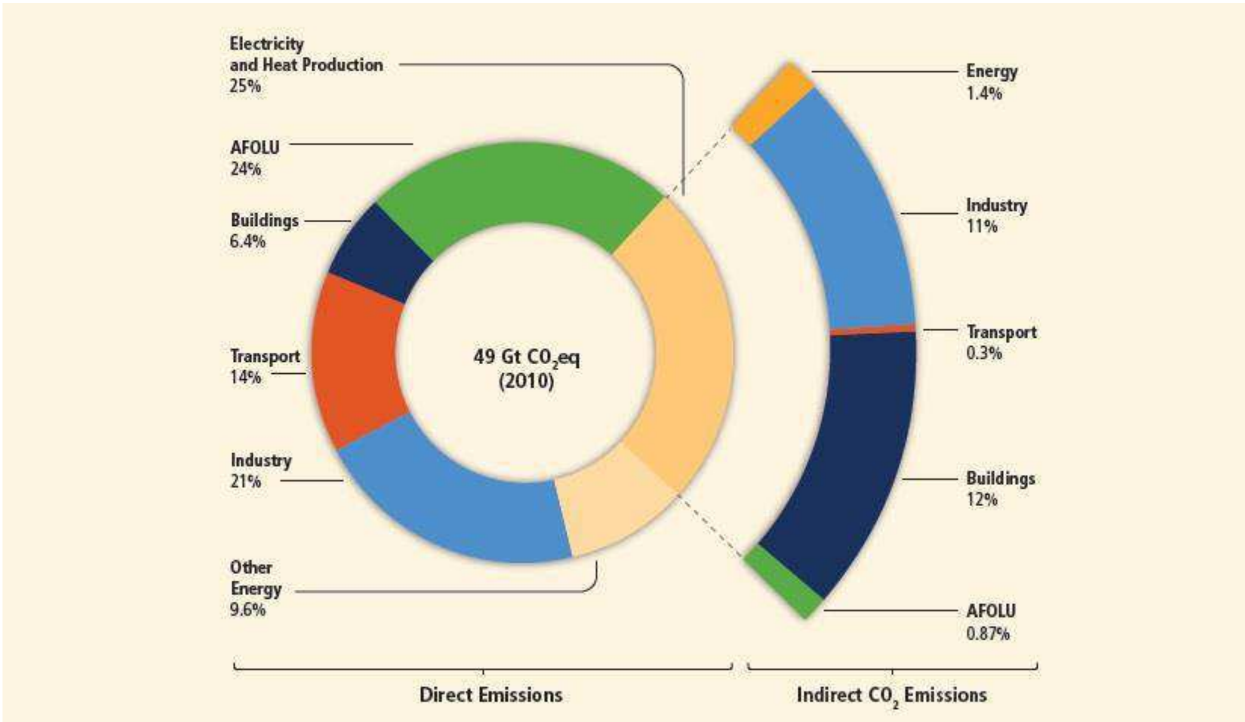

Figure 2.8. GHG emissions by economic sector (IPCC, 2014b)

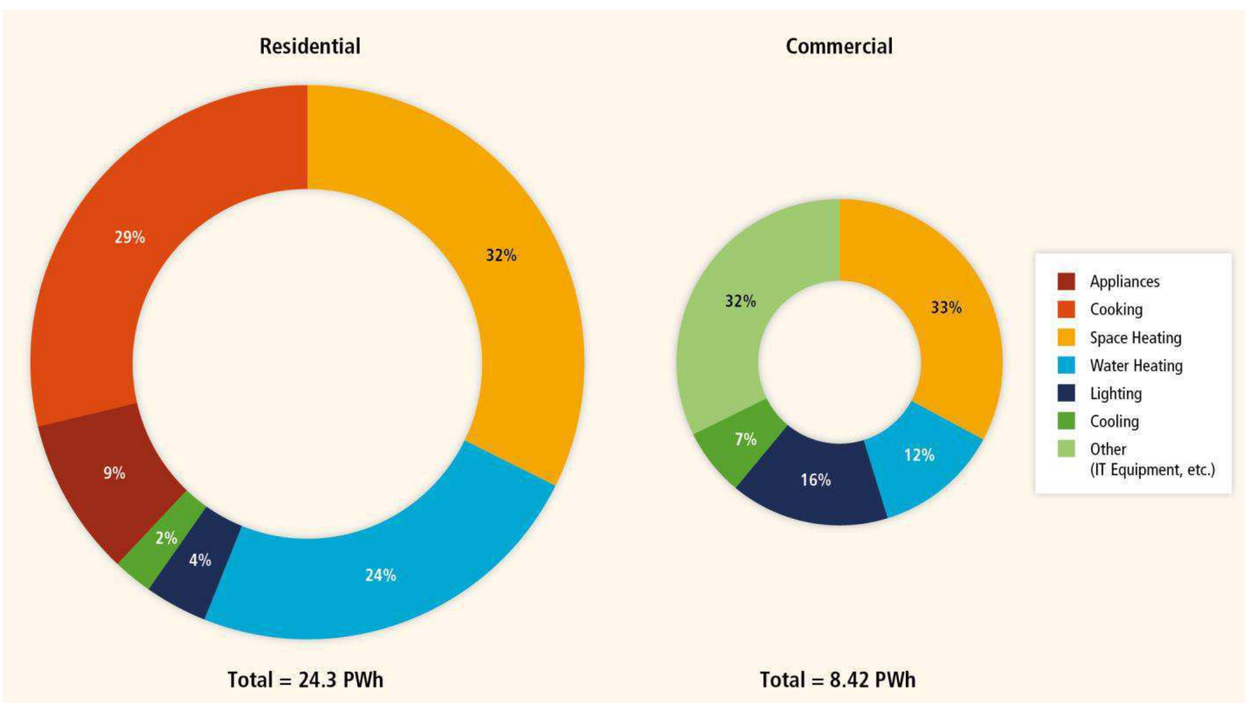

Figure 2.9. Global building energy consumption (IPCC, 2014c)

2.2.4. Projections of climate change

- **Projections in global mean temperature and a rise in sea-level:** The recent temperature increase might be considered by some as unimportant whereas, in fact, it is critical. Indeed, a temperature increase of over 2°C has not been experienced by humans during last 125,000 years; an increase of 2-4°C would mean a climate never experienced by human beings; an increase over 5°C has not been experienced for tens of millions of years (Krause, Bach & Kooney, 1995).

  In figure 2.10 two possible scenarios are introduced for temperature behaviour up to the year 2100. The red line indicates medium confidence, while the blue one indicates high confidence. There are two sections in the curves, from 2016-2035 there is a possible increase in temperature between 0.3°C to 0.7°C. For the second period, there is a potential increase of between 0.3°C to 1.7°C for the red line, while the blue one has a possible increase of between 2.6°C to 4.8°C. Thus, according to figure 2.10, it is highly likely that the suspected goal temperature of 2°C will be exceeded by 2100. Figure 2.12(a) shows similar temperature ranges but is detailed by geographic area.

  With an increase in temperature, the Arctic will continue warming and will accelerate the rise in the sea level. It is highly likely that the sea level will rise between 0.44 m and 0.78 m (see figure 2.11).

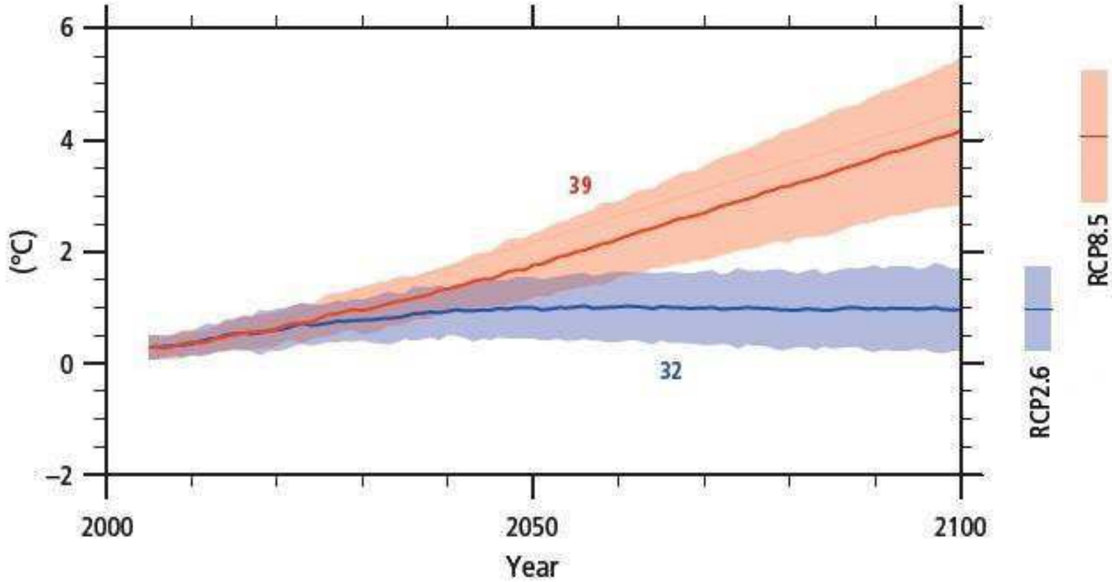

Figure 2.10 Global average surface temperature (IPCC, 2014a)

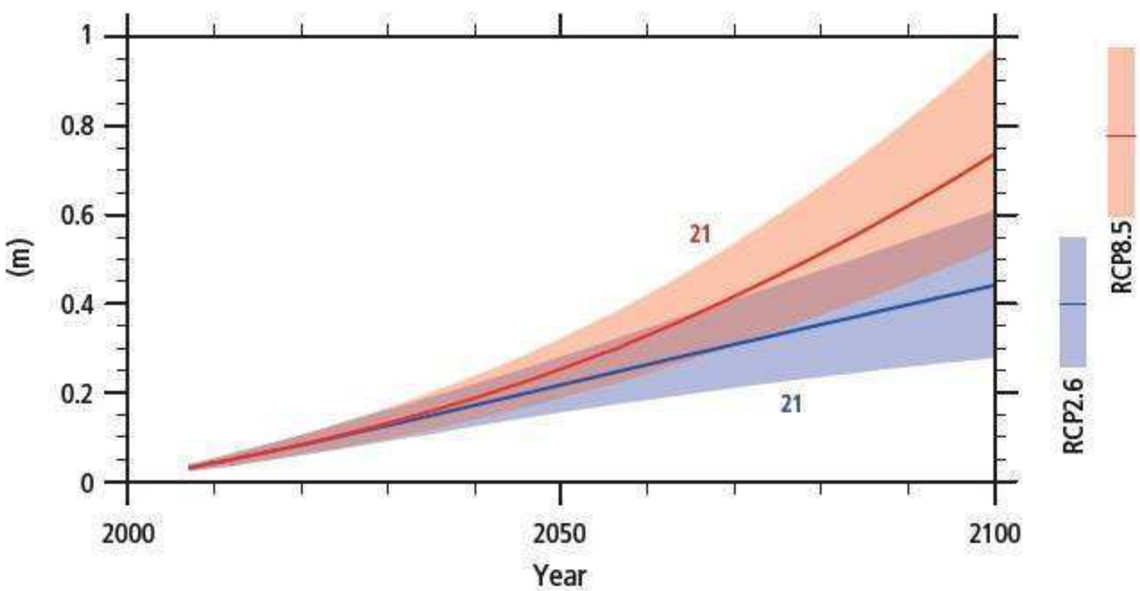

Figure 2.11 Global mean sea level rise (IPCC, 2014a)

- **Precipitation:** Figure 2.12(b) shows that changes in precipitation patterns will not be regular. The high latitudes and the equatorial Pacific region will increase their precipitation by around 20%. In the mid-latitude dry areas and dry subtropical regions, the rainfall will decrease by 10%while in the mid-latitude wet regions precipitation will increase. Extreme precipitation will intensify in the mid-latitude wet regions and wet tropical areas.

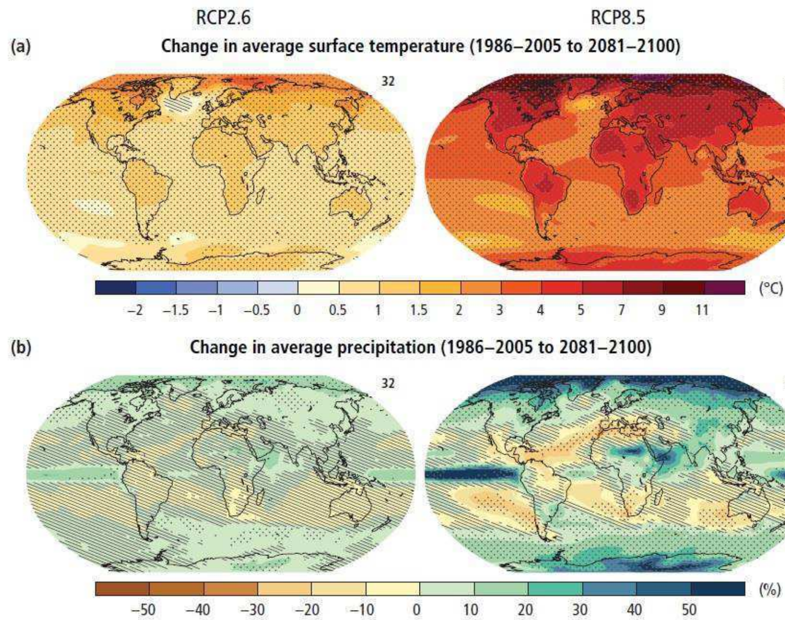

Figure 2.12 Projected changes in temperature and precipitation (IPCC, 2014a)

- **Changes in regional climate variables:**

In the coming future, the impact of global warming will keep growing and will continue affecting the climate. These changes will increase the risk of negative impacts on the environment in different ways, e.g. the oceans will increase in acidification, the levels of oxygen will decrease, and the rising temperatures will generate unbearable conditions for marine ecosystems; subsequently the extinction risk for several marine species will increase. Furthermore, climate change will have an impact on human activities, increasing illnesses in developing countries, economies and ecosystems.

Current and future risk is detailed in figure 2.13. The risk is described in four categories; the first one is the current scenario, the second one is a near future scenario (2030-2040) and the third and fourth are long-term scenarios (2080-2100). These last two scenarios are differentiated by an increase in temperature of 2°C and 4°C respectively.

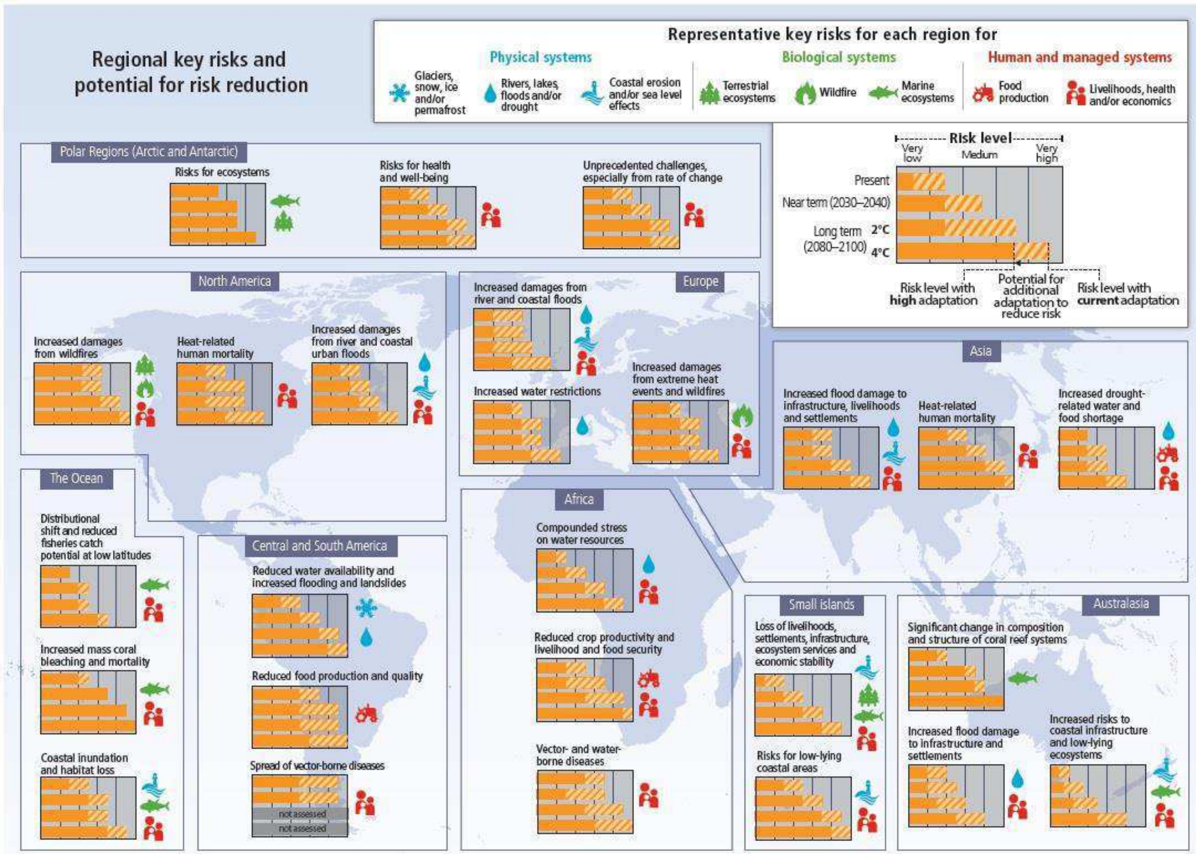

Figure 2.13 Projected risks (IPCC, 2014a)

From figure 2.13 the following effects can be observed.

- Vulnerable ecosystems such as the Arctic, the Antarctic and the oceans have already been affected without a chance of decreasing the current risk.
- In North America, currently, the risk levels are medium; however, they might increase quickly over the 2030-2040 period.
- In South America, the current level of risk on activities is rated as medium. Food production might suffer in the near future and can be identified as having a high risk in the short term . Additionally, the current risk for diseases is high, but there is

a great chance for the mitigation of this. However, a high-risk level might occur in the near term.

- Africa has a similar situation to South America. It is currently at medium risk, but there is a high potential to increase this risk in the near term.
- Europe might have increased risk from floods in the current term and the near term. Also, there is a possible medium risk level for water restrictions.
- Asia will need to face many flood issues in the short term and the near term. Also, an increase in heat will affect human life conditions causing high mortality in the short, near and long terms.
- Australasia will have to face a change in its coral reef systems in the short, near, and long terms. Also, there is a risk that floods will be experienced in the short, near and long terms.

2.3. Carbon emission reduction agreements

Since the 1970s multiple meetings have been held to deal with climatic issues such as the Stockholm Conference (1972), the Brundtland Report (1987) and the Rio de Janeiro Earth Summit (1992), just to name a few. All these conferences have focused on setting out concepts, principles and plans for action rather than calling for action through setting measurable objectives. The Kyoto Protocol was the first conference able to set out clearly measurable goals with deadlines and to propose methods to fulfil the objectives. Below the main meetings that have set goals regarding climate issues are introduced.

2.3.1. The Kyoto Protocol

In 1997 the United Nations Framework Convention on Climate Change (UNFCCC) obtained an agreement with 39 developed countries incorporating the European Union, United States, Australia and transition economies such as Bulgaria, Croatia, the Czech Republic, the Russian Federation, to name a few. In this protocol, the above countries agreed to reduce the emission of the main GHGs (carbon dioxide, methane and nitrous oxide) in a range of between 8 to 10% with respect to the 1990 levels for the commitment period of

2008 to 2012 (UNFCCC, 2014a). The protocol assigned a range of reducing emissions as a goal rather than listing specific values; in so doing , it recognised different contribution levels in the creation of GHGs for each country. As a consequence, the reduction efforts were to be greater for the most polluting countries (Grubb, Vrolijk and Brack, 1999).

The Kyoto Protocol proposed multiple methods for achieving carbon reduction:

- International Emissions' Trading: this allowed guarantor countries to exchange emissions in the form of units of one tonne of CO_2. In this method, the emission units can be traded like any other commodity, and thus a guarantor country can buy emission units from other guarantors with spare units and can redistribute the emissions with this transaction (Grubb, Vrolijk and Brack, 1999).
- Joint implementation: this allowed guarantor countries to sponsor projects in other guarantor countries that had as an objective the cutting of GHGs e.g. reforestting or research projects to reduce carbon emissions. In exchange, the sponsored country will provide emission reduction units to the investor country (UNFCCC, 2014b).
- Clean development mechanism: this is similar to joint implementation but it differed in that guarantor countries could sponsor non-guarantor countries' projects. The objective was to promote clean development in developing countries with activities such as investing in renewable energies (INFCCC, 2014c).

2.3.2. The Copenhagen Accord

In 2009 the UNFCCC called for a new meeting in Copenhagen to discuss a new framework regarding carbon emissions that would come in force in 2012 when the Kyoto Protocol expired. This meeting was attended by 115 world leaders and more than 40,000 people representing governments, nongovernmental and intergovernmental organisations amongst others (INFCCC, 2014d).

The major global economies agreed with the key points in the agreement, and they offered to pledge specific actions to mitigate the GHG emissions (C2ES, 2010). The main points agreed were (INFCCC, 2014d):

- The long-term goal of limiting the maximum global average temperature increase to no more than 2°C above pre-industrial levels.
- Developed countries promised to fund actions to reduce GHGs; the capital committed would be US$30 billion for the period 2010-2012, and US$100 billion a year by 2020.
- Developing countries with significant GHG contributions (Brazil, Indonesia, Saudi Arabia, South Korea and China) would report their emissions and mitigation actions.

Unfortunately, the Copenhagen Accord was legally weak and non-binding (Marshall, 2010; Spak, 2010); thus the key points set in the Accord could not be forcibly implemented; instead, they were based on the goodwill of each country who voluntarily pledged to reduce its emission targets (Yamaguchi 2012). Because there was little pressure to take much action, the most polluting countries were weak in tackling their objectives e.g. the U.S. and China gave vague promises about reducing their emissions in the next one or two decades (Spak 2010). The EU, Australia, Russia, Norway and New Zealand committed to the lower end of their previously pledged ranges (Marshall, 2010).

2.3.3. The Paris Agreement

After the failed Copenhagen Accord, the UNFCCC called for a new meeting in Paris during 2015. In this meeting, 196 countries discussed a new legally binding framework to replace the Kyoto Protocol in an effort to reduce carbon emissions. Paris provided a significant and substantial international Agreement that removed the differences between developed and developing countries, pushing them to make their best efforts to reduce GHGs (C2ES, 2015). While this Agreement removed the differences between developed and developing countries, it still recognised the differences in the responsibilities and resources of countries (ClimateFocus 2015). Furthermore, the Agreement changed the emphasis from mitigation to adapting processes that were able to reduce emissions at source (ClimateFocus 2015).

The key points from the Paris Agreement were (ClimateFocus, 2015; C2ES, 2015; Willis et al., 2014):

- Reaffirmation of the long-term goal of keeping global warming below 2°C but with an urgent call to limit it to 1.5°C above pre-industrial levels. The idea of reducing the maximum temperature is to stabilise the atmosphere as soon as possible during the second half of this century.
- All countries would communicate their target emissions and the progress made in implementing and achieving them through successive nationally determined contributions (NDC). This data will be reviewed every five years.
- The current funding of US$100 billion a year in support by 2020 is extended up to 2025; after that year, a higher goal will be set.

2.4. Sustainable building rating system and standards

In 2003 the Energy Building Performance Directive (EPBD) was created with the objective of promoting the energy performance of buildings within the EU. This organisation is focused on four key points (BRE, 2006):

- Setting a calculation methodology for the energy performance of buildings.
- Regulating a minimum energy performance requirement for new buildings and the large existing building stock.
- The need for an energy performance certificate that is available whenever buildings are constructed, sold or rented out.
- The inspection of boilers and air-conditioning.

To achieve the above points, the AEC industry uses building rating systems such as LEED and BREEAM together with low energy standards such as PassivHaus. Below are introduced the main rating systems and standards that are used for buildings to improve their energy performance.

2.4.1. Sustainable building rating systems

A sustainable building rating system is a tool to evaluate a project based on assigning a score given to the features of the project in achieving specific national building regulations and standards (CIBSE, 2015; Fowler & Rauch, 2006). The rating system offers a reliable basis for comparing and evaluating the technical aspects of different projects (Fowler & Rauch, 2006).

There are multiple rating systems, e.g. Fowler and Rauch (2006) identified at least 34 different systems, most of them adaptations of LEED or BREEAM in a local context. Say and Wood (2008) pointed out that LEED, BREEAM, GreenStar and CASBEE are the most popular systems around the world. Despite the several rating systems that exist the literature is clear in identifying to BREEAM and LEED as the most used across the world (Rivera 2009; Say & Wood 2008). The key features of both systems are analysed below.

2.4.1.1. BREEAM

BREEAM (Building Research Establishment Environmental Assessment Method) was developed in the United Kingdom in 1990. This system is able to analyse a series of projects including offices, homes, industrial units, retail units, and schools (Fowler & Rauch 2006). This system focuses on evaluating the reduction of CO_2 in particular categories such as management, health and wellbeing, energy, transport, water, materials, waste, land use and ecology, and pollution (CIBSE, 2015). Subsequently, each of these categories is weighted to reflect the contribution to the overall Energy Performance Ratio of the new construction (Portalatin et al., 2010). The building is classified under one of the following categories: Unclassified (<30%), Pass (≥30%), Good (≥45%), Very good (≥55%), Excellent (≥70%), or Outstanding (≥85%) (Portalatin et al., 2010).

2.4.1.2. LEED

LEED (Leadership in Energy and Environmental Design) was developed in the U.S. in 1998. The system focuses on evaluating the energy savings of a proposed building (CIBSE, 2015).

In the same way as BREEAM, LEED is a point based system, but the categories that are evaluated in this case are sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, and the innovation and design process (Fowler & Rauch, 2006).

The project team collects evidence for the assessment process; then this information is sent to the U.S. Green Building Council (USGBC). This organisation checks the evidence and calculates the final score. Accordingly, a project can achieve a certification of Silver, Gold or Platinum (Portalatin et al., 2010).

2.4.1.3. Criticism of sustainable building rating systems

While sustainable building rating systems have been adopted worldwide within several projects, they are not free of issues. Heard and Jessop (2008) point out that these rating tools have confused the terms ´green´ with ´sustainable´ building. The first concept considers the environmental dimension while the second term considers the social and economic aspects of a problem. Hes (2007) supports this idea. Studying the effectiveness of rating tools Hes concluded that rating tools are useful in improving energy use, water use and waste reduction; however, only some social issues were improved while the economic dimension showed unpredictable behaviour. In addition, Hes (2007) highlights the bureaucratic nature of these tools in that they do not seem to support dynamic behaviour in design and development.

2.4.2. Energy efficiency standards

2.4.2.1. PassivHaus

PassivHaus is a methodology that defines a very high standard for the design and construction of a wide range of projects, from houses to schools, supermarkets, offices and apartment buildings (PassREg, 2015). This standard will ensure high quality, comfort, low energy consumption , low bills (PassREg, 2015; PassivhausTrust, 2011) and, consequently, a meaningful reduction in CO_2 (PassREg, 2015). However, it must be borne in mind that the focus of this methodology is on reducing energy consumption rather than on reducing CO_2 emissions (PassivhausTrust, 2011). The concepts ´PassivHaus´ and

´Passive house´ must not be confused. The first one refers to applying a well-defined standard while ´Passive house´ refers to using passive design features (e.g. a passive solar design) (BRE, 2010).

To achieve the PassivHaus standard it is necessary to demonstrate that the project meets the quality assurance requirements. If it is not possible to demonstrate this, the project will not be awarded the certification even if the project meets the performance requirements.

2.4.2.3. ZEB

According to EPBD 2010/31/EU, a nearly zero-energy building (ZEB) indicates 'a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby´ (EU, 2010). Also, the EPBD sets out that Member States shall ensure that by 31 December 2020, all new buildings will be nearly zero-energy buildings and, after 31 December 2018, new buildings occupied and owned by public authorities will be nearly zero-energy buildings (EU, 2010).

A ZEB contains at least three elements (see figure 2.14):

- A physical boundary which can be a building or a group of buildings that are connected to a particular electrical grid. The physical boundary, shown in red in figure 2.14, allows for the identification of the elements in the system where the energy will be imported or exported (Sartori et al., 2012).
- A balance boundary which determines which energy uses will be connected to the grid (heating, cooling, ventilation, domestic hot water and fixed lighting) (Sartori et al., 2012).
- Boundary conditions which are a series of parameters (functionality, space effectiveness, climate and comfort) that allow monitoring of the system and an understanding of the causes of any performance deviation (Sartori et al., 2012).

A ZEB uses local renewable systems to produce energy on site. If the ZEB system is not able to generate enough energy, then it will be taken from an energy grid that works at providing energy via renewable methods such as biofuel. If the ZEB produces more energy than it can use then, this difference will be exported to the energy grid (Dokka et al., 2013).

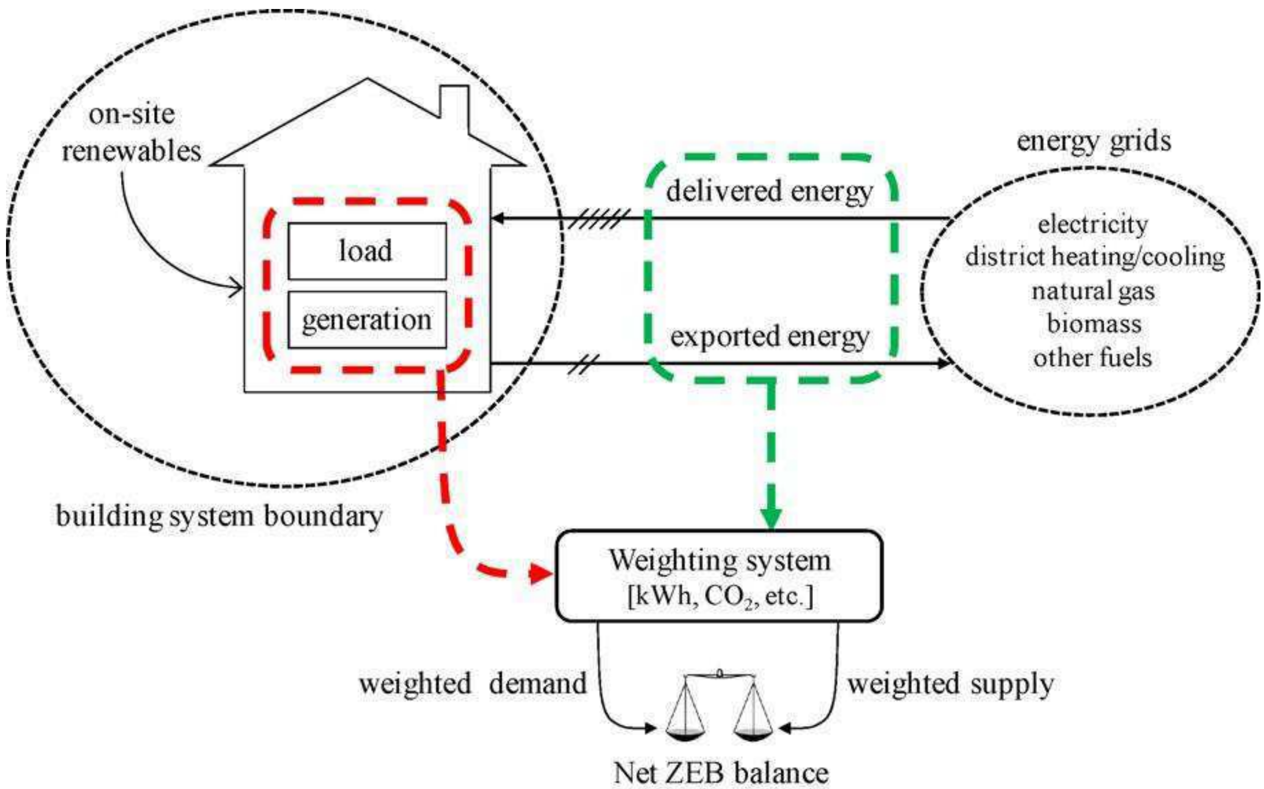

Figure 2.14 ZEB system (Sartori et al., 2012)

2.4.2.3. Drawbacks of standards

There are drawbacks within the standards as presented below.

- PassivHaus

    - It is not a zero carbon standard. While this specification reduces energy consumption, it is not synonymous with zero emission. Indeed, because energy consumption is 15kWh/m2/yr, there will be an amount of carbon emission (Jones, 2013).
    - It is a very hard standard to meet (Jones, 2013).
    - It requires knowledge to manage the building during the operational stage, e.g. it is not possible to open windows when the ventilation needs boosting, or filters will need to be replaced (Jones, 2013).

- ZEB

    - It requires the creation of a roadmap where each EU member would show their objectives and the concrete measures undertaken to achieve ZEB (Janssen, 2011).
    - A zero-energy building needs to be fed from the grid in periods of high demand and to be able to deliver the ZEB surplus when the demand decreases. However, a building will not experience a reduction in energy costs if the peak demand and utility bills are not managed (Zeiler, 2010).
    - The smart grid works in the same way as traditional grids. Thus it needs to respond to energy demands in real time. However, energy production is not constant because it depends on weather conditions (sunlight, wind, etc.). Thus, at some point, the grid will require energy from a traditional grid (Zeiler, 2010).

Chapter 3 Building Information Modelling and sustainable development

Building Information Modelling (BIM) has had a quick adoption in the architecture, engineering and construction industry (AEC). This methodology provides a valuable driver to deal with multiple problems in data coordination throughout the life cycle of a project. While BIM has been well received because of the possibility of addressing chronic issues in the AEC industry, there is a more valuable reason for its adoption: the chance of improving project performance. In this way, the eruption of BIM has reawakened interest in Building Performance Simulation (BPS) as a complementary discipline. This discipline allows for evaluating architectural design from an energy point of view, allowing the simulating and predicting of the energy consumption of multiple systems such as heating, cooling, electrical, and renewable energies (CIBSE, 2015). The outputs from a BPS simulation will allow stakeholders to take better decisions (Eastman et al, 2011). Nonetheless, BIM and BPS lack integration currently making bidirectional communication difficult (CIBSE, 2015). As a consequence the interaction is undermined because the only way to overcome this situation is to manually re-enter the data, a time-consuming process and on that can be prone to errors (Krygiel & Nies, 2008).

In this chapter BIM and BPS concepts are discussed in addition to their features and the challenges which highlight the integration that both disciplines demand. To finally analyse the state-of-the art in interoperability and the challenges to allow the integration of BIM-BPS.

3.1 Building Information Modelling

In the literature is possible to find multiple definitions for BIM (Eastman et al., 2011; Kumar, 2015) e.g. for HM Government BIM is defined as:

"*…a collaborative way of working, underpinned by the digital technologies which unlock more efficient methods of designing, creating and maintaining our assets. BIM embeds key product and asset data and a 3 dimensional computer model that can be used for effective management of information throughout a project lifecycle – from earliest concept through to operation*" (HM Government, 2012, p.3).

The National Building Specification (NBS) in the UK defines BIM as:

"A process for managing the information produced during a construction project, in common format, from the earliest feasibility stages through design, construction, operation and finally demolition." (NBS, 2013, p.17)

More important than finding a unique definition for BIM is the requirement to identify the common elements in each definition. Elvin (2007) says that the collaboration and workflow between different stakeholders during a lifecycle are fundamental elements within the BIM concept. Otherwise, BIM might be considered as a CAD tool with a new name (Deutsch, 2011; Kumar, 2015; Pramod, 2012) rather than thinking of it as a game changer of workflows and procurement processes (Azhar et al., 2012; Deutsch, 2011). Smith & Tardif (2008) say that BIM covers further drafting activities and that real benefits cannot be achieved by focusing on using it merely as a tool.

In part this confusion about BIM's scope is because of the multiple connotations that the acronym has. Three meanings can be assigned to BIM: as a product, a collaborative process or a facility management tool (Eastman et al., 2011; Mordue et al., 2016):

- BIM as a product: it consists of an intelligent digital representation of a project made using a BIM authoring tool.

- BIM as a collaborative process: it is the process of creating a BIM model using open standards that will smooth the workflows between stakeholders.

- BIM as facility lifecycle management tool: a set of data exchanged with multiple stakeholders throughout the lifecycle of a project which is undertaken by using a BIM model.

3.1.1 BIM characteristics

BIM is based on the use of parametric rules to represent an integrated digital database that can be shared with other stakeholders during different stages in the lifecycle of a project (Eastman et al., 2011; Holness, 2008). These rules bring into BIM models specific features such as parameterization, intelligence, consistency and coordination (Eastman et al., 2011). Further details on these characteristics are given below.

- Parameterization: the objects are created or edited through its parameters, then the user accesses the database to change a parameter rather than introducing a change manually (Kymmel, 2008).

- Intelligence: each element in a digital model ´knows´ what it represents in the real world; as a consequence, it has the same behaviour. For example, a slab knows that it is a slab and it is not possible to add a window into the slab because it goes against the structural behaviour of the slab (Crotty, 2012; Kumar, 2015).

- Consistency: the data is interconnected, then when an object changes its parameters in the database, all other objects, properties and data related to the element are automatically updated (Elvin, 2007).

- Coordination: all the views of a model are represented in a coordinated way (Kumar, 2015).

3.1.2 Uses of BIM in the design process

BIM responds to a large number of tasks during a lifecycle,. The Computer Integrated Construction Research Program (CIC) at the Pennsylvania State University has already identified 25 different applications that BIM can undertake throughout the whole lifecycle of a project (CIC, 2010). Additionally, CIC recognises the chances of finding more uses for BIM. In this regard Eastman et al. (2011) point to the owner as being mainly responsible for pushing out the adoption of BIM technologies and the new uses of it.

In figure 3.1 BIM uses identified by CIC are shown. This dissertation focuses on a problem generated in the design stage. Thus it will be described the BIM uses during that stage. These are:

- Existing conditions' modelling
- Cost estimation
- Phase planning
- Site analysis
- Programming
- Design reviews
- Design authoring
- Energy analysis
- 3D coordination

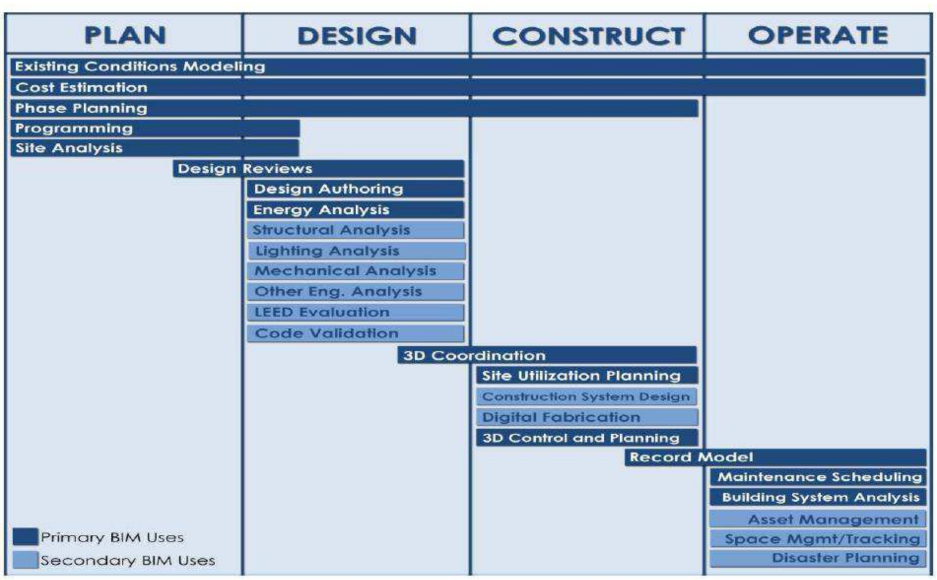

Figure 3.1 BIM uses throughout a building lifecycle (CIC, 2010)

- Existing conditions' modelling

Existing conditions' modelling is a process to create a BIM model from an already existing model. Using a 3D laser scan the existing conditions of a project are captured. This data will be useful in comparing the conditions on-site against the design conditions. Also, it can be used in rehabilitation work and capturing as-built models (Eastman et al., 2011).

- Cost estimation

The BIM model is used to generate a quantity take off and cost estimate during early design. Also, it is possible to create different scenarios to understand the impact of modifications to the project in terms of time and budget (CIC, 2010).

- Planning (4D modelling)

The dimension of time is added into the 3D model, allowing the simulation, planning and development of multiple scheduling scenarios (Kymmell, 2008). As it is a visual process, it improves the communication between different actors and brings a better understanding of milestones and construction plans (CIC, 2010).

- Programming

Programming is a process that allows for the analysis of space requirements to compare them with standards and regulations. Then an appropriate decision will be taken because there is the possibility of analysing all these different alternatives by the stakeholders (CIC, 2010).

- Site Analysis

BIM and GIS models are put together to evaluate properties in a site context and to determine an optimal location for future projects (CIC, 2010).

- Design Reviews

Design reviews allow the showing of alternative designs to the stakeholders to evaluate each option in terms of programmes, lighting, security, ergonomics, acoustics, textures, colours and so on (CIC, 2010).

- Design Authoring

Design authoring is a process in which 3D software is used to generate a BIM model based on some design criteria. This model will be rich in data and will contain information such as properties, quantities, means and methods, costs and schedules (CIC, 2010).

- Energy analysis

A simulation software is used to determinate the energy performance of a project. Then, through an iterative process, it will be possible finding an optimal solution to reduce energy consumption during a lifecycle with a low investment cost (CIC, 2010).

- 3D Coordination

3D coordination is commonly used to evaluate and coordinate spatially multiple BIM models with the objective of detecting and correcting any clash between specialities, allowing the elimination of a large number of conflicts before starting the installation phase (Eastman et al., 2011).

3.1.3 BIM benefits

The literature shows a significant number of benefits associated with BIM. This is because BIM can support many business practices (Eastman et al., 2011). For example, Deutsch (2011) listed 48 different benefits classified in two categories, qualitative and quantitative. On the other hand, Eastman et al. (2011) listed benefits by each stakeholder in each stage of a project's lifecycle. The Cooperative Research Centre for Construction Innovation (CRC, 2007) and Kymmell (2008) introduced a more integral view of BIM benefits pointing out that the most important advantage achieved by BIM technologies is the reduction in risk for any stakeholder as a consequence of the accuracy of the BIM model allowing illustrate the design intent in a central database.

Kymmell (2008) complements this saying that BIM technologies reduce risk by using three elements: visualisation, collaboration and waste reduction. Visualisation provides an improvement in the understanding of a project for any person independently of his/her background. Collaboration is encouraged and facilitated in the early stages as a result of having data of better quality. Waste is reduced as a consequence of the early visualisation of problems, giving the chance of solving them before they exist on site.
From an integral point of view, the main benefits of adopting BIM are (CRC, 2007):

- Faster and more efficient processes because information is easily shared.
- Better design; the design proposal is analysed and improved in an iterative process using simulation tools.
- Controlled whole life cost and environmental data which are better understood as a result of a more predictable project performance.
- Automated assembly: product data can be used downstream for the manufacturing/assembling of structural systems.
- Better customer service: any proposed design is better understood because of accurate visualisation.
- Lifecycle data: it is possible to collect any data generated during the lifecycle (requirements, design, construction and operational data) for it be used in the facility management stage.

3.1.4 BIM challenges

Despite the clear advances that BIM brings into the AEC industry, its implementation has not been smooth and there is a series of obstacles that the industry needs to overcome in the next few years to achieve the benefits claimed by BIM methodologies. Bernstein and Pittman (2004) discuss these barriers pointing out that most of the literature highlights interoperability as the only problem in the implementation of BIM. However, Bernstein and Pittman (2004) recognise that improving interoperability will not be useful in the adoption of BIM if other issues are not dealt with too. There are three possible barriers to overcome in BIM implementation (Bernstein & Pittman, 2004):

- A well-defined transactional construction process model, BIM allows the flow of data connecting processes, however it does not solve the lack of business process integration.

- The digital design data must be computable; this means that every element created by a BIM tool must be readable and interpreted as an element rather than as an interpretation of the observer, e.g. in CAD a group of lines might represent a door for the observer but the software does not interpret those lines as a door. Thus there is a requirement that BIM tools will be able to identify each element.

- There is a need for well-developed interoperability which will allow the exchange of data between different BIM tools; then any stakeholder will be able to reuse this data and eventually send it back with comments or changes.

3.1.5 BIM information delivery

How to implement a BIM project is something that has only relatively recently been discussed. Currently most of the literature has focused on exploring the potential of the technology (Kumar, 2015). Bolpagni (2013) discusses different initiatives used in countries such as Singapore, USA, Finland, UK, Norway, Denmark, Netherlands, South Korea, Hong Kong, Australia, New Zealand, Iceland, Estonia, Sweden, Germany, China, Ireland, Taiwan and Italy. Unfortunately, most of these initiatives have focused on describing how to fulfil some codes (naming rules, representations, etc.) rather than defining the data requirement in each stage of a project (Bolpagni,2013).

In 2011 the UK Government launched the Construction Strategy in which are defined a series of objectives that would change the relationship between the Government and the construction industry. Included in those objectives was the demand for BIM as a minimum requirement in all publically procured projects from 2016 (Kumar, 2015). By adopting BIM, the UK Government hopes to reduce the operation and maintenance costs of a project by 20% as a consequence of better design (BSI, 2013; Kumar, 2015). The Construction Industry Council (CIC) have supported the BIM implementation process through a Publically Available Specification (PAS) developed by BSI Standards Limited (BSI, 2013). The developed document is called PAS 1192:2 and has set a series of steps to manage the information in projects via BIM (Kumar, 2015). The next section explains this methodology.

3.1.5.1 PAS 1192:2

The information delivery process is illustrated in figure 3.2. The information workflow starts at the upper right hand corner of the figure with the assessment and needs' stage; then the information goes through the procurement, post-contract award, mobilisation and production stages. In each of these steps, the information is refined, especially in the production stage where the data is exchanged between team members (green ovals) and between team members and the client (red ovals).

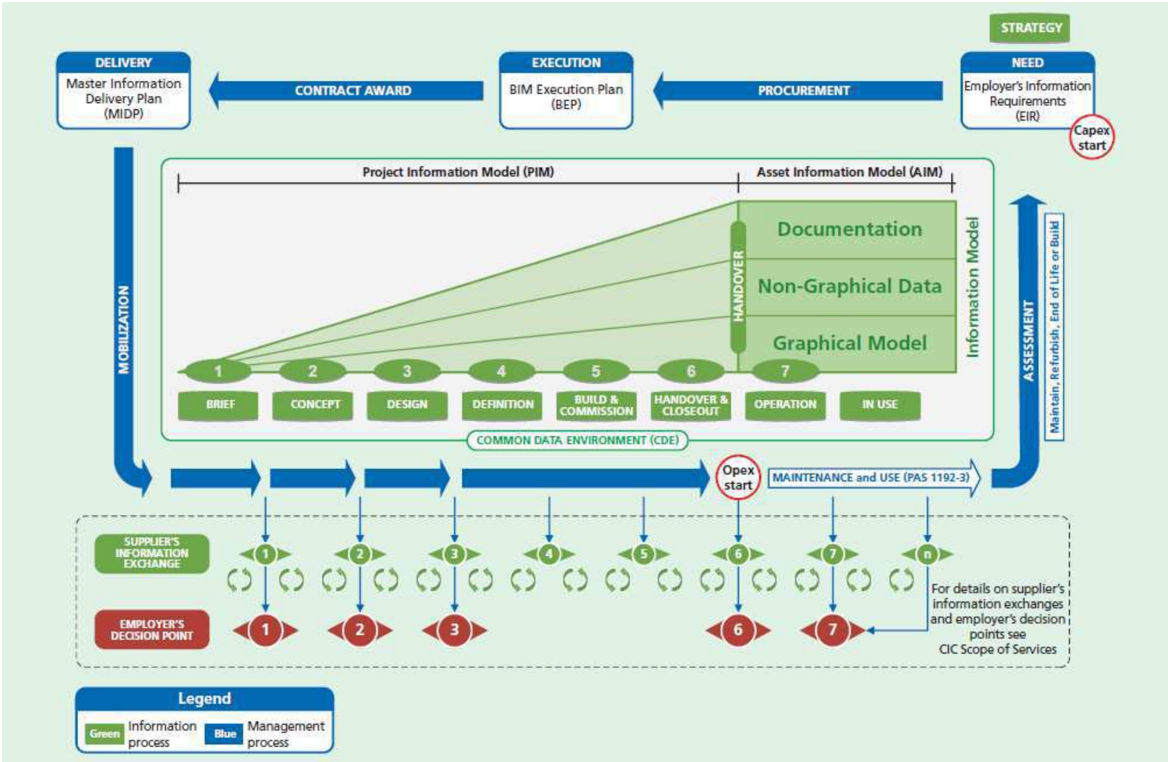

Figure 3.2 Information delivery cycle (BSI, 2013)

- *Assessment and need*

The first stage introduces the Employer Information Requirements (EIR). This document sets out the information to be delivered and the standards and processes to be adopted by the suppliers (BSI, 2013). This information has three categories, technical (software platform, data exchange format, coordinates, level of detail and training); management (standards, roles and responsibilities, collaboration process, security) and commercial (data drops and deliverables, defined BIM deliverables, BIM specific competence assessment) (Kumar, 2015). This document is fundamental in enabling bidders to create their initial BIM execution plan (BEP).

- *Procurement*

In this stage, the employer will ask the bidders to develop a BIM Execution Plan (BEP) detailing the proposed approach, capability and competence to meet the requirements set in the EIR. The BEP will be used by the employer to determine if the bidder can fulfil the requirements asked in the EIR (BSI, 2013).

In addition to the information asked in the EIR, the BEP needs to include the Project Implementation Plan (PIP), project goals for collaboration and information modelling, major project milestones, and the Project Information (PIM) deliverable strategy (BSI, 2013). The PIP is a group of forms to demonstrate the suitability of the technology suppliers, while the PIM is the design intended for the architectural and engineering models.

- *Post-contract award*

Once the contract is awarded, it is necessary to refine the BEP to facilitate the management of the project delivery. The most important points to add in the BEP post contract fall under four categories (BSI, 2013):

- Management:

1) Roles, responsibilities and authorities

2) Major project milestones consistent with the project programme

3) Project information model deliverable strategy

4) Survey strategy including the use of point clouds, light detecting and ranging or global navigation satellite systems

5) Existing legacy data use

6) Approval of information

7) PIM authorization process

- Planning and documentation:

1) Revised PIP confirming the capability of the supply chain

2) Agreed on project processes for collaboration and information modelling

3) Agreed matrix of responsibilities across the supply chain

4) TIDP

5) MIDP

- Standard method and procedure:

1) The volume strategy

2) PIM origin and orientation

3) File naming convention

4) Layer naming convention, where used

5) Agreed on construction tolerances for all disciplines

6) Drawing sheet templates

7) Annotation, dimensions, abbreviations and symbols

8) Attribute data

- IT solutions:

1) Software versions

2) Exchange formats

3) Process and data management systems

Within the points listed above the most important are Master Information Delivery Plan (MIDP) and the Task Information Delivery Plan (TIDP). In the first one, the project delivery manager sets up a meeting to confirm the availability of resources and capacity against the responsibility matrix while the TIDP is developed by each team manager to detail their milestones (BSI, 2013).

- *Mobilisation*

The mobilisation stage is developed before starting any design work and it has as its objective the testing and implementing of software, IT systems and infrastructure. Additionally, it should be ensured that the documents which support the information process have been prepared and that the team has right skills and competencies to develop the work adequately (BSI, 2013).

- *Production*

Production is the last stage where the PIM is developed progressively through each of the seven stages shown in figure 3.2. During this process, information is exchanged several times between team members or with the client, perhaps to enquire for a solution or for more data for a design problem. This information is transferred via the Common Data Environment (CDE); this is a means of promoting collaboration (BSI, 2013).

3.2 Building Performance Simulation

Building performance is a multivariable problem in which the interaction of multiple factors are evaluated such as heating, ventilation and the air-conditioning system (HVAC); solar heat gain; sun shading devices; daylight dimming; lighting levels, number of occupants and their activity levels (Krygiel & Nies, 2008). To solve this multiple variable problem requires using Building Performance Simulation (BPS) tools (Papamichael, 2002). However, the development of such tools is low because of a lack of interest from the market (Papamichael, 2002). As a result of this low development of tools, designers have based their design methods on rules of thumb and codes (Cotgrave & Riley, 2013; Hetherington et al., 2011). However, these methods do not necessarily result in an energy efficient design (Papamichael, 2002).

The limitation in BPS tools forces a consideration of simulations during the detailed design stage or later when it is no longer possible to add significant changes in a project (Jansson et al., 2013; Schlueter & Thesseling, 2009). Nonetheless, BPS tools are gaining in popularity because of the cost of energy, environmental concerns (Azhar & Brown, 2009), and government policies to reduce carbon emissions (Adamus, 2013).

3.2.1 Benefits of BPS

Despite the fact that BPS is an underdeveloped subject with technical issues which means that it has not been broadly adopted for the AEC industry, there is a series of factors which will increase interest in energy simulations. Firstly, governments will increasingly demand that projects are energy efficient is an effort to reduce the negative impact that they have on the environment. Secondly, owners too will ask for this as a means of reducing the operation costs within their projects.

The great benefit of BPS is increasing the performance of a project through an integral understanding of how each climate element affects the project (Krygiel & Nies, 2008). The design follows a series of steps: understanding the climate, reducing loads, using free energy, and using efficient systems (Krygiel & Nies, 2008). Each of these steps is supported by BPS tools to introduce a few changes in the design e.g. changing the building orientation, façade shape, materials, system passive cooling or heating systems, etc. Then, through a comparison of each alternative it will be possible to select the most suitable design with the lowest relationship construction/operation cost, e.g. it might be possible to determinate choosing a triple glazed window which is more expensive than a double one, but this will mean higher energy saving during the life cycle of the project.

A better design will have, as a result, a decrease in energy consumption (for cooling, heating or lighting) and a lower energy consumption will mean a reduction in the carbon emissions generated by the operation of the project (CIBSE, 2015).

3.2.2 Limitations of BPS

Factors are presented below that limit the extensive adoption of BPS.

- **Lack of interoperability:** the interoperability or ability to exchange data between applications is low in BPS tools, hindering the interaction between actors that use different tools (Häkkinen, 2011). This lack of communication in the early stages will affect any design decision because there will not be sufficient knowledge available to support any decisions taken (Häkkinen, 2011).

Many authors (Attia et al., 2012; Clarke & Hensen, 2015; Deane, 2008; Malkawi & Augenbroe, 2003) have identified the need for support for a collaborative approach to facilitate the early communication and integration of data between different parties (architect, structural engineer, energy expert, cost estimator, etc).

- **User-friendly interface**: BPS tools are hard to use because they require modelling skills and making assumptions in the models. To manage these factors a consultant will be required to be involved in a project (Papamichael, 2002). However, even with the utilisation of a specialist to create an energy model it is a time-consuming task (Garcia, 2014). The 'unfriendly' interface has its origins in the 1980s when these tools were developed by researchers and specialised consultants for research purposes (Hetherington et al., 2011; Papamichael, 2002). As a consequence, non-technical users are not able to interpret and explore new design options (Hetherington et al., 2011).

- **Suitable software**: there is a lack of energy simulation tools available even though the US Department of Energy (DOE) has identified around 440 different BPS tools (IBPSA, 2015). These tools have not had the impact required (Hopfe, 2009; Schlueter & Thesseling, 2009) as they are inadequate to support the early stages in the design process (Crawley, 2008; Jankovic, 2012). From the tools identified by DOE, almost 90% are suitable for engineers in a post design evaluation; 10% for architects in a post design evaluation and less than 1% is suitable for architects during the pre-design stage (Attia et al., 2012). As a result, available BPS tools can check codes rather than achieve an optimal solution through an iterative design process (Cemesova, 2013; Hopfe, 2009).

3.2.3 Review of software

As stated above, the DOE has identified around 440 different BPS tools. Understanding that a rigorous analysis of all these tools is out of the scope of this dissertation, a few of them will be selected so they can be analysed. Even though the literature provides some reviews undertaken by some researchers (Zhu et al., 2012; Attia, 2011; Zhu et al., 2013), these studies are usually quite old or it is not clear what parameters are used to select a particular software.

To select the software involved in this review the data from the US DOE's website was used (figure 3.3). Utilising this site all the software able to run a whole building energy simulation were filtered and compared, In doing so the database was reduced to five tools: Sefaira Architecture, DesignBuilder, IES Virtual Environment, OpenStudio, and Autodesk Green Building Studio. Additionally, Green Building Studio was not considered as it is regarded as being a calculation engine rather than design software with a graphical interface.

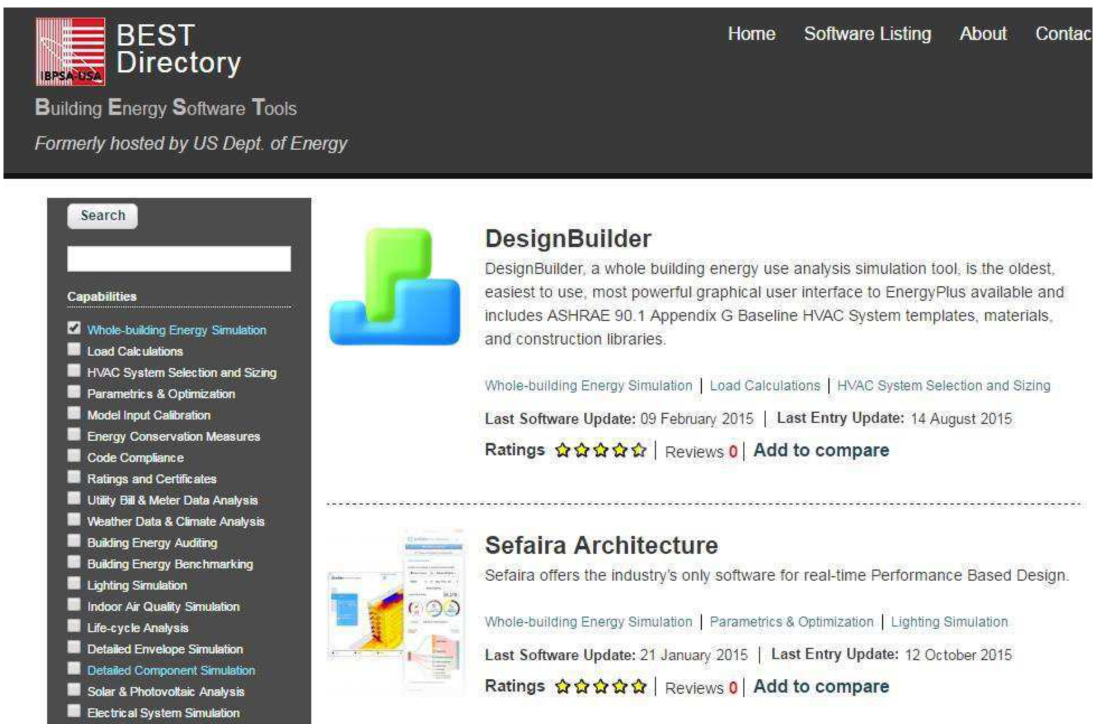

Figure 3.3 US DOE´s website

From table 3.1 is possible to see that the software that covers more type of users (IES and OpenStudio) is more complicated to use, requiring specific training. On the other hand, Sefaira and DesignBuilder cover a few kinds of users then the interface of this software is simpler with no specialised training required to operate them. Also, it is remarkable that Sefaira and OpenStudio provide the opportunity to run analyses using a cloud service.

	Sefaira Architecture	DesignBuilder	IES Virtual Environment	OpenStudio
Expertise Required	No specific expertise is required	Beginning to advanced capabilities	Training is required	Training is required
User	Architect, engineer and consultant	Architect, engineer and builder designer	Engineers, architects, sustainability and energy consultants, building owners, facilities managers and contractors.	Mechanical, architectural, and energy engineers; energy-efficiency programme administrators; energy-efficiency policy analysts; researchers; students and educators; software application developers.
Input	SketchUP, Revit,		Revit/SketchUp/ Trelligence/ Vectorworks/ Graphisoft	
Country	UK & the USA	United Kingdom		United States
Major Capabilities	Whole-building Energy Simulation Parametrics & Optimization Lighting Simulation	Whole-building Energy Simulation Load Calculations HVAC System Selection and Sizing	Whole-building Energy Simulation Code Compliance	Whole-building Energy Simulation Energy Conservation Measures Lighting Simulation
Platform	Windows Mac OS X Web/SaaS	Linux Windows	Windows Mac OS X	Linux Windows Mac OS X Web/SaaS

Table 3.1 A comparison of BPS tools

3.3 Integrating BIM/BPS

There is a real need for to integrate BIM with BPS (Clarke, 2001; Hensen, 2004; Papamichael, 2002) especially in projects where the architecture is irregular enough so that a performance evaluation is undertaken by rules of thumb or by codes. Integrating both methodologies will allow for dealing with complex problems and to obtain performance optimisation. However, the integration sets a series of challenges such as making available meaningful data for everyone involved in the project independently of the platform used or the project stage in which they are involved (Kymmell, 2008). To do this will require the replacing of the traditional sequential methods for a concurrent interactive design (Dong et al., 2007).

3.3.1 Integrating workflows

To integrate BIM and BPS requires the integration of the workflows into an integrated system which allows a smooth flow of the information. Currently the industry uses three approaches to achieve integration: combined model, central model or distributed model.

- Combined model method

This approach provides modelling and simulations' functionalities in an integrated environment (figure 3.4a) and the user does not need to use different platforms to create the model and run the simulation. Autodesk Green Building Studio and IES are examples of this approach (Negendahl, 2015)

The disadvantage of this model is that the whole group of users need to agree to use a single platform for the entire project. Additionally, the users will be restricted to the options and features offered by that environment (Negendahl, 2015)

- Central model method

The model and simulation are undertaken by different tools, but the data is shared with other users through a standard exchange format such as IFC or gbXML (fig 3.4b). The integration through this scheme might be time-consuming because of the need for setting protocols and agreements with different parties. Simergy and OpenStudio are examples of this approach (Negendahl, 2015).

The limitations of this approach are related to the ability of each software to write and read the standard format that might result in a poor interoperability (Negendahl, 2015).

- Distributed model methods

The integration is undertaken by using a middleware (figure 3.4c). This tool is responsible for filtering, modifying and extending user definitions to make the data meaningful for a BPS tool (Negendahl, 2015).

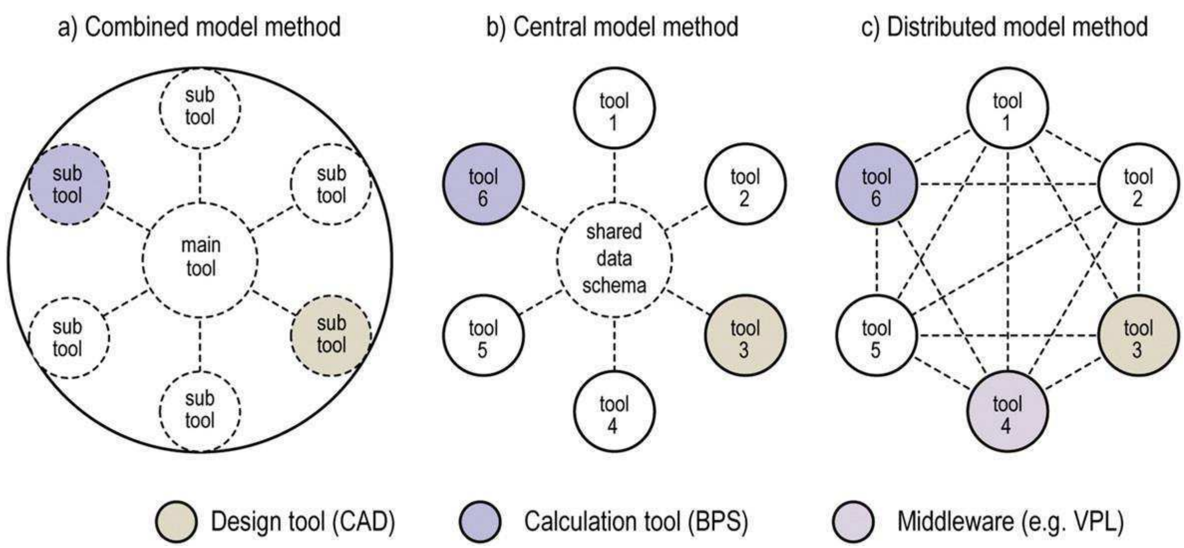

Figure 3.4 Integrating BIM and BPS tools (Negendahl, 2015)

3.3.2 Benefits of an integrated workflow

The integration of BIM and BPS leads to a series of benefits that is not possible to get in standalone workflows. The major advantage of integrating both workflows is the chance of bringing the energy design into the project at an early stage in order to obtain a better energy performance within the project, with a low cost for changing any part of the design. The benefits of an integrated workflow are detailed below:

- Improvement in early collaboration

Because BIM technologies bring a better understanding of a project in its early stages, then it is possible to collaborate early on with multiple designers. A new actor in this collaborative work is the energy engineer who will be able to discuss recommendations with other specialists and agree an early solution to any problems (Eastman et al., 2011).

- Improvement of Energy Efficiency and Sustainability

A full integration between BIM and BPS will give the energy expert a large amount of high-quality information in the early stages. Because of the quality of the data available the energy expert will not spend large periods of time checking the quality of the models received or in adding some missed data manually. Because he/she will no longer need to check data activities, the energy expert will be able to spend time in creating the design and consequently he/she will be able to produce multiple alternatives to be evaluated by the multiple actors involved in the design (Krygiel & Nies, 2008).

Creating more alternatives will allow the energy expert to improve his/her understanding of the project and the problems in it. Presenting different alternatives for the design will allow for better decision-making based on multiple options rather than on one or two proposals.

3.3.3 Integration challenges

The integration of both systems is not about developing the energy design as soon as possible, instead the integration demands the achievement of a better information exchange between both systems. In achieving this it will be possible to overcome the obstacles existing in current practice.

3.3.3.1 Interoperability BIM/BPS

The lack of interoperability between BIM and BPS tools has been highlighted by multiple authors (Attia, 2010; Krygiel & Nies, 2008; Hemsath, 2014; Levy, 2012). Most BIM tools can translate from their native formats into a standard format readable by any BPS tool (Kymmell, 2008). However, it is not just a translation problem from one application to another. It is also about supporting each relationship that describes how those data were defined (Eastman et al., 2010). Unfortunately, the universal formats that exist are not able to capture these relationships and thus some data are missed in the translation process (Eastman et al., 2011; Smith and Tardiff, 2009).

As a result of poor interoperability, the energy consultant will need to make some manual corrections in the geometry and data every time the BIM model is imported into the BPS tool (Krygiel & Nies, 2008; Sanguinetti et al., 2014). Krygiel and Nies (2008) point out that most of the time used in energy simulations is spent correcting data or re-entering data manually (fig 3.5), not leaving much time to explore design options. (Madjidi & Bauer, 1995)

Due to the large amount of time required to modify the energy model, such modifications are usually done during detailed design stage when the design is well defined and does not require iterations. Doing this avoids introducing any early change in the design when the changes have a large impact on the project but at low cost (Krygiel & Nies, 2008). The re-entry data process is prone to errors due to human interpretation (Hemsath, 2014).

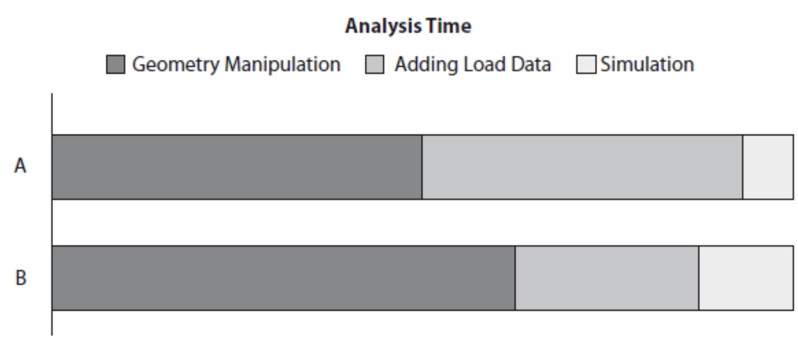

Figure 3.5 Time consumed in energy analysis (Krygiel & Nies, 2008)

3.3.3.2 Dealing with interoperability

- Data and process model integration

Data and process model integration is the most used approach for interoperability. It consists of using tools from the same vendor for different purposes e.g. thermal simulation, modelling HVAC systems, lighting calculation, etc. Because all these tools are from the same vendor, there will not be any problem with the interoperability between the software (Eastman et al., 2011; Hensen 2004).

However, data and process model integration does not mean to adopt an open approach; Indeed the user will keep on being restricted by the solutions provided by the software developer. In this sense, it is possible that the provider will not be able to provide a solution for a specific problem in a project during the lifecycle (Smith & Tardiff, 2009), at some point it is likely that another solution will be required to solve certain problems.

- Data model interoperation

This approach achieves interoperability between programmes on the level of a product model There are two approaches for it (Hensen, 2004):

1) Product model data sharing: used to extract a specific portion of data for a specific purpose, avoiding data redundancy.
2) Product model data exchange: extracts a model as a whole or part by using neutral formats such as IFC or XML.

- Process model interoperation

Interoperability is achieved for models that describe physical processes such as thermal simulation and flow (Hensen, 2004).

- Data model and process model co-operation

In this approach, the tool has a link to call on other applications asking them for the exchange of data during a simulation (Hensen, 2004).

3.4 Exchange schemas for interoperability

A schema is an abstract representation or a model of data that is used to create and to operate database schemas (Eastman et al., 2011). In figure 3.7 are illustrated the most common schemes that deal with interoperability (IGES, IFC, CIS/2, STEP, etc.). Each schema is defined by a single language, but a language can define multiple schemes. The interoperability issues require being able to use a schema and language to build a database readable by any tool supporting the language schema (Murata et al., 2000). Creating this data schema will allow for the creation and validation of documents using computer tools (Murata et al., 2000).

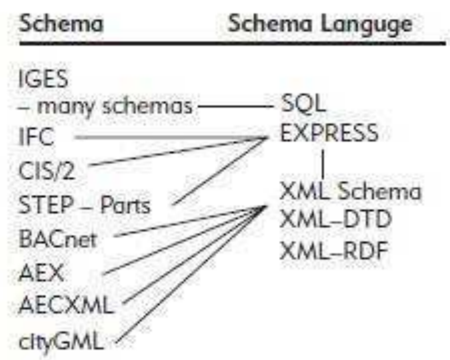

Figure 3.6 Relationship schema-language (Eastman et al., 2011)

3.4.1 Model schema

- STandard for the Exchange of Product (STEP)

The coverage of the Standard for the Exchange of Product (STEP) schema is broad and it describes the methods used to present the standard, the implementation architectures, the conformance testing procedures, the information resource models, and the application protocols (Loffredo, 1999).

The STEP schema (figure 3.7) can be divided into (Eastman, 1999; Loffredo, 1999):

- Description methods: which contains the language to be used in the description of the model, e.g. EXPRESS language, NIAM and IDEF1x.
- Integrated resources: these are the common model subsets used to define a model. There are two types of subsets: generics items such as geometry, material properties and project classifications which can be shared in different software; an application that is a specific subset used in industry which includes electronics, drafting, kinematics, finite elements, and building.

- Application protocols: these are divided into two areas: the application reference model (ARM) and the application interpreted model (AIM). The former describes the requirements that need to be considered in an application in a way that is understandable for user. The latter describes the elements detailed for ARM, but in technical terms from a pre-existing definition library.

- Implementation methods: these include the basic elements required for a STEP implementation.

- Conformance test: this checks the AIM and the AIM implementation to corroborate that the STEP language and tools have been properly used and interpreted.

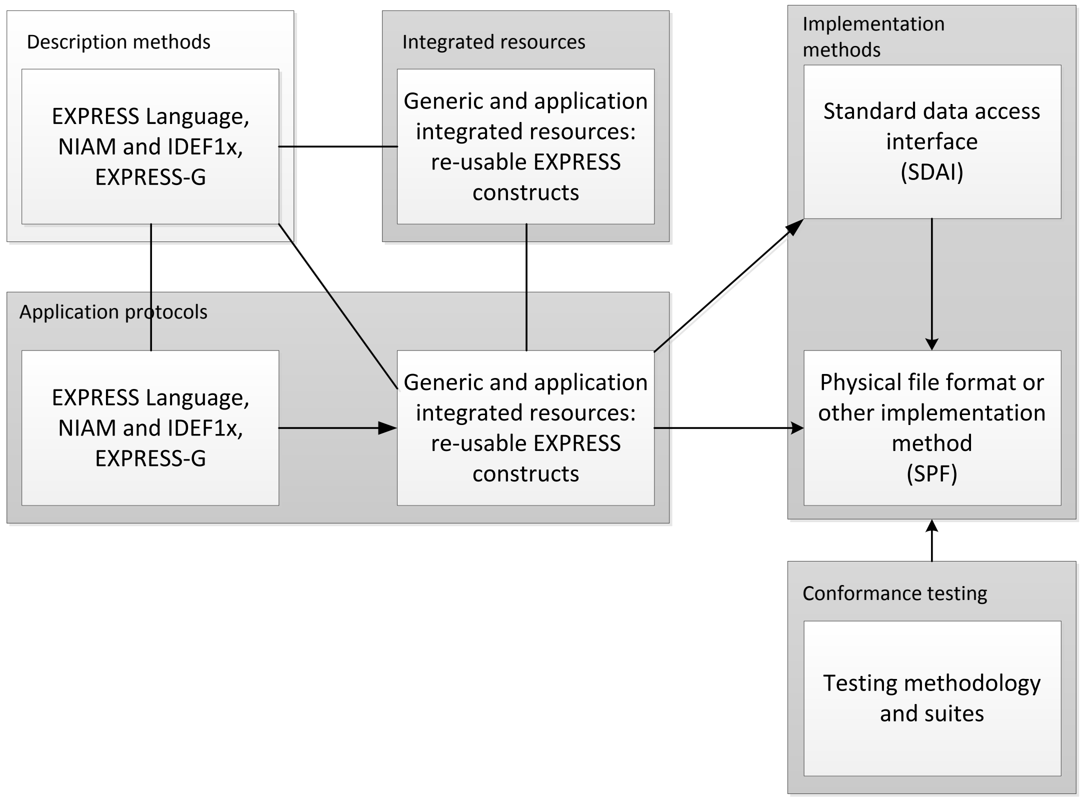

Figure 3.7 STEP schema (Eastman, 1999)

- Industrial Foundation Classes (IFC)

IFC is a schema to represent building information for exchange between different AEC applications (Eastman et al., 2011). This schema is based on EXPRESS language; thus the format can manage a large amount of data over the whole lifecycle, from feasibility to building operation (Eastman et al., 2011). Being based on EXPRESS language gives to IFC schema the chance of expanding the data carried by adding new entities in case they are required for the exchange process (Eastman, 1999).

The data covered for the IFC schema can be classified into four categories (Eastman et al., 2011):

- Geometry: The IFC schema can support a wide range of geometries, such as wall systems and extruded shapes.

- Relations: these describe how an element is linked with another. Because of the multiple relations that are possible to set between the elements, this subset has many subclasses to describe most of the relationships.
- Properties: these define the element materials, type of performance, and the contextual properties e.g. wind, geological information or weather data.
- Metadata: allows for the addressing of information ownership, tracking of changes, controls and approvals.

The IFC schema is organised in four layers to describe the data shown above (figure 3.8):

- **Resource layer**: the bottom layer in figure 3.8 describes the elements commonly used such as a generic wall, floors, structural elements, building service elements, process elements, management elements, and generic elements (Eastman et al., 2011). Because of the repetitive nature of these elements, it is possible to reduce the file size referencing multiple elements to the same instance of a resource (BuildingSMART, 2014).

- **Core layer**: this is the most important layer in the IFC schema. It provides the fundamental relationships and common concepts to present further aspects of the models (BuildingSMART, 2014). It contains the kernel, control extension, product extension and process extension. The kernel defines the objects, relationships and location of products in space (Eastman et al., 1999).

- **Interoperability layer**: this defines objects that can be shared by more than one application (Eastman et al., 1999).

- **Domain layer**: the top layer deals with specific entities used in particular cases such as structural elements and structural analysis extensions, architectural, electrical, HVAC, and building control element extensions (Eastman et al., 1999).

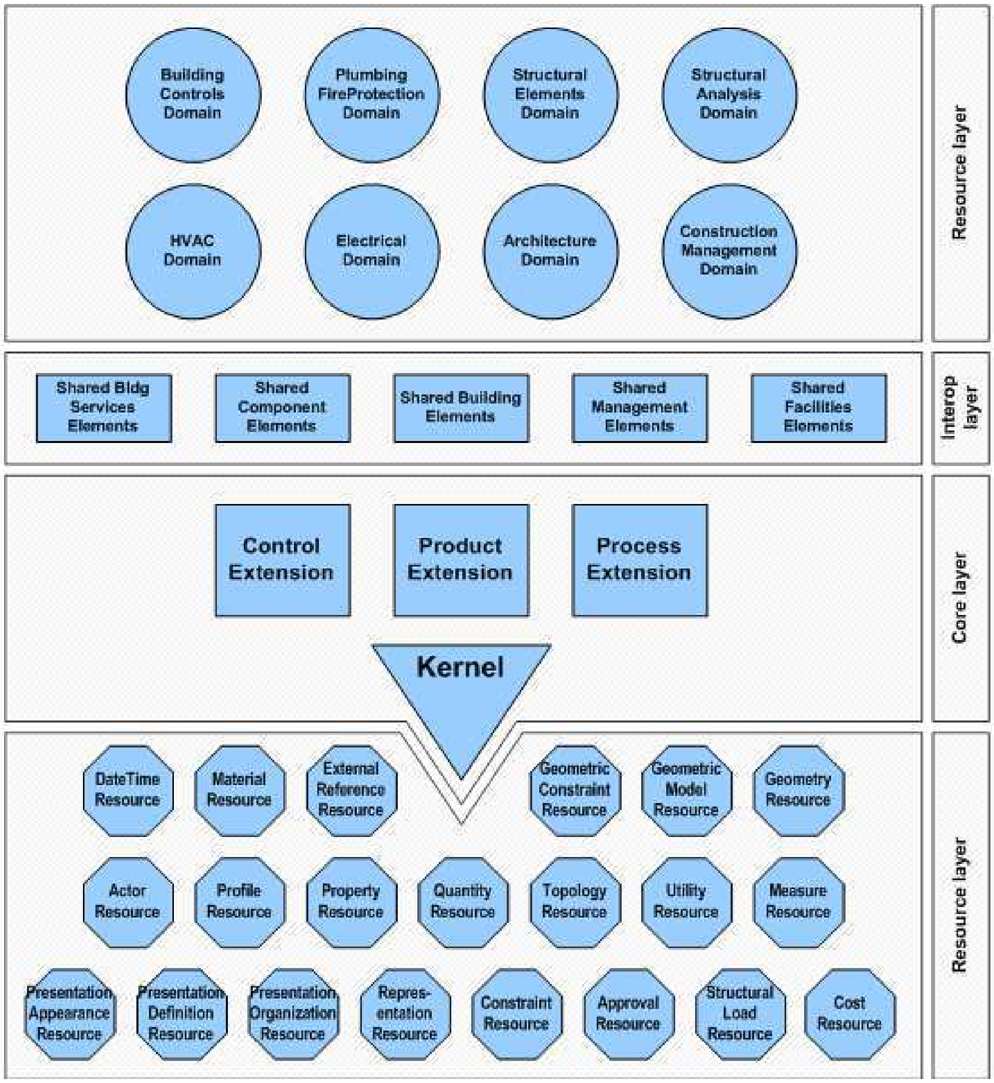

Figure 3.8 IFC schema architecture with conceptual layers (BuildingSMART, 2014)

3.4.2 Schema languages

- Extensible Markup Language (XML)

BuildingSMART suggests using XML as a schema language to describe the interoperability with MVD (BuildingSMART, 2012). This format has been widely used as a standard for data exchange because of its ability to manage a small amount of data and facilitate the exchange over the web (Eastman et al., 2011). Despite its broad acceptance, the schema is not adequate to describe the interoperability between BIM tools because the schema is unable to capture the relationship between the elements specified in the IFC models (Dong et al., 2007). As a result, it is not possible to handle complex models because some properties and elements are missed during the exportation process (Abanda et al., 2013; Donnell et al., 2011).

In 2012, BuildingSMART developed a subset of XML called MVD-XML. The proposed scheme has as a purpose the support of the automated validation of IFC data sets. It generates documentation for specific model views and the IFC version, it supports software vendors allowing them to filter IFC data based on model views and it limits the IFC scope to subsets for particular applications (Chipman et al., 2012). Nonetheless, it has the same problems with regard to the impossibility of describing the relationship between the elements (BuildingSMART, 2012).

- EXPRESS language

The EXPRESS schema describes a product model (product and processes) using a series of attributes such as entities, functions, procedures and it also describes the relationship between the elements (Eastman, 1999, Goh et al., 1996). The output from this description process can be automatically interpreted by software tools compatible with the language (Goh et al., 1996). Nonetheless, to develop an EXPRESS code is a challenging task because of the complexity of the processes to be managed. Subsequently, the developer will need to go through a large amount of data until he/she can find an available definition and establish their relationship (Goh et al., 1996).

The implementation of this language is undertaken using a graphical protocol known as EXPRESS-G. Then the data will be available to application developers (Loffredo, 1999).

- EXPRESS-G language

The implementation of EXPRESS language is simplified using EXPRESS-G. It allows a graphical definition of data structures, relationships and attributes of a major subset of the EXPRESS language. This graphical definition is readable by a computer and can generate most of the EXPRESS schema automatically (Eastman, 1999; Loffredo, 1999).

The EXPRESS-G language has the following features (Goh et al., 1996):

- Types, entities and relationships are easily selected because of the graphical representation of these elements.
- Flexibility to allow the breakdown of a model into multiple pages
- Translation of the model into an EXPRESS code by using a graphical representation that will make it possible to identify the relationship between the entities.

Figure 3.9 illustrates the EXPRESS-G language applied to the IFC schema. Within it is possible to distinguish (BuildingSMART, 2014):

- **IfcRoot**: this is the most abstract and is the source for all entity definitions linked with the kernel of the IFC schema. It defines independent entities by name and description. The IfcRoot concept is supported by ifcRelationship to describe the relation between ifc entities; IfcPRopertyDefinition describes the characteristics that can be used in other objects.
- **IfcObjectDefinition**: this entity allows the creation of library elements through the description of elements as independent pieces of data that can be referenced to other objects.
- **IfcObject**: this entity describes particular and tangible objects or processes, then it is possible to define actors, resources, processes,, etc.

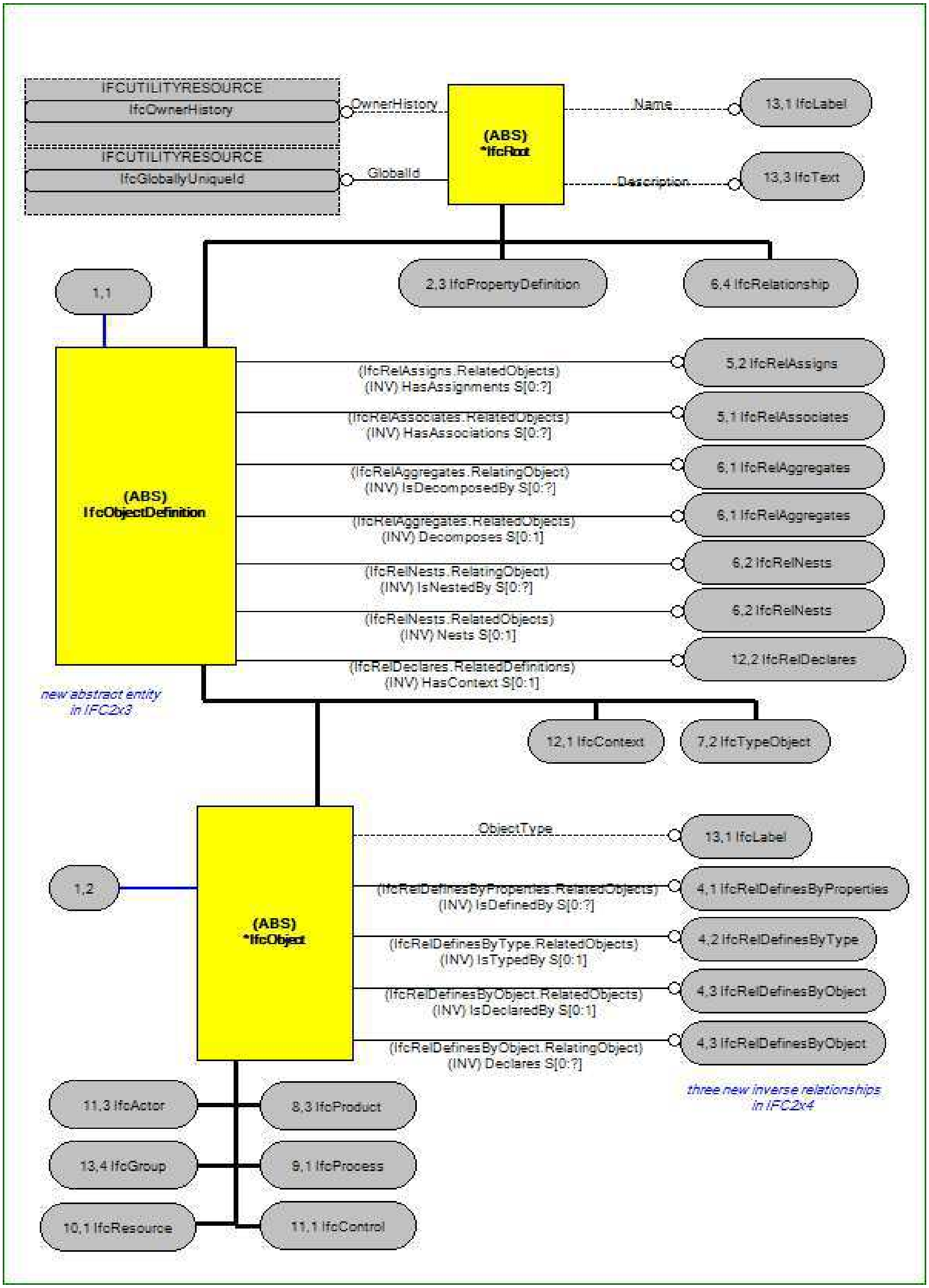

Figure 3.9 EXPRESS-G schema (BuildingSMART, 2014)

Chapter 4. Methodology and research design

Once the literature review has been undertaken, the research process is developed. There are multiple methodologies that can be utilised in research. The selection of one methodology over another will depend on a researcher's skills and understanding how a particular methodology fits the goals and objectives set by his/her research.

This research had adopted the onion methodology proposed by Saunders et al. (2009) because it is a well-structured guide that leads from the philosophy right up to the data collection and analysis methods. Each component of this methodology is introduced in the sections below and then the research is designed selecting the most suitable elements from the onion methodology to deliver a view of how this research will be developed from the data collection to the analysis.

4.1. Research methodology

Research methodology is defined as ´a systematic and methodical process of inquiry and investigation with a view to increasing knowledge´ (Collis & Hussey, 2014). Research methodology covers a full spectrum from theoretical underpinning to the collection and analysis of data (Collis & Hussey, 2014) which leads to better decisions and results than those based on intuition or personal likes and dislikes (Ghauri & Grønhaug, 2005).

It is necessary to choose the most suitable methodology based on the research objectives to achieve the expected results (Dawood & Underwood, 2010). The right research methodology will allow conceptualising and explaining the occurrence or not of a particular phenomenon (Gill & Johnson, 2010; Leedy & Ormrod, 2005).

This dissertation will use the 'onion' methodology (figure 4.1) proposed by Saunders et al. (2009). It is characterised by structuring the research through six layers (philosophies, approaches, strategies, choices, time horizons, and techniques and procedures) to show a clear picture of the research process that is easily understandable by researchers (Dawood & Underwood, 2010). Each of the six layers shown in figure 4.1 will be explained in detail in sections 4.1.1 to 4.1.6.

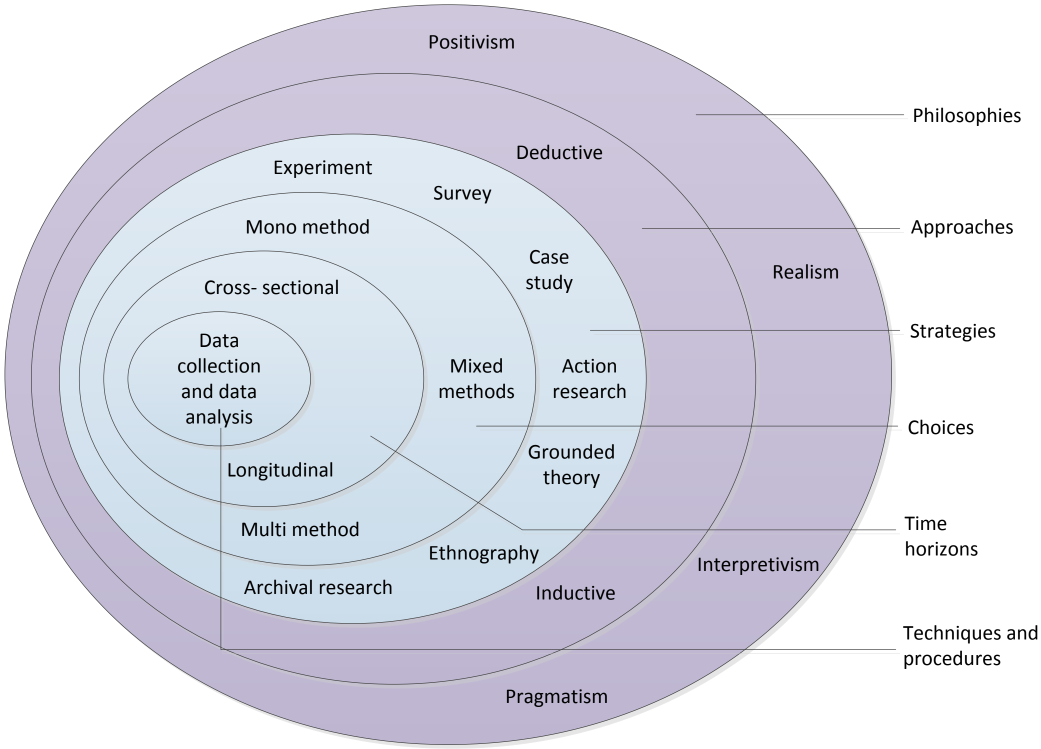

Figure 4.1. Research methodology based on the Onion Model (Saunders et al., 2009)

4.1.1. Research philosophy

The external layer in the onion model (figure 4.1) represents the research philosophy. It is a foundational layer that is related to the development of knowledge and the nature of it (Saunders et al., 2009). Each philosophy has its methods and assumptions to explain the world and, consequently, to address a piece of research. Nonetheless, Saunders et al. (2009) recognised that the assumptions and method are not decisive factors to select one philosophy over another; indeed the most important element is the researcher´s view of the relationship between knowledge and the process by which it is created (Saunders et al., 2009).

Saunders et al. (2009) identified four philosophies (positivism, realism, interpretivism and pragmatism) in this methodology. An understanding of each philosophy will allow the clarification of the research design, the detection of the most suitable research design, and the identification or even the creation of new designs not existing previously in the research´s experience or literature (Easterby-Smith et al., 2012). Each of the philosophies considered by the onion model is explained below.

- **Positivism:** this philosophy argues that reality consists of what is perceived by the senses (Gray, 2014; Collis & Hussey, 2014) and that it is possible to measure the properties of this reality through scientific methods (Easterby-Smith et al., 2012). The outputs from this philosophy are easily replicable and objective rather than subject to free interpretation (Collis & Hussey, 2014). The characteristics of the outputs make them easily generalizable to produce a theory (Saunders et al., 2009).

- **Interpretivism:** this approach states that research may not deal with subjects and objects in the same way (Gray, 2014; Saunders et al., 2009) as the positivism philosophy does. Interpretivism tries to explain the social reality of humans as social actors, and that it is fundamental to the researcher to be empathetic with the studied subjects to gain access to their reality. As a result, the study may change according to the researcher's feelings during the process (Saunders et al., 2009).

- **Realism:** in this philosophy, the world exists externally and acts independently of the observer (Gray, 2014). According to Saunders et al. (2009), realism is subdivided into two types: direct realism and critical realism. Direct realism says that what is perceived by the senses (vision, listening, touch, taste) is the real world. On the other hand, critical realism states that the senses can capture a projection of the consciousness and cognition (Saunders et al., 2009).

- **Pragmatism:** is not committed to any philosophical system in particular; instead it is focused on the problem to be studied and the questions to be asked. Under this approach, the researcher is free to use any method, technique and procedure that fulfil their needs (Creswell, 2007).

4.1.1.1. Philosophical assumptions

In addition to choosing a philosophy to guide the research, the researcher will need to set a stance and make some assumptions about some points such as the nature of data (ontology), the relationship between the researcher and the subject under analysis (epistemology), and the role of values in the research (axiology) (Creswell, 2007). Even though the literature introduces other assumptions such as rhetorical (Collis & Hussey, 2014) and methodological (Creswell, 2007), only ontology, epistemology and axiology will be considered as they are the most common assumptions shown in the literature (Easterby-Smith et al., 2012; Gray, 2014; Saunders et al., 2009). The main assumptions are presented below.

- **Ontology:** deals with the nature of reality and its characteristics (Easterby-Smith et al., 2012; Gray, 2014). It recognises that each individual experiments with different realities (Creswell, 2007). This assumption is particularly useful for qualitative research that needs to capture the opinions of multiple individuals (Creswell, 2007; Gray, 2014). Ontology redefines the realities described by positivism and interpretivism. Positivism assumes that reality is external and independent of the researcher (Collins & Hussey, 2014) while the interpretivism stance states that reality is a social phenomenon created by an observer´s consciousness and cognition (Gill & Johnson, 2010).
- **Epistemology:** provides the researcher with a philosophical background to allow him/her to choose what kind of knowledge is valid and adequate (Gray, 2014). Epistemology reinterprets the knowledge gained from the positivism and interpretivism philosophies. With regard to epistemology, positivism´s knowledge is independent and objective, while interpretivism is subjective and built on internal beliefs (Collins & Hussey, 2014).

- **Axiology:** this philosophy is concerned with the research process at different stages and how it affects the results (Saunders et al., 2009)**.** Axiology considers positivism as value-free which means that the researcher is detached and independent of the investigated phenomena. On the other hand, researchers involved in an interpretivism project can modify the values in the research (Collins & Hussey, 2014).

Table 4.1 summarises the main ideas about each philosophy and the assumptions introduced above.

	Positivism	Interpretivism	Realism	Pragmatism
	Working with observable phenomenon	Understanding differences between humans as social actors	Do objects exist independently of researcher knowledge?	Focus on research question
Ontology What is the nature of reality?	External, objective and independent of social actors	Socially constructed, subjective, may change, multiple realities	It is objective. Exists independently of human thoughts and beliefs or knowledge of their existence (realistic), but is interpreted through social conditioning (critical realist)	External, multiple, viewchosen to best enable the answering of the research question
Epistemology What constitutes acceptable knowledge?	Only observable phenomena can provide credible data, facts. Focuses on causality and law like generalisations, reducing phenomena to simplest elements	Subjective meanings and social phenomena. Focuses on the details of a situation, the reality behind these details, subjective meanings motivating actions.	Observable phenomena provide credible data, facts. Insufficient data means inaccuracies in sensations (direct realism). Alternatively, phenomena create sensations which are open to misinterpretation (critical realism). Focus on explaining within a context or contexts	Either or both observable phenomena and subjective meanings can provide acceptable knowledge dependent upon the research question. Focus on practical applied research, integrating different perspectives to help interpret the data
Axiology What is the role of values?	Research is undertaken in a value-free way, the researcher is independent of the data and maintains an objective stance	Research is value bound, the researcher is part of what is being researched, cannot be separated and so will be subjective	Research is value laden; the researcher is biased by world views, cultural experiences and upbringing. These will impact on the research	Values play a large role in interpreting results, the researcher adopting both objective and subjective points of view
Data collection techniques most often used	Highly structured, large samples, measurement, quantitative, but can use qualitative methods	Small samples, in-depth investigations, qualitative	Methods chosen must fit the subject matter, quantitative or qualitative	Mixed or multiple method designs, quantitative and qualitative

Table 4.1. Summary of research philosophies and assumptions (adapted from Saunders et al., 2009).

4.1.2. Research approach

The second ring in the onion methodology (figure 4.1) introduces the research approach or theory for the sequential order of each stage considered in the framework used in the research design (Saunders et al., 2009). The components of a framework are: purpose, conceptual framework, the research question, methods and sampling strategy. The order of these elements will change based on the research question and the decisions made by the researcher about methods and procedures (Robson, 2011).

There are multiple research approaches classified by purpose, process, outcome and logic (Collins & Hussey, 2014). Saunders et al. (2009) proposed choosing research approaches by logic (deduction and induction). Each of these approaches will lead to proceeding in different ways for the data collection. Then it is important to ensure a correct selection to obtain the expected results (Creswell, 2014). In the following subsections both approaches are explained.

4.1.2.1. Deduction

This approach ´moves from theory to data´ to understand the relationship of the cause-effect of different phenomena (Gill & Johnson, 2010). Before it is used, the deduction approach will need to develop a theory and hypothesis (Saunders et al., 2009). Then the steps suggested by Croswell (2014) (see figure 4.2.) will need to be used. The researcher will create a research strategy that will be used to test a hypothesis or research question set previously. Then some parameters will be defined to control the hypothesis to finally measure and analyse the outcome of the test. If the results are not consistent with the hypothesis, then the test has failed. Deduction is used with quantitative research. It requires a highly structured methodology and a large number of samples to be statistically significant (Saunders et al., 2009).

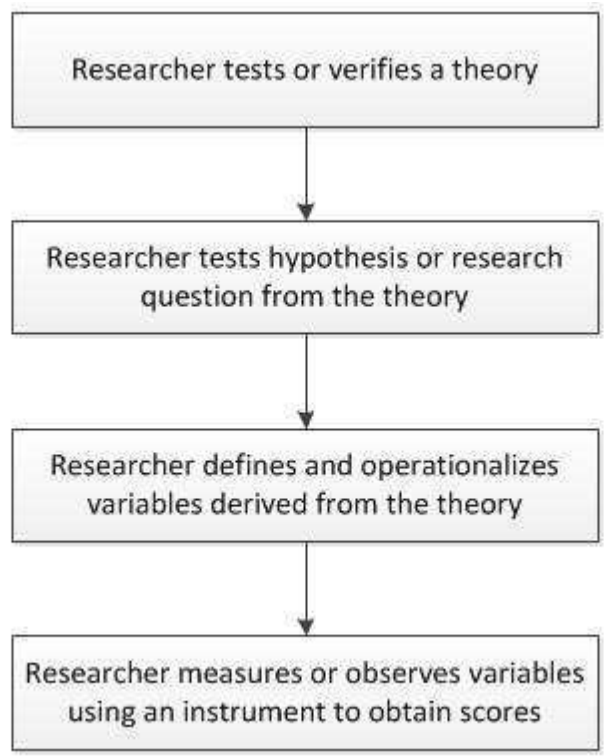

Figure 4.2. Deductive approach (Creswell, 2014)

4.1.2.2. Induction

The induction approach is opposite to the deduction approach. It is focused on describing the context in which a problem happens rather than describing the problem itself (Gill & Johnson, 2010). In figure 4.3, the process starts from the bottom with data collection and then the data is analysed looking for any pattern of association between the phenomena to generate a theory and generalisation (Gill & Johnson, 2010).

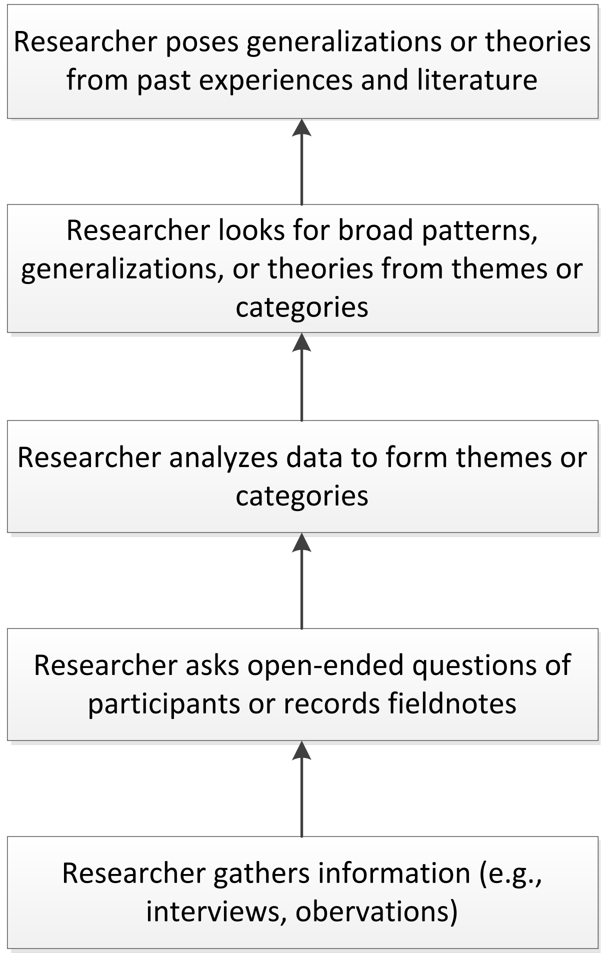

Figure 4.3. The Inductive approach (Creswell, 2014)

4.1.3. Research strategy

The third ring in the onion methodology (figure 4.1) introduces the research strategy. This is the plan that the researcher will follow to answer the research question (Saunders et al., 2009). There are multiples research strategies: experiment, survey, case study, action research, to name a few. The researcher will need to pay attention to the research question, objectives and philosophy to choose a suitable strategy (Saunders et al., 2009). The chosen strategy will determinate the left rings within the onion methodology (collection, measurement and analysis of data) (Gray, 2014).

4.1.3.1. Experiment

An experiment is a methodology used to understand the relationship of cause-effect on a particular phenomenon (Easterby-Smith et al., 2012). In an experiment, the variables can be put under control and then a researcher can alter the independent variable (cause) to analyse how that change has an influence on the dependent variable (effect) (Gray, 2014). This methodology is used in exploratory and explanatory approaches to answer ´how´, ´why´, ´when´ and ´why´ questions that have emerged in fields such as psychology and medical research (Saunders et al., 2009).

Because an experiment is usually developed in a laboratory with most of the variables under control, then the results can have a high internal validity, that is the findings can be extended to similar situations (Saunders et al., 2009)thus making it easy to replicate the findings by any researcher (Easterby-Smith et al., 2012). Nonetheless, an experiment does not have validation in the real world because of the limited number of variables used (Robson, 2011).

4.1.3.2. Survey

A survey is research method that collects data through different tools such as interviews, questionnaires and observation tools (Robson, 2011). The collected data form a detailed and quantified description of a sample population (Sapsford, 2011). These datum are analysed statistically to set and explain the relationships between different variables and to create models for these relationships (Saunders et al, 2009).

The survey method is divided into descriptive and analytical approaches. The former describes a particular situation at a specific point in time e.g. a customer´s views of a new product. The latter is used to determine a possible relationship between multiple variables (Collins & Hussey, 2014). This method is used in business and management research and commonly tries to answer ´who´, ´what´, ´where´, ´how much´ and ´how many´ questions. It is suitable for exploratory and descriptive research (Saunders et al., 2009).

4.1.3.3. Case study

A case study is a research method focused on understanding a particular contemporary phenomenon within a real context using multiple sources of evidence (Saunders et al., 2009). This approach is useful under any of the following conditions: in research areas where there is a lack of theory and there is a need to gain an understanding of a particular phenomenon (Collins & Hussey, 2014); where the boundaries between the phenomenon and its contexts are not clear (Yin, 2014).

The case study focus is wide. It can be considered as both a quantitative and qualitative method (Robson, 2011) allowing the answering of a wide range of questions such as ´why´, ´what´, ´how´. The wider focus of this approach means that it can be adopted in multiple fields such as anthropology, business studies, marketing, medicine, organisational behaviour, politics, psychology, public administration, public health, social work and sociology (Gerring, 2006). Multiple applicability fields demand various data collection techniques such as interviews, observation, documentary analysis and questionnaires (Saunders et al., 2009).

The main criticisms of this approach concern a lack of rigorous process, generalisation of the findings is not possible for similar phenomena happening in a different context, and the generation of a large amount of data in order allow a researcher to make any inferences (Easterby-Smith et al., 2012).

4.1.3.4. Action research

This is an iterative method focused on identifying and analysing problems inside an organisation. A solution is proposed and implemented. Finally, the effectiveness of such a solution is evaluated and then the cycle starts again (Collins & Hussey, 2014).

For the success of action research, it is fundamental that there is involvement by all the participants in a collaborative partnership between practitioners and researchers (Saunders et al., 2009) with the objective of gaining an understanding of the problems and process through the feedback from each member. The process must be adjusted continuously to reach the goals set (Collins & Hussey, 2014).

4.1.3.5. Grounded theory

This method seeks to generate a theory about the particular situation under study through a combination of induction and deduction (Robson, 2011). In grounded theory, data collection starts without developing a hypothesis, literature review or research question (Gray, 2014). The collected data are used to generate a theory to predict human behaviour (Saunders et al., 2009). This approach is used in education, evaluation research, nursing and organisational studies (Gray, 2014).

4.1.3.6. Ethnography

This is an approach that has come from the field of anthropology. The aim is to understand a culture from a person's point of view. To reach this objective the researcher will immerse himself or herself in the culture to acquire knowledge by observing the behaviour patterns of human activity (Collins & Hussey, 2014).

4.1.3.7. Archival research

This research method is based on the use of administrative records and documents as the sources of data (Saunders et al, 2009). An archival research may have an exploratory, descriptive or explanatory approach to answering questions about the past (Saunders et al., 2009).

4.1.4. Research choices

The research strategies introduced in the previous section are not applicable individually in a real context. Usually, they are combined (Saunders et al., 2009). The way in which quantitative and qualitative research is mixed is known as the research choice.

4.1.4.1. Quantitative research

Quantitative research uses a well-structured framework to investigate the connection between numerical variables (Robson, 2011). These variables can be measured by instruments and analysed with statistical methods (Creswell, 2014).

The research strategies that can be utilised under this approach are experiment and survey (Gray, 2014). They can generate group properties and general tendencies' results which can be generalised to other research groups.

4.1.4.2. Qualitative research

Qualitative research is a method that is not built on a unified theory. It is an approach for exploring and understanding the context of a problem (Creswell, 2014). The research process is focused on questions and assumptions (Creswell, 2014). The data for this type of research are texts or images (Creswell, 2014) coming from diverse sources such as interviews, observations, focus groups and document analysis (Gray, 2014). This research requires a flexible framework that allows high levels of interpretation by the researcher (Gray, 2014).

Ethnography, grounded theory, case study, action research and archival research are considered qualitative methods (Gray, 2014). Any of these approaches is especially useful to gain knowledge in areas where there is not enough information and the researcher wants to understand the phenomena in the context where they happen (Gray, 2014).

4.1.4.3. Multiple methods

This method puts together quantitative and qualitative methods to integrate philosophical assumptions and theoretical frameworks within the same research (Creswell, 2014).

The multiple methods' approach can be divided into two categories (Saunders et al., 2009):

- Mono method: this uses a single quantitative data collection technique (survey, experiment) alongside analysis techniques or a single qualitative data collection technique.

- Multiple methods: this uses more than one data collection technique, qualitative and quantitative, but there is a restriction to one of these views.

4.1.5. Time horizons

The literature shows two types of time horizons in which to develop a research (Saunders et al., 2009): cross-sectional and longitudinal. In a cross-sectional time horizon the data are collected at one single point in time. This data are studied during a brief period of time (Robson, 2011). Usually, this time horizon relates to the survey strategy (Easterby-Smith et al., 2008). With the longitudinal time horizon, the data are collected at more than one point in time; it then allows an understanding of changes over time (Robson, 2011).

4.1.6. Techniques and procedures

Because there are multiple techniques and procedures based on the research design, further details will be given in the next section wherein the research design that will lead this dissertation will be defined.

4.2. Research design

The previous section has presented the main ideas and concepts concerning research methodology. This section will use the previous ideas to create the research design. But before this, it will review the goal and objectives set in chapter 1, with the purpose of keeping in mind the main characteristics that the research design will require to achieve the proposed goals.

Figure 4.4 summarises each element considered for the research design. This research will adopt pragmatism as its philosophy; induction as its approach, case study as its strategy; the mono method as its choice, and cross-sectional as its time horizon.

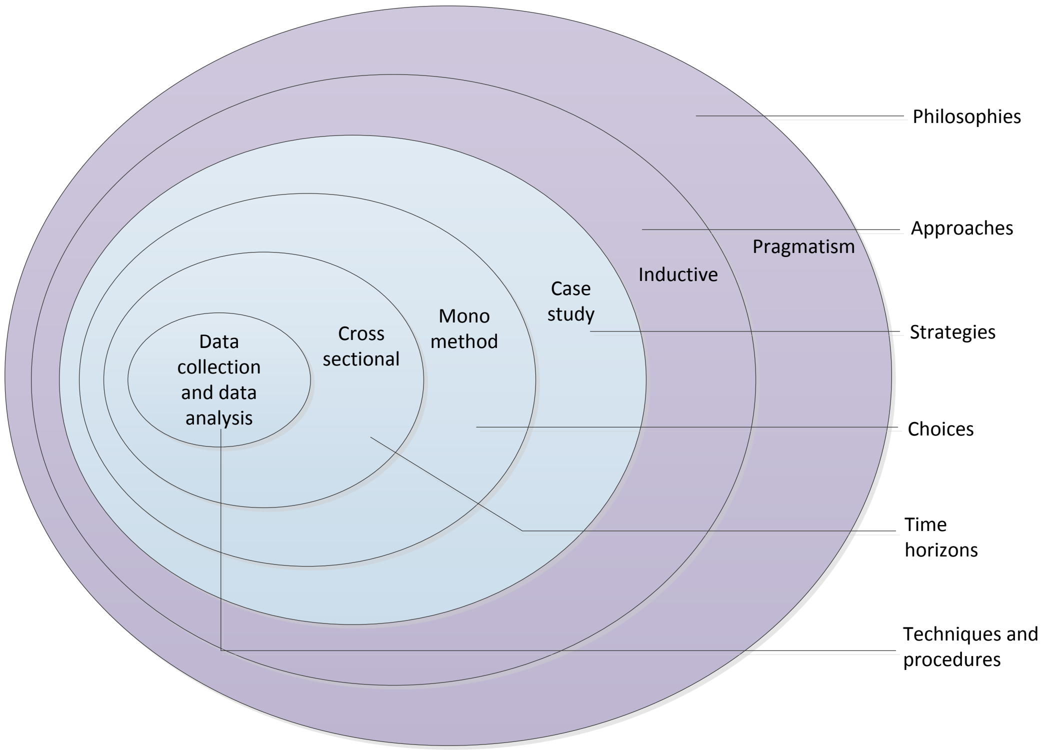

Figure 4.4. The research design

4.2.1. Philosophy

To find a suitable philosophy requires reviewing the goals and objectives set in chapter 1. In that chapter was stated the following research question:

> *How can BIM/BPS tools work collaboratively to enhance energy efficient design during the design stage?*

A ´how´ question suggests that the research might have a descriptive or explanatory purpose (Gray, 2014). On the other hand, an exploratory purpose would be useful to understand the context in which the collaboration issue exists (Gray, 2014; Saunders et al, 2011). Also, taking an explorative purpose aligns with the research objectives which are related to exploring concepts and identifying challenges.

Once the research purpose has been selected, the next step is to choose the most suitable philosophy among following alternatives: positivism, interpretivism, realism or pragmatism. Positivism is based on highly structured methods and produces numerical or quantitative data (Robson, 2011); it is a rigid method focused on explaining the cause-effect of phenomena rather than explaining their context (Collins & Hussey, 2014; Gray, 2014). Additionally, positivism methods can handle quantitative data (Saunders et al., 2009) while the exploratory approach can produce qualitative data (non-numerical); in such circumstances, there is no correspondence between the required and generated data. As a consequence, this philosophy is not compatible with an exploratory approach.

Interpretivism is not applicable in this research because it focuses on how the social world is interpreted by the subjects being studied (Robson, 2011). Thus this research scope is out of the limits of this study. Realism is another philosophy that has no application for this research. It is a subject of interest in practice-based and value-based professions such as social work (Robson, 2011).

Finally, there is pragmatism. Saunders et al. (2009) stated that it is the best paradigm when research is not clearly suitable for either positivism or interpretivism. By adopting the pragmatism approach, the focus will be on the research question rather than on a philosophy with a specific set of data collection tools (Collins & Hussey, 2014). As a consequence the research will be sufficiently flexible and the researcher can choose any data collection method (Collins & Hussey, 2014; Creswell, 2007). Indeed, pragmatism can deal with both quantitative and qualitative data. Thus it will be possible to select a method to collect qualitative data as the research requires.

In the light of the facts shown above, it is clear that the most suitable paradigm for this research will be pragmatism which will allow focusing on the research question and giving it the flexibility required to explore the context of the issue and to build knowledge.

4.2.2. Research approach

As mentioned in the previous section, this research will investigate an area where there is a lack of knowledge, namely the collaborative work that can be undertaken by BIM and BPS tools. This characteristic is essential in selecting a research approach that will guide the research process and in defining whether it will start from a general or particular paradigm.

This dissertation will adopt inductivism to deal with the research question and the nature of the data. Creswell (2014) suggested using inductivism where there is a lack of knowledge, this being the case set in the research question and objectives. Inductivism moves from specific data to general patterns or laws (Gill & Johnson, 2010). In the same way, this research will need to move from the data collection to describing the context in which the collaboration issues exist.

4.2.3. Strategy

The strategy will determine the method for the data collection. During the philosophy selection it was stated that this research would have an exploratory approach and, consequently, this approach would generate qualitative data (Creswell, 2014). Because it is already known that the only useful data for this research will come from qualitative methods, then it is possible to reduce the methods that need to be considered during the strategy stage and quantitative methods (survey and experiment) can be discarded.

With regard to the remaining five methods (case study, action research, grounded theory, ethnography and archival research), most of them have a specific study field e.g. grounded theory is used for education evaluation research, nursing, and organisational studies (Gray, 2014); ethnography is used for anthropology (Collins & Hussey, 2014); archival research is used for historical research (Saunders et al., 2009), and action research is used for managing change inside an organisation. These methods are not applicable in this research.

This research will use a case study approach as its strategy because the features of this method can overcome the challenges set by the research question and objectives. A case study will allow focusing on the research question and going deep in the investigation (Saunders et al., 2011) even if there is a lack of knowledge concerning the collaborative work that can occur between BIM and BPS tools. Indeed, Saunders et al. (2011), Yin (2014) and Gray (2014) suggested utilising a use case in such research where there is not enough theory. Also, the flexibility that is required by this research is achieved through the ability of this method to deal with a wide range of questions (why, what, how) and to generate qualitative and quantitative data (Robson, 2011; Saunders et al, 2009). The objectives of this research can be reached in this way and can achieve an understanding of a particular phenomenon (Collins & Hussey, 2014).

4.2.4. Research choice

The research choice chosen is a mono method study. This means that the data will be collected using one method at one time. However, the research will consider multiple data sources.

4.2.5. Time horizon

Because of the brief period of time available to develop this research, the time horizon will be cross-sectional. The data will be collected at one single point in time.

4.2.6. Technique and procedures

Creswell (2007) discussed the existence of several methods of conducting a case study. Although there are multiple methods, all of them share common elements (Stake, 1995) such as identifying cases, data collection, data analysis, and interpretation. This dissertation will adopt the procedure suggested by Yin (2014).

The procedure put forward by Yin (2014) has three stages (figure 4.5):

- *Defining and designing*: this is an essential stage for any research and it is where the research question, aim and the objectives to achieved are defined (Stake, 1995). This data will lead to determining whether the research is suitable to be answered through a case study. At this point the type of case to use will be chosen, whether it is single, holistic or multiple cases. Also, it is chosen the selection or designing of a proper method to collect the data to be generated in the next stage.

- *Preparing, collecting, analysing*: this stage starts developing all the supporting activities including creating protocols, accessing data agreements and ethical considerations. Then the data are collected, analysed and summarised (Gray, 2011).
- *Analysing and concluding*: finally, an analysis method is selected to examine the case study outcomes and the results of the case study are written up.

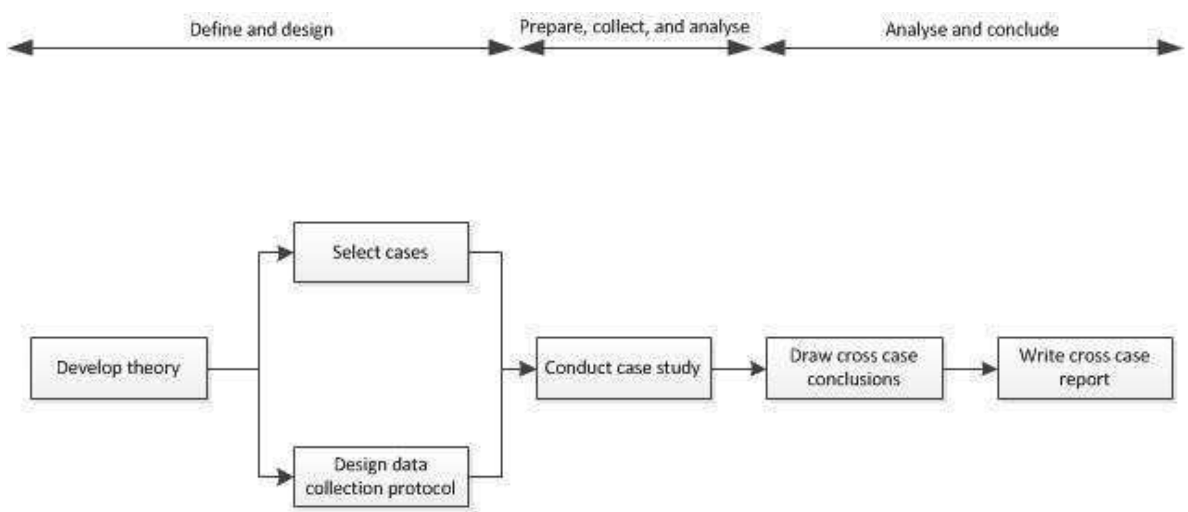

Figure 4.5. Case study procedure (Yin, 2014)

Once this chapter has explained each of the stages in the procedure suggested by Yin (2014), it will explain the assumptions to be considered and the way in which this research will develop.

4.2.6.1. Defining and design

- *Developing theory*: this stage has already been undertaken in chapter 1 where the research question, aim and objectives have been set. They will integrate the theory that leads the research.
- *Select cases*: this consists of choosing the number and units of analysis to be considered (Gray, 2014). Even though there is not a formal procedure for undertaking this, Yin (2014) proposed the matrix shown in figure 4.6. According to him there are four possible cases to choose from:
    - *Type 1*, single case, holistic: this examines a single case as a whole or as a single unit of analysis. It is used when the focus of the study is on the entire phenomena (Gray, 2014).
    - *Type 2,* single case, embedded: This considers a single case too, but with multiple units of analysis, because attention is paid to the units that form the case (Gray, 2014).
    - *Type 3,* multiple cases, holistic: this uses multiples cases with the objective of generalising the results, but it uses a holistic approach because of the impossibility of identifying more units of analysis (Gray, 2014).
    - *Type 4,* multiple cases, embedded: because of the use of multiple cases and units of analysis, the results from such a use case are likely to be replicable and generalizable (Gray, 2014).

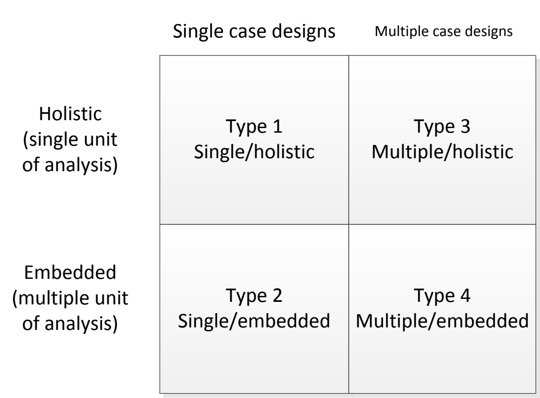

Figure 4.6. Types of case study design (Gray, 2014)

In this dissertation, a single holistic case will be used. The single case is chosen because the case study is unique (Saunders et al, 2009). On the other hand, it will be holistic because the unit of analysis is just one (whereas using multiple units would require considering how the design process is undertaken by multiple companies, and then generalising the process).

- *Design data collection protocol*: this case study will generate qualitative data as the outcome. Suitable methods for generating qualitative data are observations, interviews, documents or audio-visual material (Gray, 2014). The data collection will focus on a literature review to understand how an energy design is developed.

4.2.6.2. Preparing, collecting, analysing

- *Conduct case study*: figure 4.7 shows the conducting of the process to develop an interoperability specification. In it are shown the two methodologies that deal with interoperability: Information Delivery Manual (IDM) and Model View Definition (MVD). IDM defines interoperability at a user level capturing processes and exchanging requirements (BuildingSMART, 2012). MVD defines interoperability at software level linking the data to exchange within the IFC scheme (Hietanen, 2006).

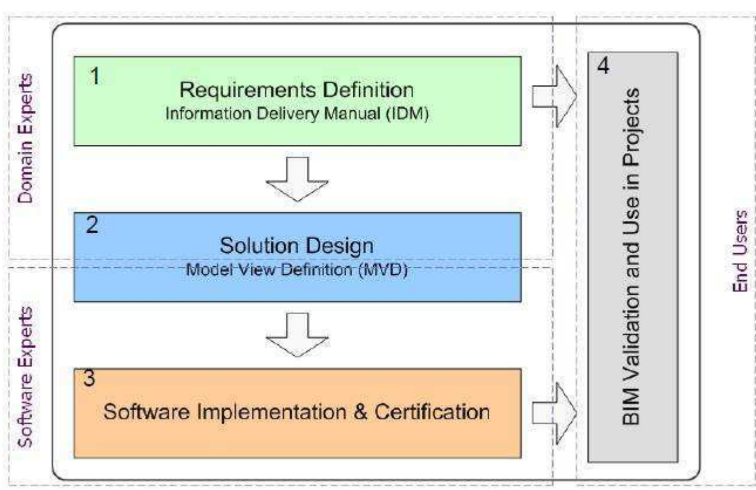

Figure 4.7. Integrated method for interoperability specification development (BuildingSMART, 2012)

4.2.6.3. Analysis and conclusion

- *Drawing cross-case conclusions*: after the case study, the researcher looks for any pattern that allows for the establishing of any conclusions.

- *Writing the case study report*: finally, the conclusions are presented in a report.

Chapter 5 Developing interoperability via IDM methodology

This chapter introduces the first part of this research, consisting of developing interoperability from a non-technical point of view using IDM methodology. Such IDM methodology allows for the communication of data problems among non-technical users to reach agreements. Even though the most used way of describing interoperability deals jointly with the non-technical and technical parts, for this dissertation, they will be dealt with separately because of a series of technical disadvantages that it may means.

In this chapter the used IDM methodology is explained, showing step by step how it works from the process modelling to the capture the of exchanged information and also the breaking down of this data to obtain the minimal units to be exchanged.

5.1 Information exchange methods

There are multiple methods of developing interoperability. BuildingSMART released in 2006 two methodologies: Information Delivery Manual (IDM) (Wix & Karshoj, 2010) and IFC Model View Definition (MVD) (Hietanen, 2006). Subsequently, the IDM guide expanded its scope from defining process maps to developing IFC concept bindings (Aram et al., 2010), merging both IDM and MVD methodologies under the name of ´An integrated process for delivering IFC-based data exchange´ (BuildingSMART, 2012). In 2007, the National Building Information Modelling Standards (NBIMS), based on BuildingSMART methodology, introduced Interoperable Exchange Development (NBIMS, 2007).

Even though the BuildingSMART method has become a standard for describing interoperability, it is not free of problems. Aram et al. (2010) criticised the method, indicating a blurred boundary between IDM and MVD. As a consequence of this lack of definition between the user and technical boundaries, the user or non-technical user will have the responsibility of developing a technical solution such as an exchange requirement model (BuildingSMART, 2012).

Another problem relating to the BuildingSMART methodology is the lack of rationalisation that would allow the identification of a similar data exchange and the simplification of the data that one deals with (Aram et al., 2010; Panushev et al., 2010). For example, the BIM model is improved continuously during the design process stages in which the same information exchange can be shared more than once, even if the value is different in each exchange. Identifying the repetitive exchanges in the same BIM model will allow reducing the number of MVD schema that requires development.

Aram et al. (2010) introduced a ´New methodology for IDM´ to overcome these problems. The proposed method is close to the MVD approach proposed by BuildingSMART in 2006 (Wix & Karshoj, 2010). The method proposed by Aram et al. makes a difference between IDM and MVD to make it easier to implement the methodology, providing a better way of communicating the exchange requirements to users and software developers (Aram et al., 2010).

Because of the multiple methods used to describe interoperability, this research will use a procedure suggested by BuildingSMART. This procedure has been set up by an international organisation and can be applied in any project. However, this dissertation will keep separate both IDM and MVD as Aram et al. suggested. Additionally, to keep as simple as possible the explanation for the information exchange method, it will be divided into two chapters: the first one describing the Information Delivery Manual (IDM), and the second one explaining the Model View Definition (MVD).

5.1.1 Integrated process for delivering IFC based data exchange

The integrated method proposed by BuildingSMART has four steps (see figure 5.1) (BuildingSMART, 2010):

- Requirements' definition - IDM: an AEC industry expert gathers a working group together to agree on a process that would be improved by using an IFC data exchange. The agreed process will develop a use case identifying the process participants, information content, format and the purpose of the data to be exchanged; then this data is used to create process maps.

- Solution design - MVD: a MVD is a document that links the use case previously defined with a subset of the IFC Model Specification. In doing so, the software provider translates the requirements from the user in technical language allowing support of the IDM defined.
- Software Implementation and Certification: this is a process to assure that the end user will have reliable exchange data. The certification is undertaken by a third party who checks each exported/imported object against the requirements defined for IDM/MVD.
- BIM Validation and Use in Projects: this process ensures that the exporting application meets the software requirements and that the end user has used the software correctly.

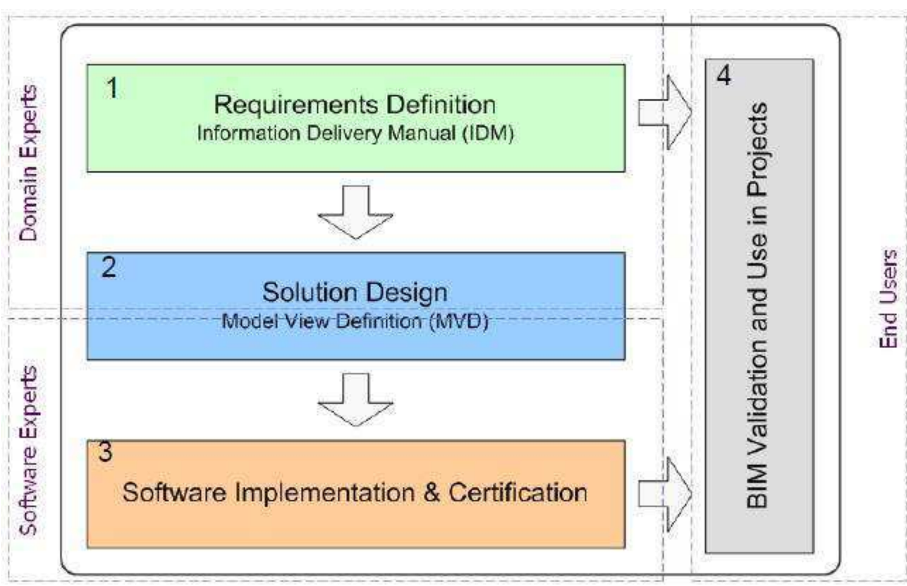

Figure 5.1 Integrated process overview (BuildingSMART, 2010)

5.2 What is IDM?

The IFC format has become the most used standard schema to address interoperability between multiple BIM applications. Through the years this format had matured enough allowing the representation of data created by different organisations during the project lifecycle (BuildingSMART, 2010).

Interoperability is not a data translation issue between BIM applications; it is about supporting the use cases defined by workflows (Aram et al., 2010). Nonetheless, the IFC format is unable to describe business processes during the project lifecycle or the information needed to complete them (Smith & Tardiff, 2009). To overcome this situation, two concepts are used: definitions and configurations. A definition captures a range of possibilities while a configuration defines how those possibilities are usedin a specific case (Hietanen, 2006). These configurations define a subset of the IFC schema (figure 5.2) with the data required to support a specific business process (BuildingSMART, 2010; Hietanen, 2006).

These configurations are selected based on the most common use cases. Subsequently, a specialised software user might require data that are not considered in the configurations detailed by the developers. The methodology to ask for this data is known as Information Delivery Manual (IDM). By using this method, the user can explain in simple language the process to be supported, the data requirements and the responsibility for creating it; in undertaking this, the BIM project will be more reliable because the information exchange between participants will be clearly defined (BuildingSMART, 2010). This information will allow developers to identify and understand the detailed process and the IFC needs that require support. Then the developer will be able to guarantee the quality of the information exchange and create a Model View Definition (MVD) suitable for the process needs (BuildingSMART, 2010).

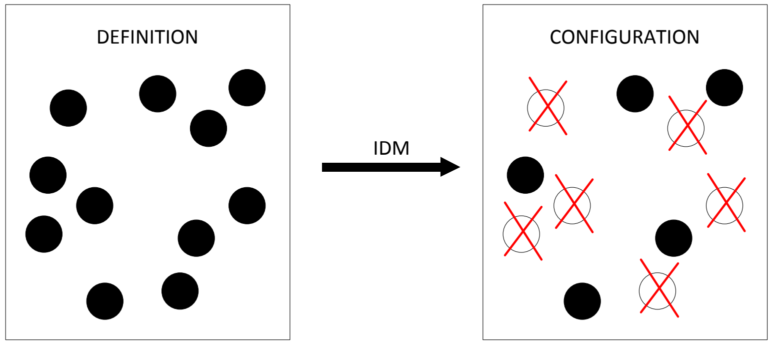

Figure 5.2 Definitions and configurations (BuildingSMART, 2010)

5.3 Design for Energy project

The results from this dissertation will be used to support the implementation of the Design for Energy (D4E) project. This is a research project funded by the EU, It aims to develop a design methodology that allows different stakeholders to predict the current and future energy efficiency of a project both at the individual and neighbourhood level.

D4E will promote collaborative work in a virtual workspace, wherein the data received from different stakeholders (architects, civil engineers, utilities, technological providers, workers) will be shared. Thus any stakeholder can consider integrating into their design the data created by others and can conduct an analysis of the project to ensure that the energy efficiency of the project is optimised. The outcomes from this methodology will allow the making of informed decisions within an optimised project at different life cycle levels.

The integration demanded by this project will require the development of interoperability that allows the right operation of tools, processes and stakeholders into an integrated supply chain.

5.3.1 Scenarios

The multiple activities, user requirements and information exchange considered in this project are divided into and described in three scenarios. These scenarios are:

- Scenario 1: the neighbourhood context: this shows how a building or a group of buildings and its neighbourhood can be analysed and holistically optimised throughout the whole life cycle.
- Scenario 2: holistic design for energy optimisation: this scenario offers multiple simulation tools and modelling techniques to improve the current practice in the early stages; thus a multi-disciplinary team can explore several option designs in a collaborative way until they achieve a suitable design.
- Scenario 3: use of operational and maintenance data in retrofit: this scenario shows how the designers simulate and evaluate the design based on historical data from similar projects.

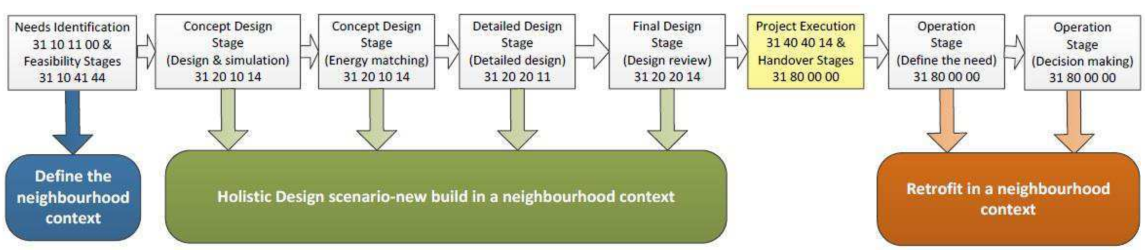

Figure 5.3 D4E scenarios

Figure 5.3 shows the whole workflow. The coloured rectangle represents the high level of the scenarios previously introduced while the white rectangles introduce use cases representing a low level for each process. The use cases considered are (see figure 5.3):

- Use case 1: this stage is focused on determining the technical feasibility of the client requirements and on setting the target levels in a neighbourhood context.

- Use case 2: this check out sustainable targets in the early stages. Some of these targets are energy consumption, operation and maintenance costs for selected equipment throughout a project lifecycle, building lifespan, energy tariff and future climate parameters. Additionally, it defines the physical appearance of the project.

- Use case 3: once the project shape is defined, it is checked in a neighbourhood context.

- Use case 4: when the architectural model is approved by the client, the structural, HVAC, electrical engineers and other design disciplines will create and improve the design for their specialities.

- Use case 5: the detailed design models of each speciality are shared and checked in a collaborative way.

- Use case 6: the facilities manager evaluates the building operation and, based on checks and controls, a retrofit intervention may be suggested.

- Use case 7: this is similar to use case 6, but it is suggested to be a maintenance intervention.

5.3.2 Interoperability framework

Figure 5.4 introduces the interoperability framework required by D4E. The framework needs facilitation in the communication between multiple systems (such as the IFC-based BIM components' catalogue, data filtering, design tools, version control system, eeBim) and the simulation platform and the collaborative workspace. Each system involved in the interoperability framework is explained below.

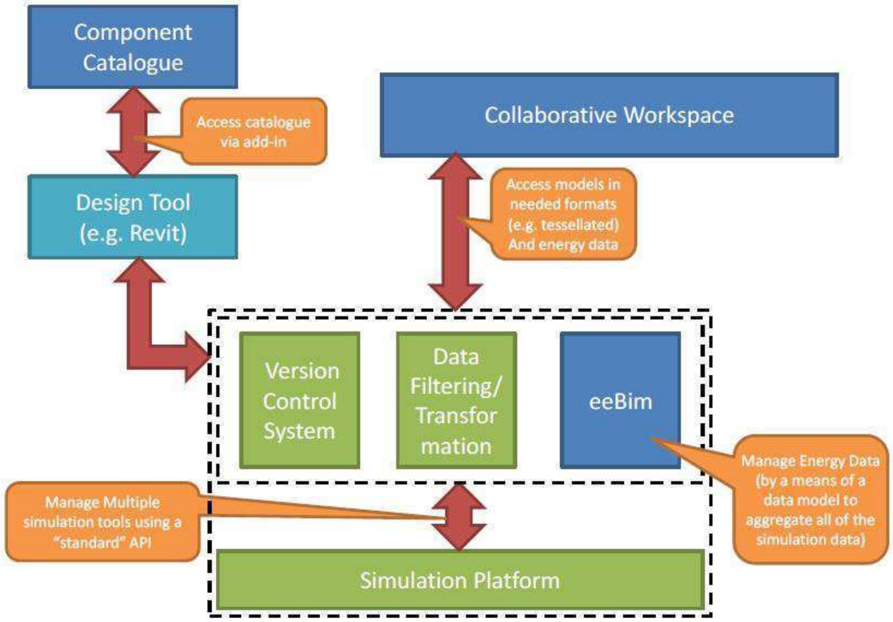

Figure 5.4 General overview of the interoperability framework

5.3.2.1 Component catalogue

The component catalogue provides to designers with the library components to use in their designs. The library components contain all the required data that will be used for further analysis (materials, components, etc). In so doing, it ensures that elements are suitable for any simulation. The access to this library will be made through a plugin which will import an element from a file or an online library into a design tool (Autodesk Revit).

5.3.2.2 Design tool

A design tool is any software used to create a BIM model from scratch (ArchiCAD, Autodesk Revit, and so on) or one modified from catalogue elements or existing projects. The integration of the design tool with the component catalogue is made through a plugin, making it possible to import and export metadata from the IFC files with extra data.

5.3.2.3 Version control system

Multiple versions of a model will be created and saved. A version control system will allow the checking of those modifications and the undoing of any unwanted changes.

Additionally, it is possible to add comments and images to communicate easily any problems to other designers.

5.3.2.4 Data filtering/transformation

This component allows for the filtering of the required data inside a model, or the modification of a model to integrate it with existing model's energy information, or the translation of several data formats to ensure communication with multiple tools.

5.3.2.5 eeBim

This component manages the energy data generated by the model during the simulation. It relates to the energy exchange in the design; thus how much heat could be lost during a winter's day or how much energy is used in a heating system.

5.3.2.6 Simulation platform

This component generates additional data when performing simulations of an existing model. Additionally, this component will be useful in identifying changes in the model and in rerunning an energy simulation to check energy data.

5.3.2.7 Collaborative workspace

In this module, the model is available to different stakeholders. In addition to the model, other information such as energy efficiency will be available.

5.4. Developing the Information Delivery Manual (IDM)

Agreements will need to be reached through Cross-organizational Process Business Processes (CBP) to ensure interoperability between multiple organisations with different software and implementations (Khalfallah et al., 2013). A CBP defines the interaction between organisations to achieve a common objective (Lazarte et al., 2013). Thus a CBP will become the main source of data for identifying processes, workflows, actors, tools and information exchange (Weise, Liebech & Wix, 2009).

The CBP will be developed using BPMN (Business Process Modelling Notation) methodology. The BPMN mapping process will identify actors, the connection between processes, and the data exchanged. The output from the BPMN mapping will be fundamental to implementing the IDM technique and breaking down the workflows into the smallest information encapsulated in an information model (the functional parts).

5.4.1. Process modelling

Process modelling describes the flows of activities for a specific scenario, the roles played by each actor, and the information exchanged (Eastman et al., 2011; BS ISO, 2010). The BPMN will be used for the mapping process (Smith & Tardiff, 2009).

Figure 5.5 shows the main components of the process model in BPMN. It uses rows and columns called swim lanes to classify activities with different functional capabilities. The rows identify the actors involved in the exchange while the columns show project phases. In the cells created by the swim lanes, it is possible to identify activities as white rectangles and the data to be exchanged are shown as corner folded blocks (Eastman et al., 2011).

The first process model to describe is the first low-level process shown in figure 5.3. This workflow focuses on describing the client requirements, and identifying the energy requirements and the potential in a neighbourhood context. The process starts with the client and the facilities manager (FM) (figure 5.5) sharing data in the virtual workspace. These data are used by the energy expert to determine the feasibility of achieving the goals set by the client and the facilities manager. Figure 5.5 illustrates the workflow. Each of the sub-stages of the process is described below:

- **Define design criteria:** the client defines the project objectives (energy consumption and saving) to be considered by the energy expert within the design of the project; then the energy expert will determine the feasibility of the project objectives.

- **Define FM requirements:** the facilities manager will also provide data (space requirements and building usage) to the energy expert. This data will help the energy expert in his work and in the operational stage of the project.

- **Review project objectives:** the energy expert uses the data provided by the client and the FM to review the objectives asked for by the project.
- **Search benchmark data:** the energy expert will look for energy indicators from external sources to determine the most likely targets to fulfil in the project.
- **Set key target levels:** the energy expert compares the design criteria and the FM requirements with the benchmark data to set the key targets to be achieved for the design from an energy efficiency point of view.
- **Collect boundary conditions:** site conditions (city plans, terrain model, climate data and energy prices) are gathered by the energy expert to develop a feasibility study considering the site's potential.
- **Choose energy alternatives to study:** the energy expert will select possible renewable energy options to be used in the project.
- **Run feasibility studies:** the energy expert will study the feasibility of each alternative. The study will set the energy requirements for the project to fulfil the regulations and standards.
- **Generate feasibility reports:** a report containing the results of, and the interpretations from, the feasibility study is passed to the client.
- **Set design performance values:** having this report, the client defines the performance values suitable for their functional and economic needs.

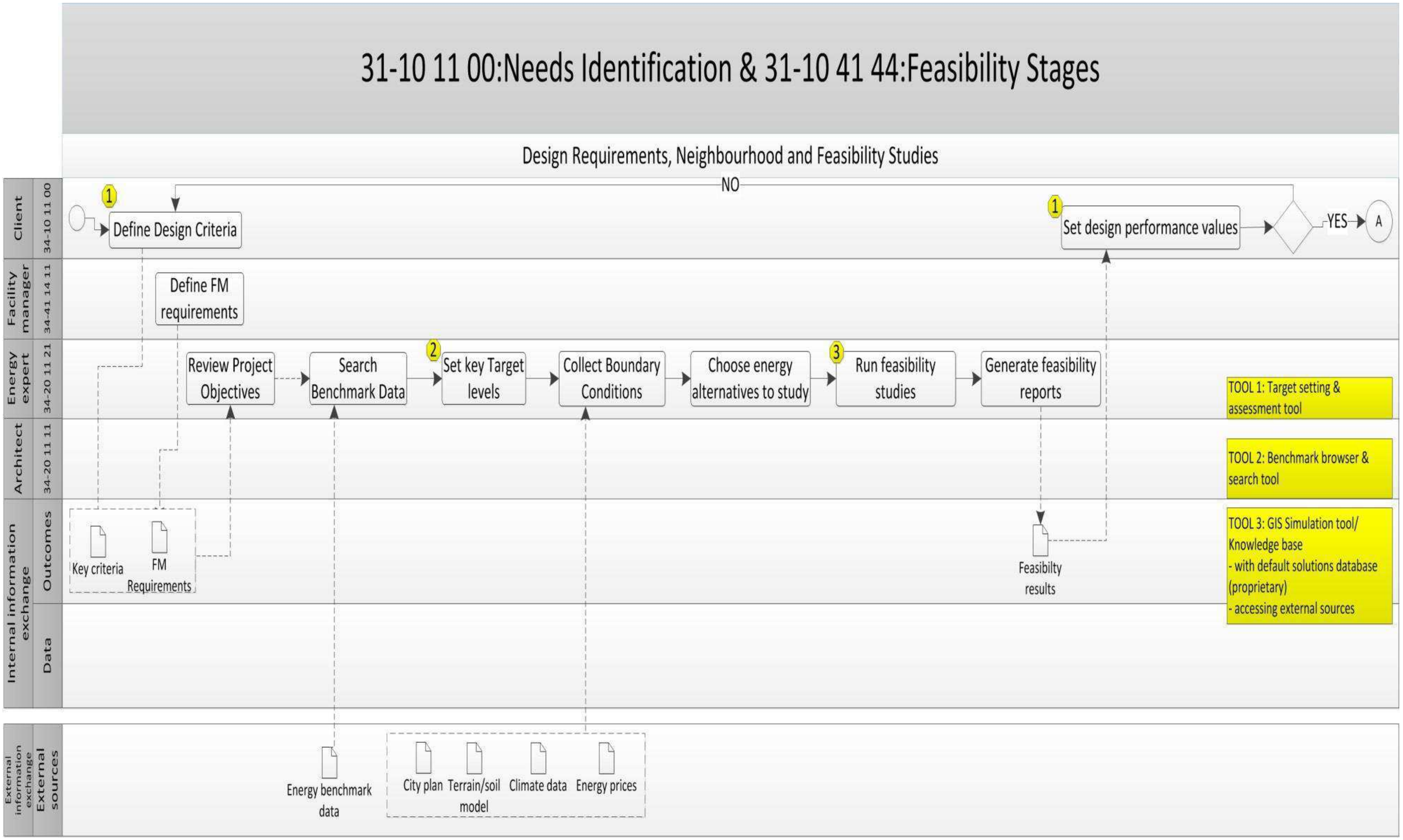

Figure 5.5 Process model for requirements' capture, neighbourhood, and feasibility studies

5.4.1.1. Use cases' modelling

Use case modelling is not included in the IDM procedure; however, it can be considered as a complementary step in the process modelling. A use case is a semi-formal model that captures the functional requirements of a system in a simple manner that is understandable by real users (Jalloul, 2004). Describing a use case will provide a chance to check key elements in a process such as actors, inputs, and outcomes (Pooley & Wilcox, 2004) thus avoiding any missed data in the process mapping (Aram et al., 2010). A visual language known as Unified Modelling Language (UML) will be used to create the use cases.

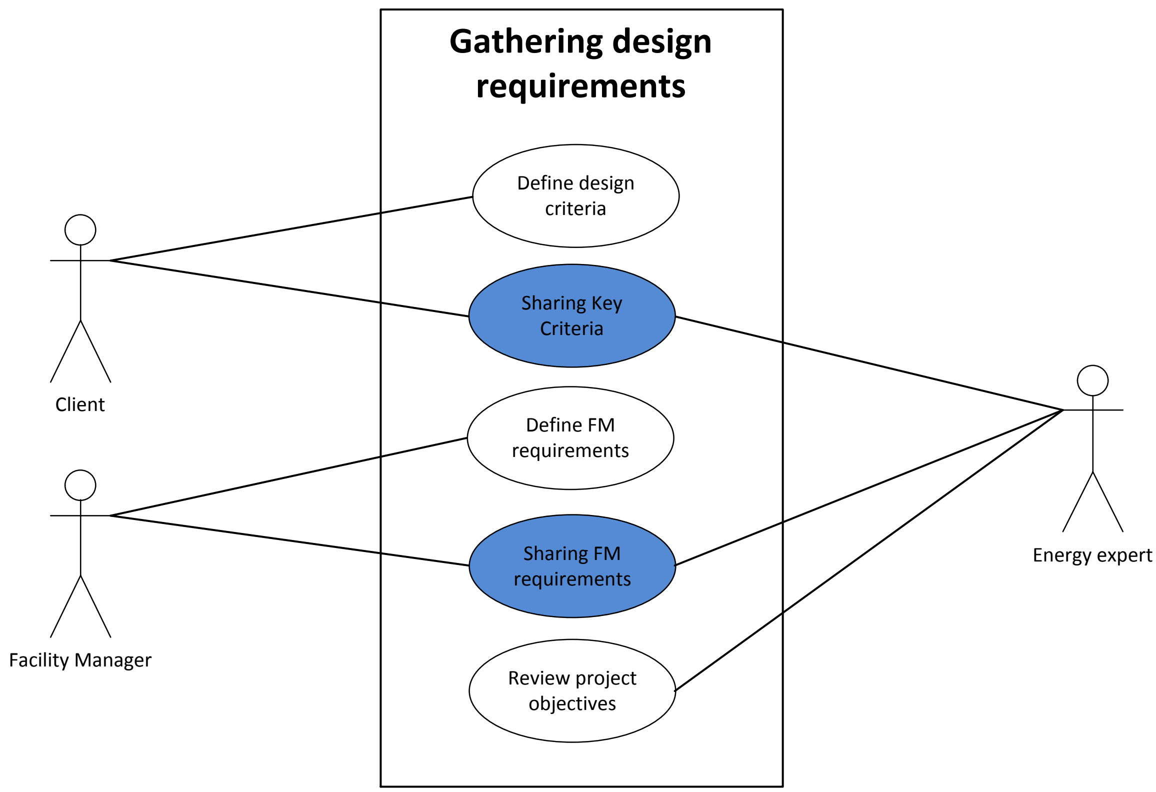

Figure 5.6 Use case model for gathering design requirements

In figure 5.6 is illustrated one of the use case models. It enables identification of the exchanges taking place and the actors who are involved in the transaction (Aouad &

Arayici, 2010). It starts with the client and facilities manager defining their own criteria to be included in the design. This data will be used by the energy expert to review the project objectives. The blue coloured ovals indicate the data to be exchanged between stakeholders.

5.4.2. Exchange models

During the process modelling and use case stages a series of data is detailed between the actors. Following this the information content is set out using a template; thus it is possible to provide the data to be exchanged using a non-technical language (BuildingSMART, 2012).

Project Stage	31-10 11 00: Needs identification stage
Exchange Disciplines	34-10 11 00 – 34-20 11 21 : Client – energy expert
Description	• Purpose: to share data that will be useful for the energy expert to understand the general objectives for the project required by the client. • Content of the exchange: Key Design criteria • Detailed exchange data: - Investment cost - LCC - Energy Efficiency - Energy matching - Eco-efficiency - Energy class - Comfort (indoor environment performance) - CO_2 - User satisfaction • Possible tools: Target setting and Assessment tool • Possible format for data exchange: CSV, XML and JSON • One way exchange
Related Exchange Models	• FM requirements • Energy benchmark data

Table 5.1 Exchange model for key criteria

Table 5.1 contains the data to be exchanged; this table is divided into four sections: header, overview, information and footer. The header gives the project stage in which the data will be shared. The overview identifies the actors between which the information exchange will be executed. The information section gives the aim and content of the exchange requirement. In this case, the exchanged data are: investment cost, LCC, energy efficiency, energy matching, eco-efficiency, energy class, comfort, CO_2, and user satisfaction. Also, there is a detailed possible set of tools to generate that data and the possible formats for carrying out the data. Finally, in the footer sections are indicated the preceding and succeeding exchanges.

5.4.3. Exchange objects

The exchange objects describe the information model to be exchanged at a high level. To exchange a project requires giving more detail to the data detailing exchange elements such as walls, windows, doors, slabs or roofs (BuildingSMART, 2012). In figure 5.7, the exchange object called ´key criteria´ is breaking down into small pieces or exchange objects: investment cost, LCC, energy matching, eco-efficiency, energy class, comfort, CO_2, and user satisfaction. Each of these exchange objects describes a small portion of the exchange information. In to describe the interoperability will require translating each of the exchange objects in a technical schema using MVD (Model View Definition).

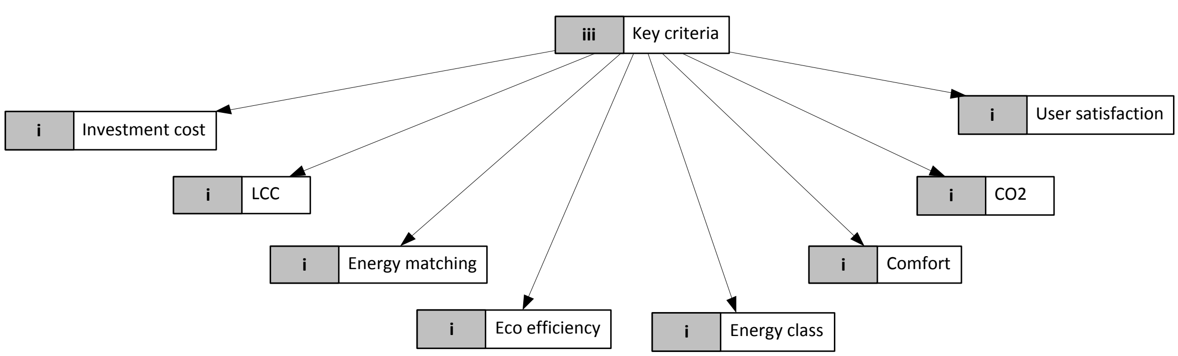

Figure 5.7 Exchange objects for key criteria

Describing the interoperability for the whole process, from scenario 1 to 5, requires the application of the same procurement for each information exchange. As a result of applying IDM to the entire workflows, it is possible to obtain 34 information exchanges and 183 exchange objects. In next chapter these exchange objects will be used and translated to technical language using MVD methodology. To simplify and to add fluency into the dissertation, the remaining IDM has been detailed in Appendix A.1 to A.5.

Chapter 6 Developing interoperability via MVD methodology

In the previous chapter, IDM methodology was used to describe the breakdown of information exchange into small and manageable units known as exchange objects. The breaking down process uses a plain language because it allows for smooth communication between non-technical users. In this chapter the requirements will be connected in a technical language using MVD methodology.

6.1 What is MVD?

The IDM outputs from the previous chapter will help developers to understand the interoperability required by a user between BIM applications (BuildingSMART, 2012). With this data as a guideline, the developer will set the interoperability from a technical point of view by creating a Model View Definition (MVD) (BuildingSMART, 2012). Thus each of the exchange elements identified in the IDM stage will be translated into a readable language schema format (figure 6.1) such as IFC or STEP (Hietanen, 2006; BuildingSMART, 2012).

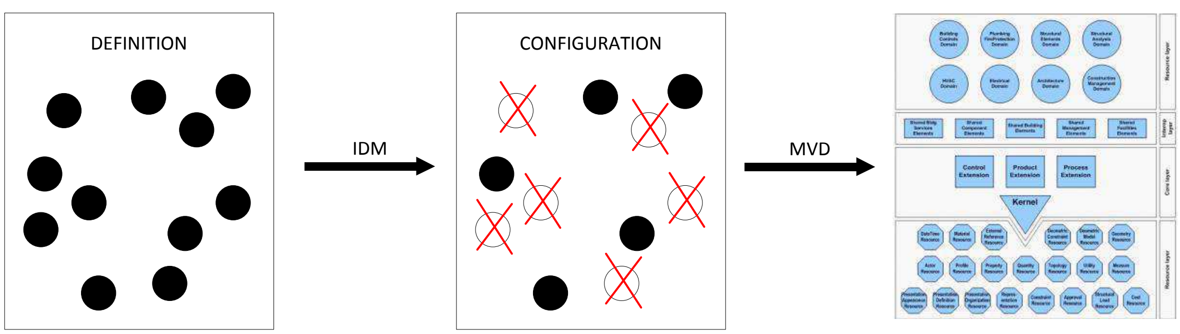

Figure 6.1 IDM and MVD processes

6.1.1 Goals for MVD

The main goal of MVD is to ensure that the data exchange will meet the requirements detailed by a user in the IDM and then he/she will know what results to expect from the export and import process (Eastman et al., 2011). Additionally, there is a series of requirements to achieve during the MVD process to reduce as much as possible the data ambiguity during the implementation process (BuildingSMART, 2012):

- Enable data exchanges. The MVD provides a structured method for refining and merging data exchange requirements into packages for software implementation.
- MVD provides support for the IFC implementation through a well-established method, avoiding falling into an iterative trying and error process. Using an MVD should be the easiest way of supporting IFC implementation in software.
- A certification process will allow industry practitioners to understand how the IFC-based data exchange works in providing data about the capabilities and the limitations that the based data exchange has created.

6.2 Developing MVDs

6.2.1. Requirement rationalisation

Before creating a MVD, there is a need to identify and to group those exchange requirements created during the IDM stage that have the same exchange objects. The idea behind this rationalisation process is to reduce the number of MVDs that need to be developed and to avoid any duplicity of data (Aram et al., 2010). Figure 6.2. summarises the outputs from use case 3 (see appendix A.3). The left column shows the exchange requirement (ER) while the right column groups the exchange objects required for each ER. A review of the ERs allows for the identification of identical exchange objects even if they belong to different ERs. For example, the ER highlighted in red (BIM model alternatives and approved design), and the ER highlighted in orange (obtaining energy data, energy matching results and indicators) contain the same parameters even if the information nuggets or values assigned to these parameters are different in various ERs.

Thus, there is no need to develop a MVD for each exchange object. Instead, it will be possible to identify equal data and reduce the number of MVDs to develop. In chapter 5, were identified 34 information exchanges and 183 exchange objects, however applying this rationalisation process makes it possible to reduce the information exchange to 18, while the exchange objects are reduced to 67, thus just 67 MVDs will need to be developed.

BIM model alternatives	IFC foundation
	IFC walls
	IFC columns
	IFC slabs
	IFC openings
	IFC roofs
	IFC spaces
Obtaining energy data	LCC
	Low energy demand
	Renewable energy source
	Self efficiency rate
	Primary energy need
	Energy supply reability
	Enviromental impact
Energy matching results	LCC
	Low energy demand
	Renewable energy source
	Self efficiency rate
	Primary energy need
	Energy supply reability
	Enviromental impact
Indicators	LCC
	Low energy demand
	Renewable energy source
	Self efficiency rate
	Primary energy need
	Energy supply reability
	Enviromental impact
BIM model alternatives	IFC foundation
	IFC walls
	IFC columns
	IFC slabs
	IFC openings
	IFC roofs
	IFC spaces
Approved design	IFC foundation
	IFC walls
	IFC columns
	IFC slabs
	IFC openings
	IFC roofs
	IFC spaces

Figure 6.2 Summary of the outputs from the design check and energy matching in use case 3

6.3 MVD example

In the previous chapter was discussed the method of describing interoperability by using a non-technical language. In this section the outputs from the previous chapter will be translated into a technical language. This will be undertaken by using the MVD procedure explained above in this chapter.

As explained in the previous section, by using a rationalisation method it is possible to reduce the number of exchange objects from 183 to 67. In addition to this consideration, from each scenario will be selected three different exchange objects to develop the interoperability. By doing so it will be possible to reduce the number of objects to consider. However, the elements that are chosen will need to describe a different kind of information e.g. a solid element (beam, slab, wall and so on), document, cost, library objects, and information objects.

Below is illustrated and explained an MVD example. The remaining MVDs are presented in detail in Appendices B. 1 to B. 5.

- **MVD # 01**

The first exchange object to describe will be ´Lifecycle cost´ in the information exchange 'Key criteria´ from the first scenario. Figure 6.3 shows the MVD for lifecycle cost. It is described through three entities:

- **ResourceLevelRelationship** is an abstract data entity to describe the relationship between resources and level entities.
- **ExternalReferenceRelationship** makes reference to the external database (libraries, documents) when the information source is not explicitly represented in the model. The lifecycle cost does not represent a particular element in the model and thus it will need to use ExternalReferenceRelationship.
- **AppliedValue** defines three sub-entities (AppliedValueSelected, Date and CostValue). These sub-entities are useful in defining an economic value, currency units, and date when it will become important for the project.

BuildingSMART suggests using CostValue to detail the amount of money in a situation such as annual rate return, bonus, contract, estimated cost, maintenance, material, overhead, profit, purchase, rental, repair, replacement, and whole life.

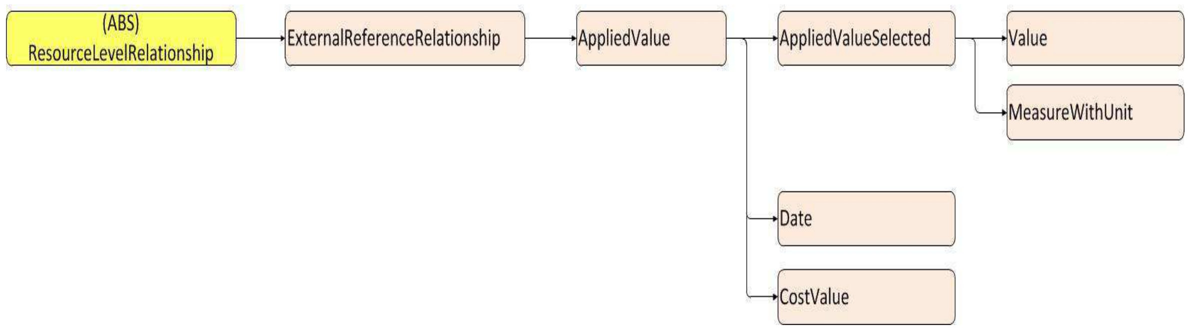

Figure 6.3 MVD for Lifecycle cost

Chapter 7 Key findings

Next are presented the main findings from this research.

About Sustainable Development

The literature review has explored the idea of Sustainable Development and how this concept is related with the near future of companies in the twenty first century. The economic activity in the twentieth century was unaware about the importance of balancing the three axis of the SD concept, this mindset has brought as consequence degradation in the environmental conditions.

The most important effect in the environmental degradation is the climate change. Even though the origin of it has being very discussed, the literature is clear in showing to human activities as the main responsible for this situation. Currently the damage in the environment is considerable and any solution will have effects in long terms then it is urgent an immediate response for reverse the effects of human activities. Many governments had recognised the climate change as a real problem and are reaching international agreements to control the carbon emissions. These protocols are useful to each country and set their own sustainable policies.

Certainly the AEC industry has a major responsibility in climate change for being one of the major carbon emission contributors. Indeed most of housing emissions come from electricity and heat production, in this way it is clearly a chance to reduce energy consumption through a better design project.

For years the energy design has being drive by rating systems (LEED or BREEAM) and standards (Passivhaus and ZEB), however these methods very not able to response to the dynamic nature of the design, being focus on setting a minimal requirements based on recommendations rather than support the design until find the best design solution that optimise the use of natural conditions on site such as wind, sunlight or shadowing to decrease the energy consumption at the lowest cost. The burocratic nature of ratings and standards is an opportunity for new tools that support the use the design using simulations.

About BIM and BPS methodologies

A review of BIM concept has allowed understanding how meaningful is becoming this methodology for projects development. Even through this methodology is been broadly spread through the project lifecycle still there are some problems that make difficult the data flow between actors or lifecycle stages. This interoperability issue is not a translation problem between software, instead it is because of a lack of tools in describing how the data is created and exchanged as a consequence these tools cannot understand in which software the data was created or in which one it will be read it, then some data is missed.

BPS tools as emerged as a complementary methodology to BIM with the objective of simulate the energy performance of the architectural design. But this discipline needs to overcome a large number of challenges to allow the integration of both BIM and BPS. Currently the ways to dealt with this problem are deficient: a combined model, in which all the stakeholders are using the same platform is a unreal approach, while a central or distributed model will still have exchange problems.

The current interoperability approaches require using universal file formats such as IFC and gbXML. But these formats are no able to exchange the need data, IFC is unable to capture how the data is created and for who, while gbXML is a low structured format then the relationship between elements is missed. Then the only way to overcome the interoperability issue is describing manually the relationship between elements and the way how it is created using IDM and MVD methodologies.

Besides of the integration problem, it is needed to highlight the low number of BPS tools on the market that are able to exchange some early data with BIM tools. This situation is worrisome considering the high demand that a better energy design will have in coming years because of requirement from governments and clients looking for more efficient projects.

About the method to develop interoperability

The existence of multiple methods for interoperability (IDM, MVD, NBIMS, New methodology to develop the IDM and Integrated Process for Delivering IFC Based Data Exchange) can be quiet confusing, even though all the methods could seem similar for having the same steps (mapping, information exchange functional parts and linking to technical language) they have small differences between them.

This dissertation used the “Integrated Process for Delivering IFC Based Data Exchange” by BuildingSMART (2012), nonetheless this method contradicts IDM and MVD methods developed by BuildingSMART in 2006. These differences are an unexisting boundary bewteen IDM and MVD, then it is not clear the operation limits for user and technical operators. Additionally the method proposed by BuildingSMART in 2012 considers that the user needs to describe the exchange requirements using the IFC structure, this task is clearly a technical one that should no be developed by a non technical actor. Because of these problems it is not possible to use an unique methodology.

Even though this dissertation used the “Integrated Process for Delivering IFC Based Data Exchange” by BuildingSMART (2012), some points from other methods were took in to consideration. Then it was made a clear division of the non technical and technical part according the indications in “New methodology to develop the IDM”, IDM and MVD methods. Additionally it was used the observation made in “New methodology to develop the IDM” to reduce the number of MVDs and avoid any duplicity of data.

Contribution to the knowledge

This research has being focus in to build up interoperability knowledge describing the challenges, process, technologies and people. The acquired knowledge has being fundamental to understand how the data is created and exchanged through the project lifecycle, in doing so has being possible to describe the interoperability for the energy design making possible the data exchange between Autodesk Revit and Design4Energy tools and facilitating the energy simulation and feedback at early design stages.

Recommendation for further work

About recommendation for develop of future work in interoperability it could follow two addresses:

- Development of a new guide to develop interoperability: because of the confusing and disunited methods already existing future research should consider to develop a unified method. This new method would be based on the method proposed by BuildingSMART in 2012, but keeping clear boundaries between IDM and MVD (User and technical user). Also it should consider a rationalisation process to identify similar information exchange and reduce the number of MVDs to develop.

Validation and certification of data exchange: this dissertation has developed the interoperability for the specific case of energy simulation between Revit and D4E software. Additionally it should be ensure that the data exchange between tools is the data required by the user.

Appendix A , Information Delivery Manuals

A.1 Needs identification and feasibility studies

The first workflow to describe is the first low-level process introduced in figure 5.3. This workflow is focused on defining the client requirements, identifying the energy needs and potential in a neighbourhood context. A detail of the process is described below (fig A.1):

- **Define design criteria:** the client defines the project objectives (energy consumption and saving) to be considered by the energy expert within the design of the project; then the energy expert will determine the feasibility of the project objectives.
- **Define FM requirements:** the facilities manager will also provide data (space requirements and building usage) to the energy expert. This data will help the energy expert in his work and the operational stage of the project.
- **Review project objectives:** the energy expert uses the data provided by the client and the FM to examine the targets asked for the project.
- **Search benchmark data:** the energy expert will look for energy indicators from external sources to determine the most likely targets that can be fulfilled in the project.
- **Set key target levels:** the energy expert compares the design criteria and the FM requirements with the benchmark data to set the key targets to be achieved for the design from an energy efficiency point of view.
- **Collect boundary conditions:** site conditions (city plans, terrain model, climate data and energy prices) are gathered by the energy expert to develop a feasibility study considering the site's potential.
- **Choose energy alternatives to study:** the energy expert will select possible renewable energy options to be used in the project.
- **Run feasibility studies:** the energy expert will explore the viability of each alternative. The study will set the energy requirements needed for the project to fulfil the regulations and standards.

- **Generate feasibility reports:** a report containing the results and interpretations of the feasibility study is passed to the client.
- **Set design performance values:** having this report, the client defines the performance values suitable for their functional and economic needs.

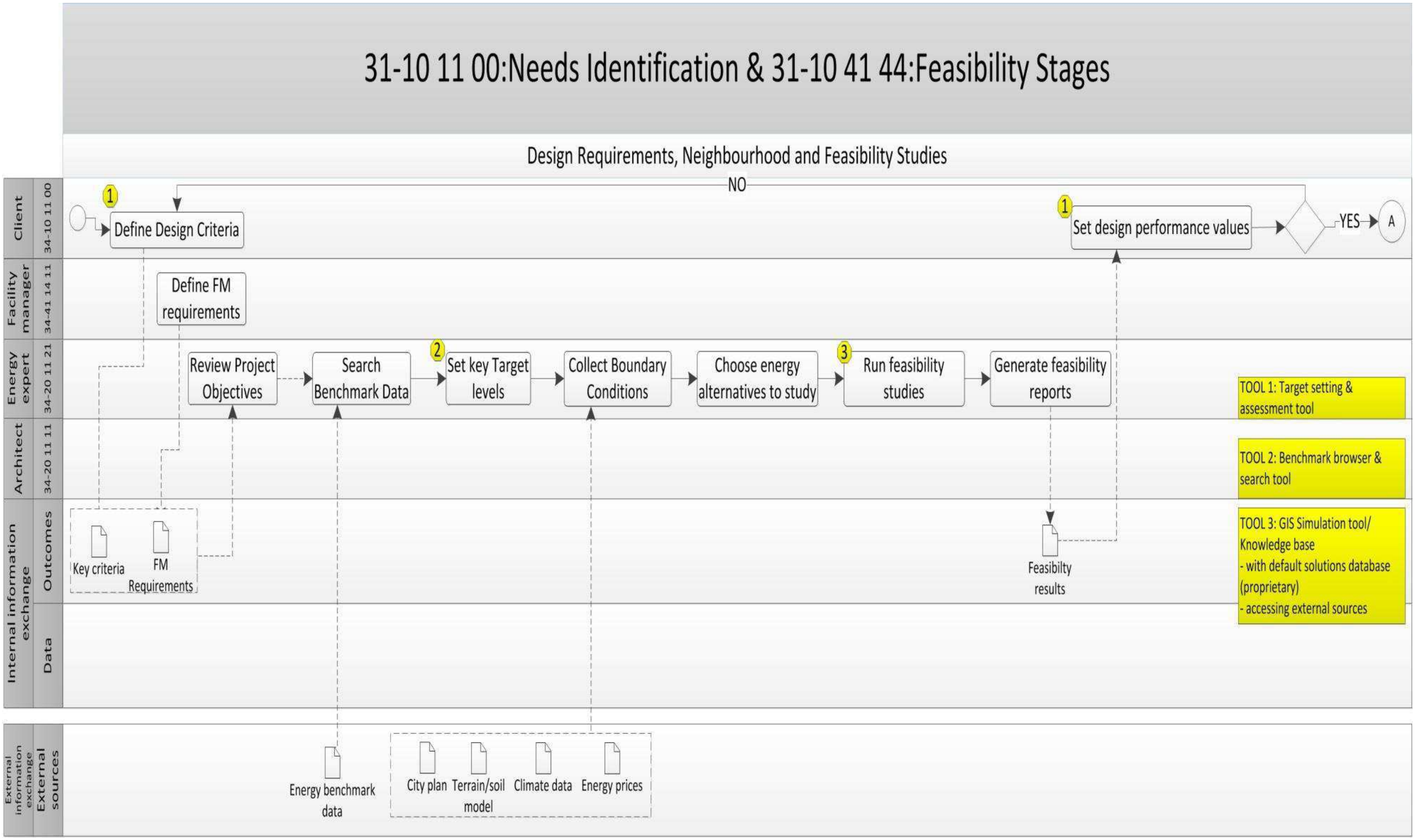

Figure A.1 Process model for requirements capture, neighbourhood, and feasibility studies

A.1.1 Use case model for gathering requirements

In this use case, the energy expert will ask the client and facility manager their requirements to consider in the design; the energy expert will analyse this data and compare it with the project requirements to determinate the feasibility to fulfil them.

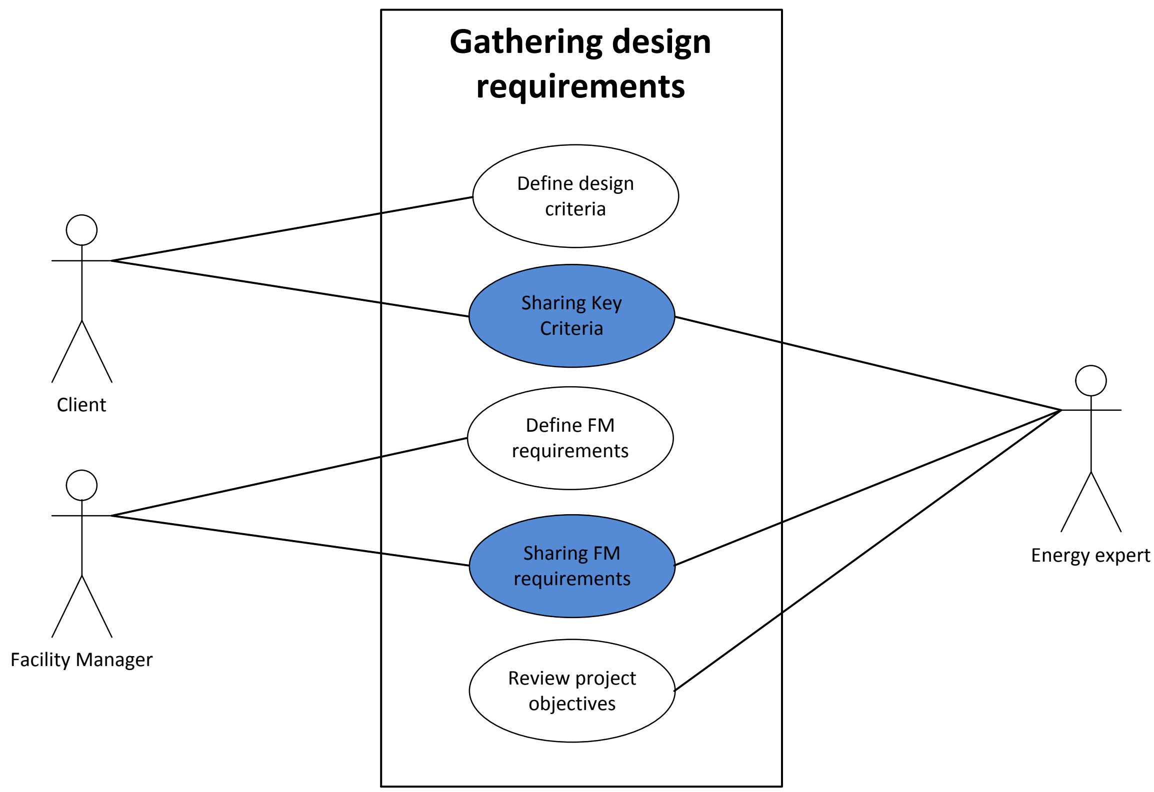

Figure A.2 Use case model for gathering design requirements

A.1.1.1 Information exchange requirements: key design criteria

Project Stage	31-10 11 00: Needs identification stage
Exchange Disciplines	34-10 11 00 – 34-20 11 21 : Client – energy expert
Description	• Purpose: to share data that will be useful for the energy expert to understand the general objectives for the project required by the client. • Content of the exchange: Key Design criteria • Detailed exchange data: - Investment cost - LCC - Energy Efficiency - Energy matching - Eco-efficiency - Energy class - Comfort (indoor environment performance) - CO_2 - User satisfaction • Possible tools: Target setting and Assessment tool • Possible format for data exchange: CSV, XML and JSON • One way exchange
Related Exchange Models	• FM requirements • Energy benchmark data

Table A-1 Key design criteria

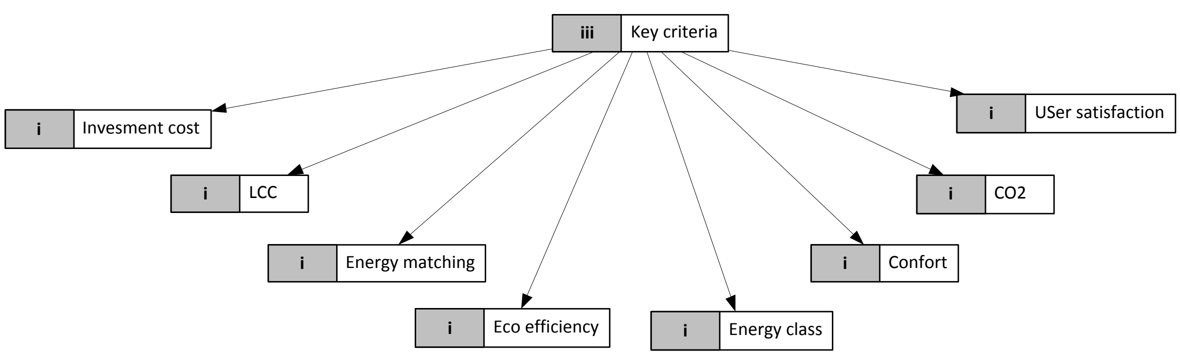

Figure A.3 Exchange objects for key criteria

A.1.2 Use case model for study alternatives

Previously, the energy expert received the design requirements from the client and facility manager. Additionally, the energy expert will obtain data about the boundary conditions. The energy expert will use all this data to study the feasibility of multiple energy alternatives, comparing their results with benchmark data.

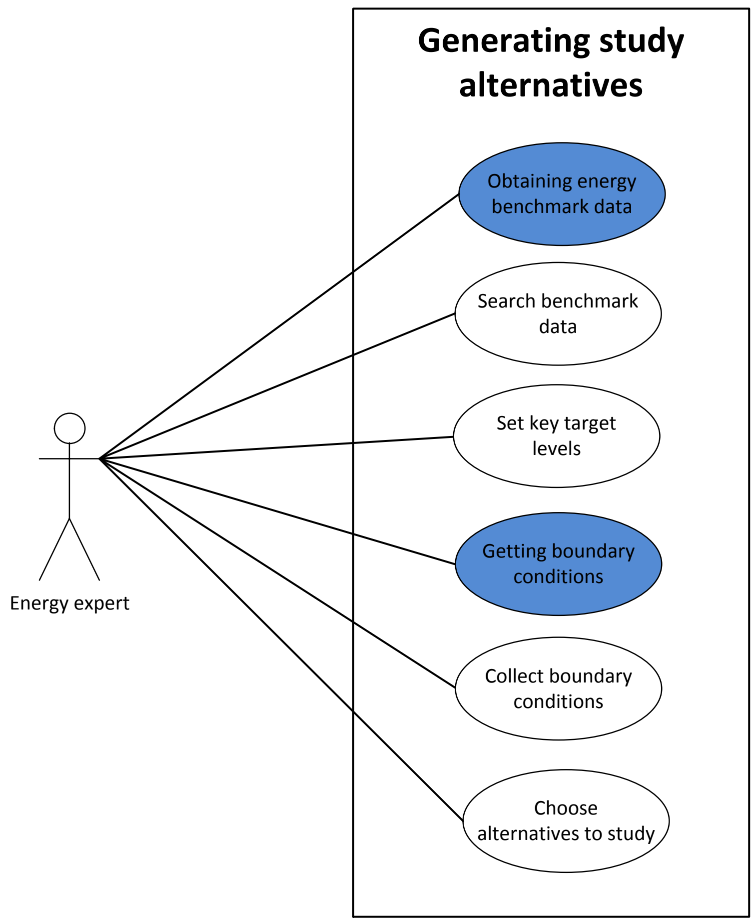

Figure A.4 Use case model for generating study alternatives

A.1.2.1 Information exchange requirement: Obtain energy benchmark data

Project Stage	31-10 11 00: Needs identification stage
Exchange Disciplines	34-20 11 21 : Energy expert
Description	• Purpose: to obtain energy information from external sources for the benchmark study and have an idea about potential energy indicators. • Content of the exchange: energy benchmark data • Detailed exchange data: - Project indicator – energy, indoor air - Usage Indicators – energy consumption, carbon footprint of usage, satisfaction with indoor environment, stand by load - Lifecycle indicators – carbon footprint of lifecycle, LCC • Possible tools: Benchmark Browser search tool (35-11 11 71 17) • Possible format for data exchange: CSV, XML and JSON • One way exchange
Related Exchange Models	• Key criteria • FM requirements • Boundary conditions

Table A-2 Information exchange for energy benchmark data

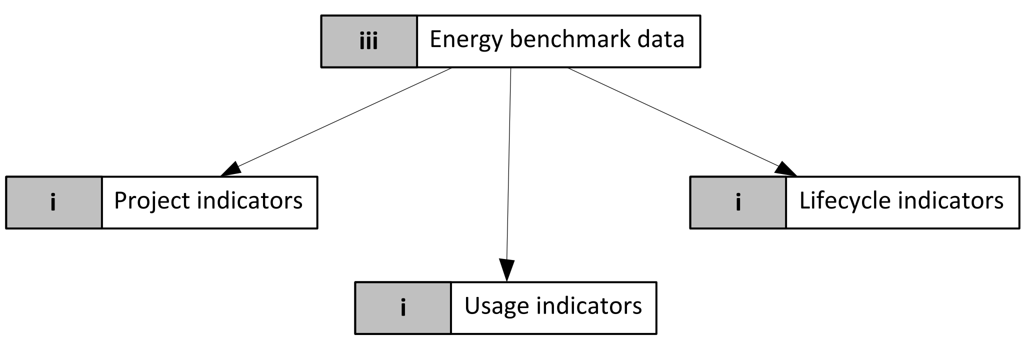

Figure A.5 Exchange objects for energy benchmark data

A.1.3 Use case model for feasibility studies

The energy expert will run a feasibility study on those energy alternatives that he/she thinks that are feasible. For those options, the energy expert will put the results and conclusion in a report. This report will be shared with the client, who will use this data to select the best design option that meets their requirements for the project.

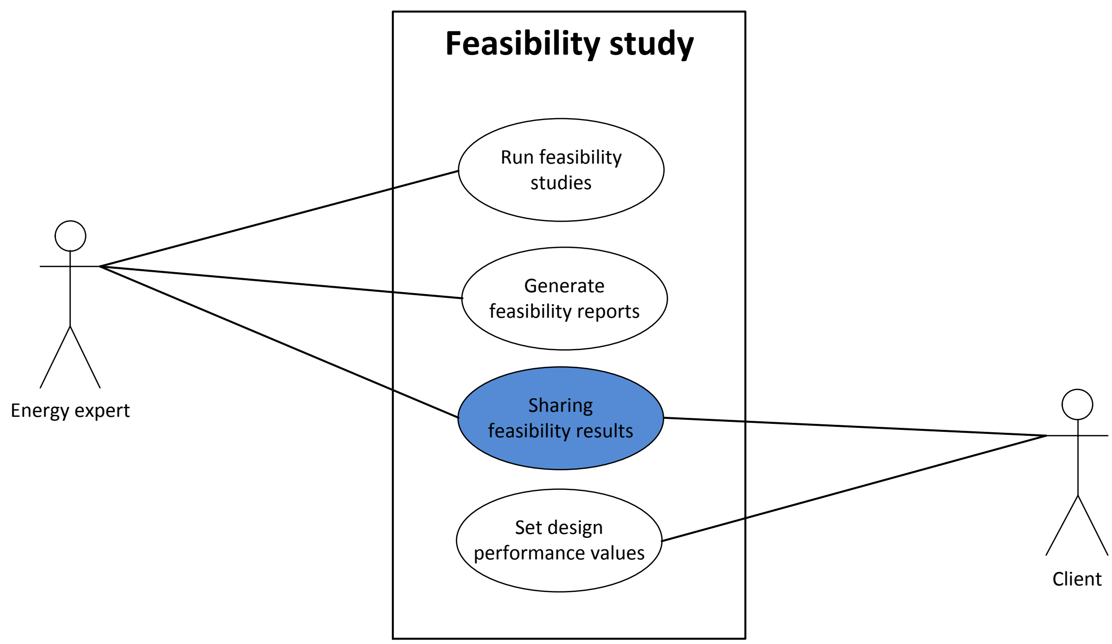

Figure A.6 Use case model for feasibility study

A.1.3.1 Information exchange requirements: feasibility results

Project Stage	31-10 41 44: Feasibility stage
Exchange Disciplines	34-20 11 21 – 34-10 11 00 : Energy expert - Client

Description	• Purpose: to share the feasibility results with the client who will use them to determine the best option according to their requirements
	• Content of the exchange: feasibility results
	• Detailed exchange data::
	  ○ LCC (Euro/m2)
	  ○ ROI (years)
	  ○ Low energy demand
	  ○ Renewable Energy Source (%)
	  ○ Self Sufficiency rate (%)
	  ○ Primary energy need for electricity, heat, cooling (kWh/m2)
	  ○ Energy Supply Reliability, including the reliability of local grid (%)
	  ○ Environmental Impact
	• Possible tools: GIS Simulation tool
	• Possible format for data exchange: GML, cityGML, XML
	• One way exchange

Related Exchange Models	

Table A-3 Information exchange requirements for feasibility results

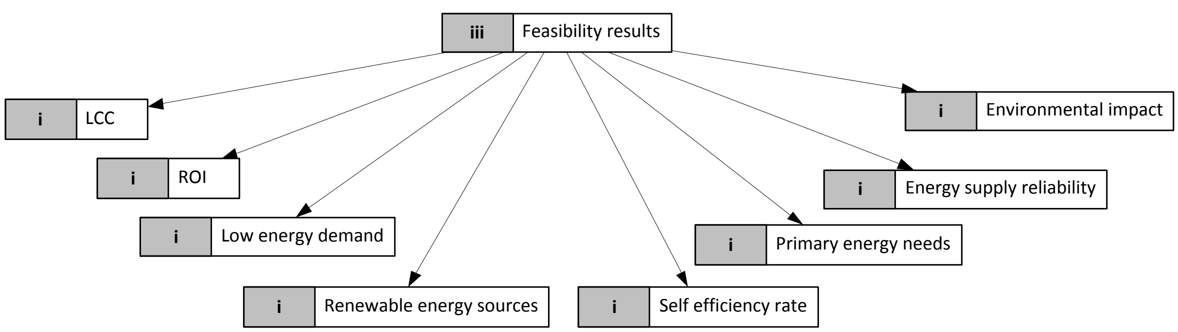

Figure A.7 Exchange objects for feasibility results

A.2 Concept design, design and simulation

In this stage, process modelling is about early design sketching and modelling, environmental analysis and building performance simulation. In figure A.8, the workflow starts with the client producing and sharing the design brief. This data will be used by the architect to provide the concept design through a series of activities such as sketching, creating models, analysing site implications, and improving the design, building performance analysis and design alternatives. The concept design alternative is shared with the client to check it against requirements and objectives.

The key activities to develop in this stage are:

- The client produces and shares the design brief
- The architect uses this data to develop the project programme and early design sketch alternatives
- These alternatives are used as input to run a building performance simulation
- The client checks the aesthetic of each design alternative
- The energy expert will analyse the energy demand and possible supply from the neighbourhood

The workflow for this stage is shown in figure A.8

Produce design brief: the client develops brief detailing energy targets, cost related objectives, and the performance required. This document is share in the virtual workspace with the architect to develop the sketches.

Produce project programme: the architect uses the information from the virtual workspace to create the project programme, this will include minimal spaces and building orientation based on the building use.

Sketching spatial outline alternatives: based on the project programme, the architect produces different sketches for the design intent.

Produce LOD1 models from LOD0 sketches: the architect will drag components from Design4Energy´s personal component catalogue to improve sketches into LOD 0 BIM model

Review site implications and adaptability: the architect will carry out site analysis to study the site effects on the design and consider the multiple ways how the site could affect the design and energy performance.

Improve design with material data for CO_2 emissions: the architect will define the materials keeping in mind the reduction of CO_2 emissions.

Building performance analysis for passive design: the architect will execute an energy performance analysis for each design alternative.

Finalise design alternatives with KPI profiles: the architect will finalise the design options by comparing the performance results with the benchmark indicators from the Design4Energy virtual collaborative workspace.

Review concept design alternatives for selection: the client checks the alternative design to ensure the fulfilment of the requirements and objectives of the design brief.

Analyse energy demand at building level: the energy expert receives the chosen design by the client in the collaborative workspace, then the energy expert will run and deliver the simulation outputs, including energy consumption, construction cost and performance cost.

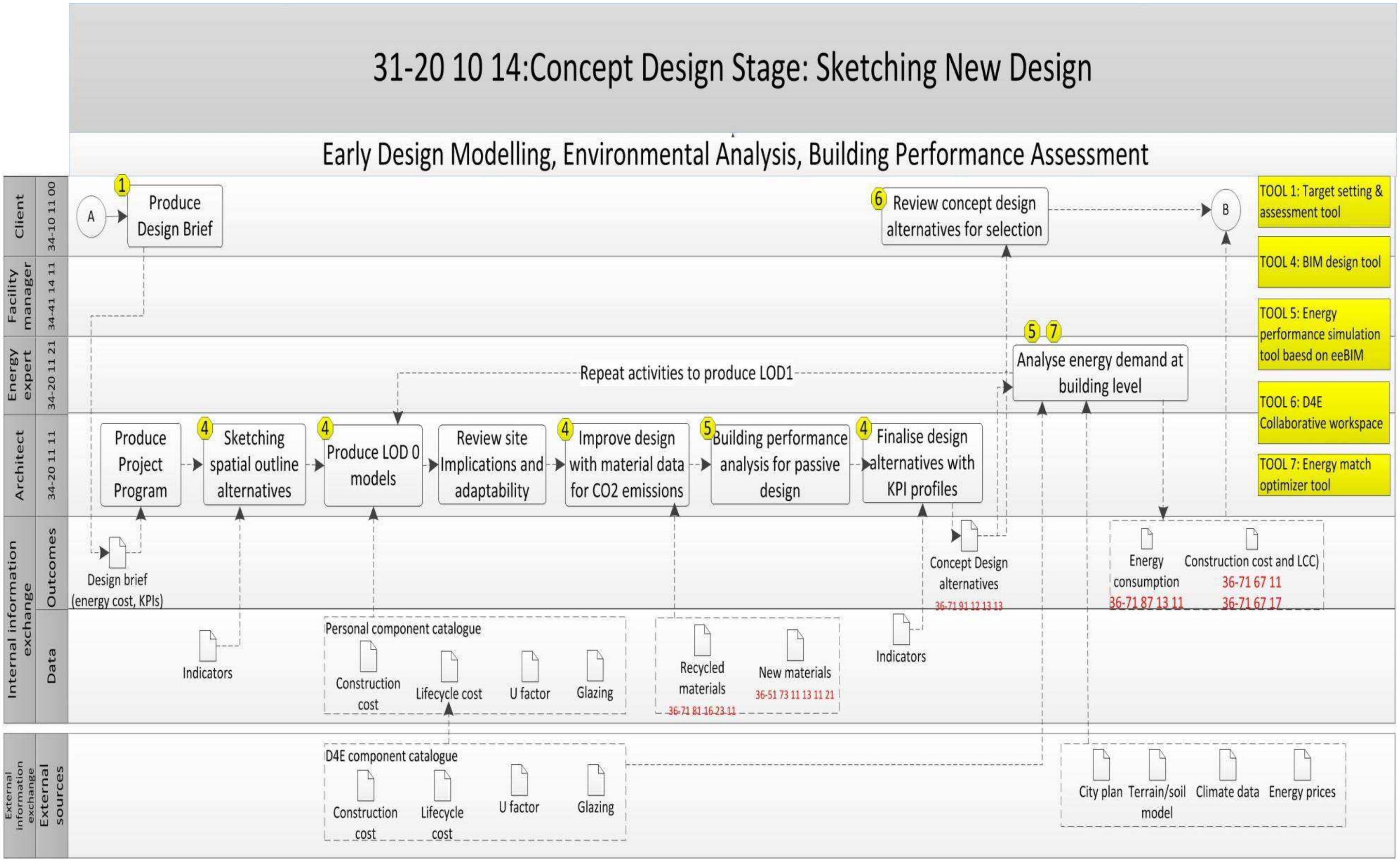

Figure A.8 Process model for early design modelling, environmental analysis, building performance assessment

A.2.1 Use case model for early design modelling

This use case (figure A.9) starts with the client creating and sharing the design brief in the virtual collaborative workspace. The architect uses the design brief to elaborate the project programme defining the objectives to achieve in the design. Then the architect drags some indicators from the personal building catalogue to sketch different design alternatives. These sketches are positions on the site to check the influence of the terrain and reduce the negative impact of it on the project. Finally, the architect selects new and recycled materials to use in the project and reducing the carbon footprint.

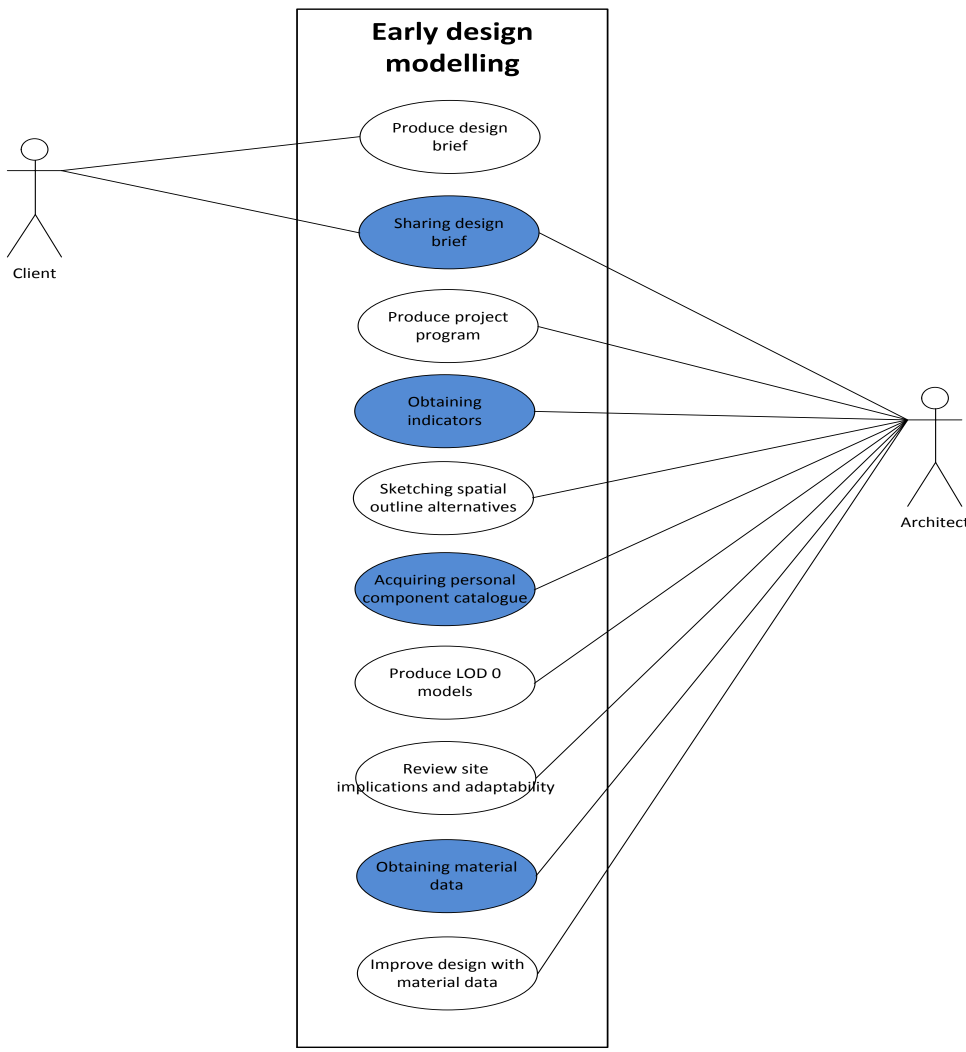

Figure A.9 Use case model for early design modelling

A.2.1.1 Information exchange requirements: acquiring building components from the personal component catalogue

Project Stage	31-20 10 14: Concept design phase
Exchange Disciplines	34-20 11 11 : Architect
Description	• Purpose: to specify and populate building components in the sketch design with the corresponding semantic information stored in the BIM components in the personal component catalogue database for LOD 0 BIM modelling • Content of the exchange: Personal component catalogue • Detailed exchange data: - construction cost - lifecycle cost - U factor - glazing • Possible tools: BIM Authoring tools (Revit or ArchiCAD) via Design4Energy virtual collaborative workspace • Possible format for data exchange: IFC • One way exchange
Related Exchange Models	• Indicators • Recycled materials • New materials

Table A-4 Obtaining building component information for personal component catalogue

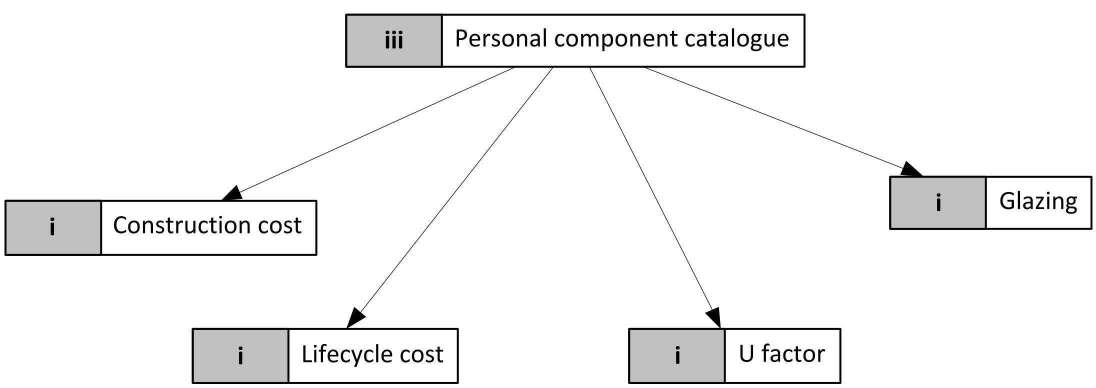

Figure A.10 Exchange objects for the personal component catalogue

A.2.1.2 Information exchange requirements: obtaining material data

Project Stage	31-20 10 14: Concept design phase
Exchange Disciplines	34-11 20 34: Architect

Description	• Purpose: the architect will drag materials from the internal information exchange hub into the design to improve it and reduce the CO_2 emissions
	• Content of the exchange: new materials (36-51 73 11 13 11 21), recycled materials (36-71 81 16 23 11)
	• Detailed exchange data:
	  - new materials to use in walls, slabs and deck
	  - insulation materials for structural walls, partition walls and floors
	  - recycled material walls
	  - recycled material slabs
	  - recycled materials decks
	• Possible tools to create data: BIM Authoring tools
	• Possible format for data exchange: IFC or XML
	• One way exchange

Related Exchange Models	• Personal component catalogue • Indicators

Table A-5 Information exchange requirements for suggesting sustainable materials

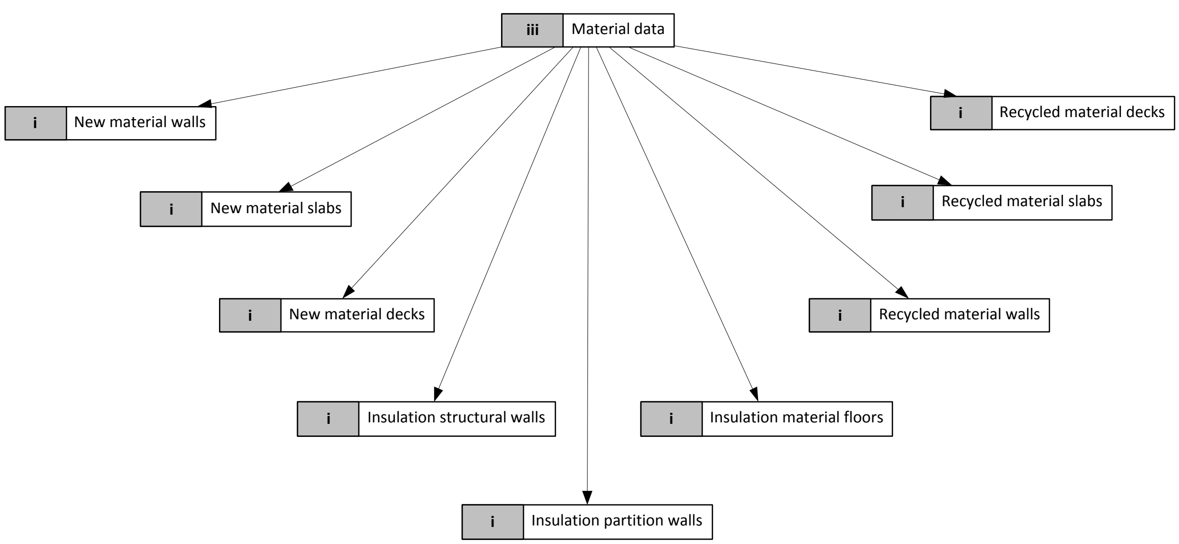

Figure A.11 Exchange object of material data

A.2.2 Use case model for environmental analysis

In this case (fig. A 12), the architect runs a building performance analysis to finalise the concept design alternatives. These results are checked by the client to ensure that the design is meeting the design requirements. Besides, the energy expert will use the design options to analyse the energy demand and savings in each alternative and will share these results in the collaborative workspace.

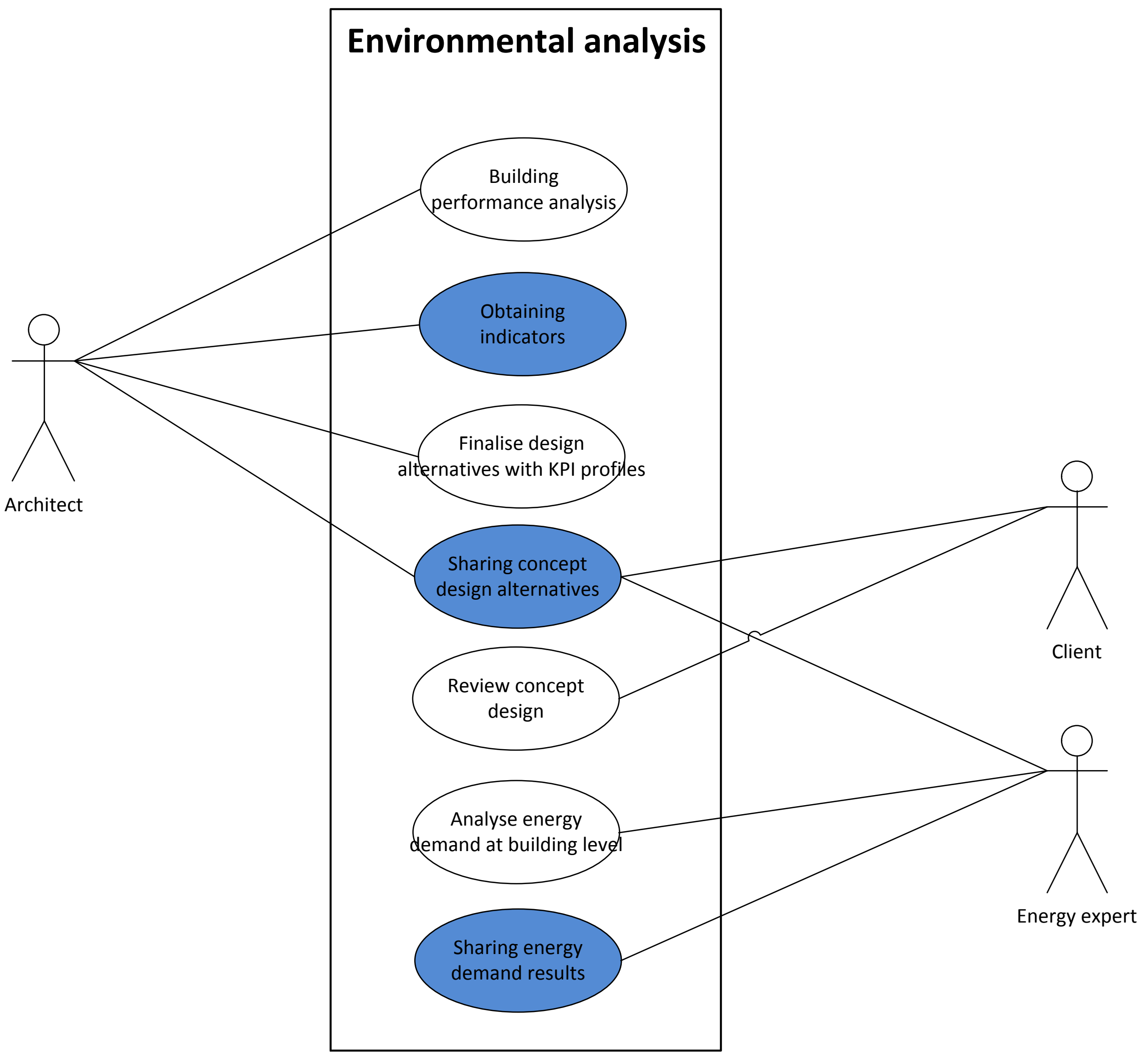

Figure A.12 Use case model for environmental analysis

A.2.2.1 Information exchange requirements: sharing concept design alternatives

Project Stage	31-20 10 14: Concept design stage
Exchange Disciplines	34-20 11 11 – 34-20 11 21 – 34-10 11 00 : Architect-Energy expert-Client
Description	• Purpose: to communicate the concept design from the architect to the energy expert. The latter will use this information to simulate the energy performance of the proposed design • Content of the exchange: Concept design (36-71 91 12 13 13) • Detailed exchange data: - IFC Foundation - IFC walls - IFC columns - IFC slabs - IFC Openings (internal/external) - IFC Roof - IFC Space • Possible tools: BIM Authoring tool (e.g.Revit architecture, ArchiCAD) • Possible format for data exchange: IFC • One way exchange
Related Exchange Models	• Indicators • Energy consumption • Construction cost and LCC

Table A-6 Information exchange requirements for sharing concept design alternatives

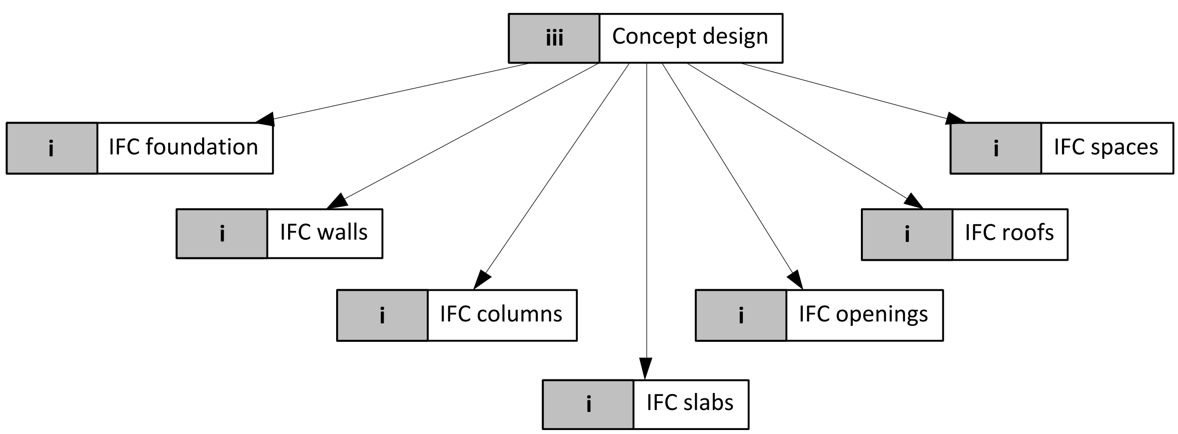

Figure A.13 Exchange objects for concept design alternatives

A.3 Concept design, energy matching

This process modelling focuses on matching the design alternatives with the neighbourhood energy requirements. The workflow starts (fig A 14) with the client checking the energy options for each design alternative created in the previous stage. Then the client will choose a few to share with the energy expert, who will add data such as energy price, energy potential maps and energy production components to match the proposed design with the neighbourhood. The outputs from this analysis are shared with the architect, who will use them to introduce a few changes in the design alternatives. Finally, these models are shared with the client, who will compare them to select the most suitable for their needs.

The key points in this stage are:

- The client and architect review and select the most suitable design options.
- The energy expert matches the design alternatives with the neighbourhood and produces simulation outputs for each alternative.
- The architect will check the results from the design alternatives and introduce a few changes based on the indicators from the collaborative workspace.
- The client checks the design alternatives to choose the most suitable according to their requirements.

In figure A 14 is illustrated a detail for this workflow:

Review energy options for the selected design alternatives: the client receives the alternative design and energy performance from previous stages. With this data, the client will choose the most suitable proposals for their financial and aesthetic requirements.

Review and check the selected alternatives for energy matching: the design alternatives, selected by the client, will be examined by the architect. Then these options are shared in the collaborative workspace.

Analyse energy matching at the neighbourhood level: the energy expert uses the models shared by the architect to run a new simulation to understand how the design should fit into the neighbourhood energy requirements.

Review design alternatives with energy matching results: the architect will use the outputs from the energy matching analysis and introduce a few changes to improve the proposed design.

Final selection and approval of a design alternative: the client reviews the BIM models proposed to choose the most appropriated according to his/her financial, functional, energy and aesthetic needs.

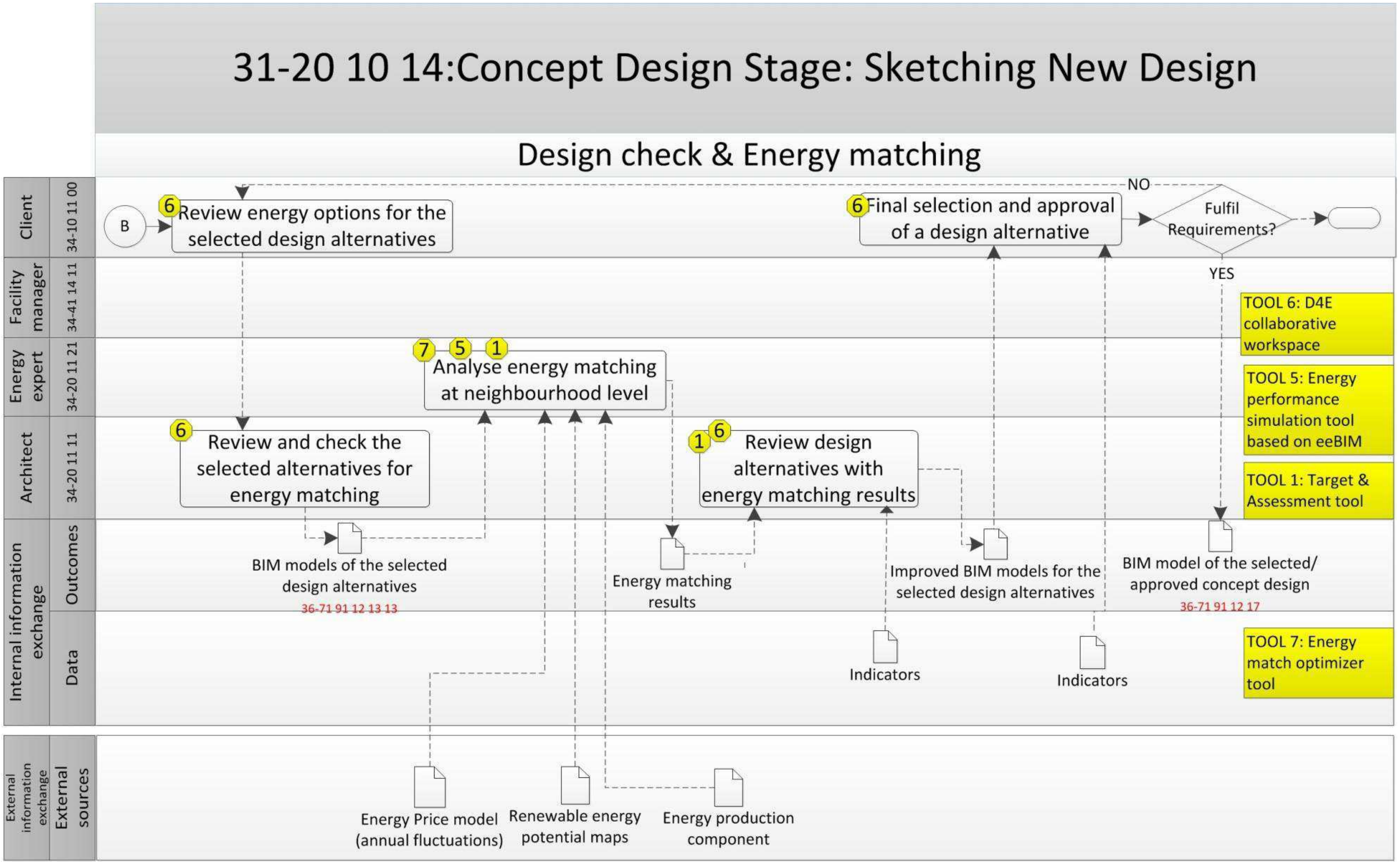

Figure A.14 Process model for concept design, sketching building design

A.3.1 Use case model for the approval of the concept design

This use case starts with the client (fig. A.15) reviewing the energy options for the chosen design alternatives. Then the architect will check the selected options for energy matching and shares the BIM models with the energy expert, who will use the BIM models and energy data from the collaborative workspace to analyse the energy matching at the neighbourhood level. The outputs from this analysis will be employed by the architect to review the design alternatives for energy matching. Finally, the BIM models for the chosen options are shared with the client for a review and select the most suitable for his/her requirements.

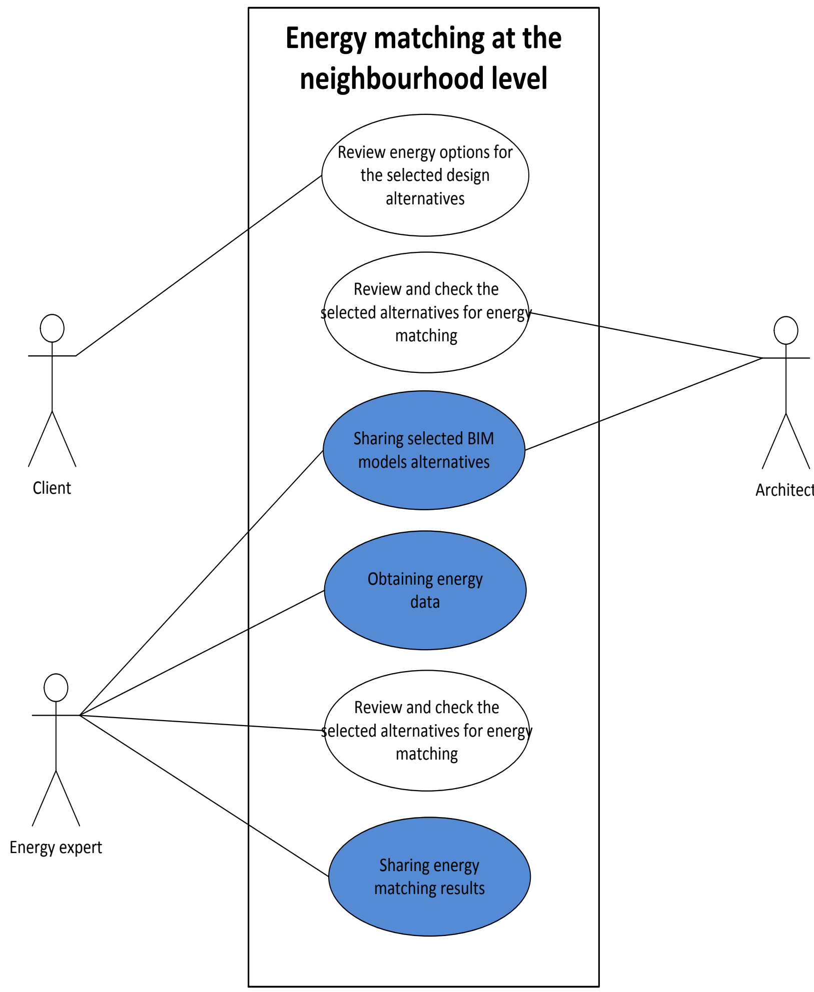

Figure A.15 Use case model for energy matching at the neighbourhood level

A.3.1.1 Information exchange requirements: sharing selected design alternatives as BIM models.

Project Stage	31-20 10 14: Concept design phase
Exchange Disciplines	34-20 11 11 - 34-20 11 21: Architect - Energy expert
Description	• Purpose: to pass the BIM design alternatives from the architect to the energy expert. • Content of the exchange: BIM models of design alternatives (36-71 91 12 13 13) • Detailed exchange data: o IFC Foundation, IFC walls, IFC columns, IFC slabs, IFC openings (internal/external), IFC roof, IFC space • Possible tools: BIM Authoring tool and Energy performance Simulation tool • Possible format for data exchange: IFC, gbXML, CSV • One way exchange
Related Exchange Models	• Energy price model • Renewable energy potential maps • Energy production components

Table A-7 Information exchange requirements for sharing the selected design alternatives

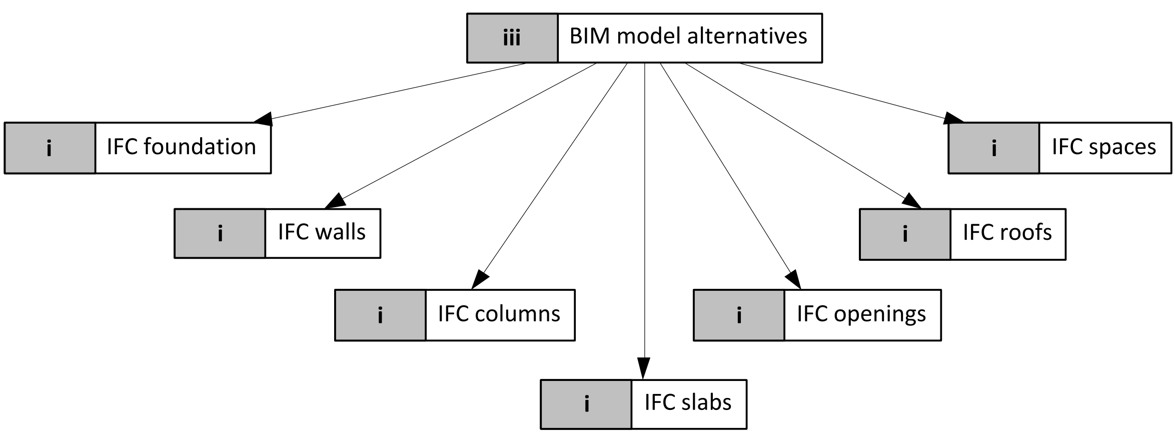

Figure A.16 Exchange objects BIM model alternatives

A.4 Detailed design, detailed design

This workflow has as objective to add detail to the project including new specialities such as HVAC, and electrical system to move the project from concept to detailed design. In figure A.17, each designer uses the data available in the collaborative workspace such as approved concept design, personal component catalogue, and related indicators. This data is used by designers to create, analyse and improve their models.

The key points for this stage are shown below:

- The client shares in the collaborative workspace the concept design chosen by him/her in the previous stage.
- MEP, electrical, and any specialist involved in the project will use the data available into the collaborative workspace to develop their specialities.
- Each specialist will add more detail into their design looking for improving and optimising.

In figure A.17 is shown the workflow for the design phase:

Delivering approved concept design: the client shares the concept design with the specialist via the collaborative workspace.

Designing systems: each specialist uses the information from the collaborative workspace to create their models.

Analyse and improve design: each specialist will analyse and improve their designs to share this data in the collaborative workspace finally. The use cases are broken down for each specialist to simplify the representation. While the use cases are similar, they need to be specified because of the information exchange for each one is different.

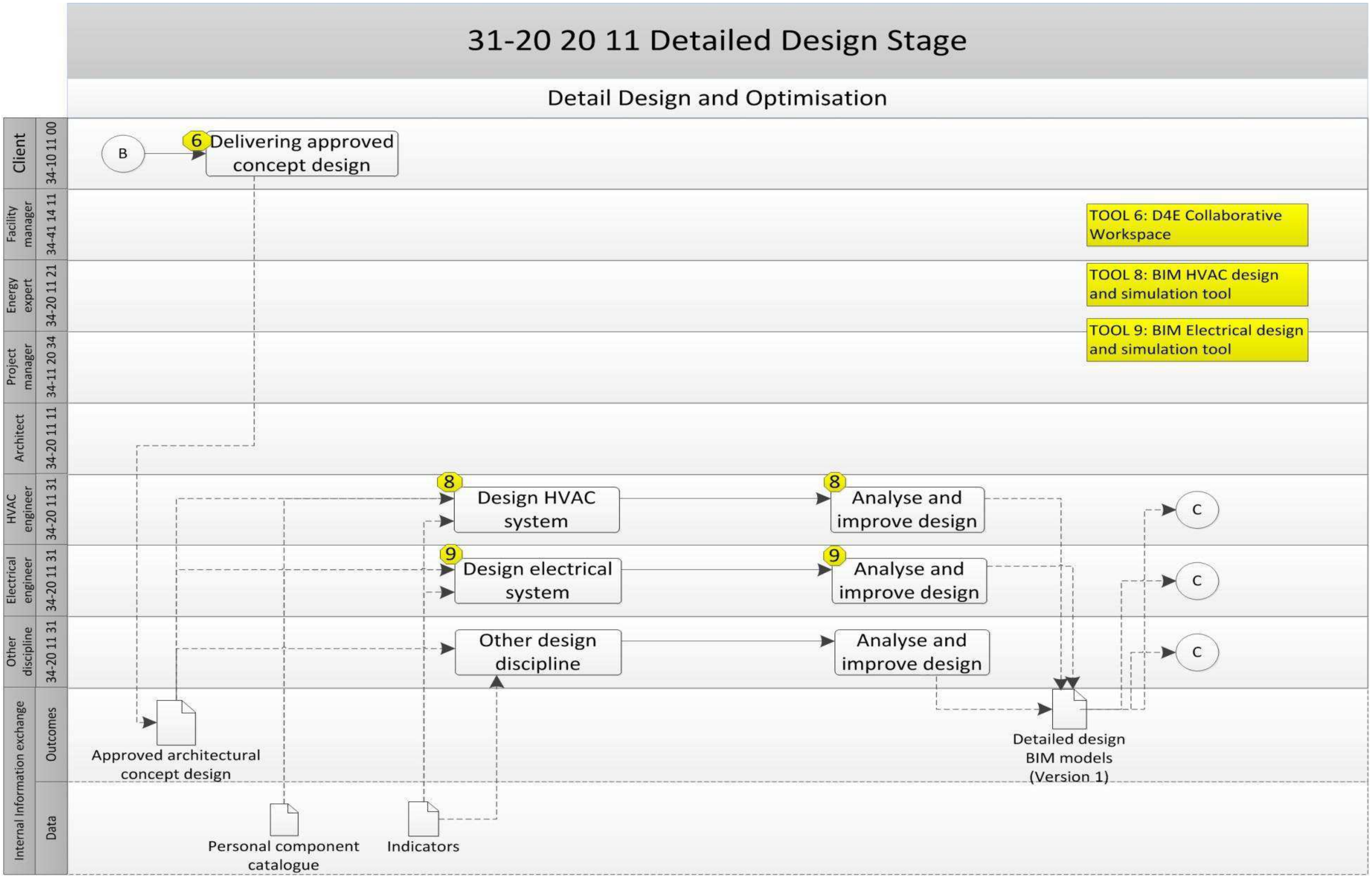

Figure A.17 Process model for detailed design and optimisation

A.4.1 Use case model for HVAC detailed design

The figure A 18 shows the use case for the HVAC engineer during the detailed design stage. The client shares the approved concept design in the collaborative workspace. This data in addition to personal components and indicators will be used by the HVAC engineer to design the HVAC system. Then this design will be checked and refined by the HVAC engineer to complete a final version of the BIM model.

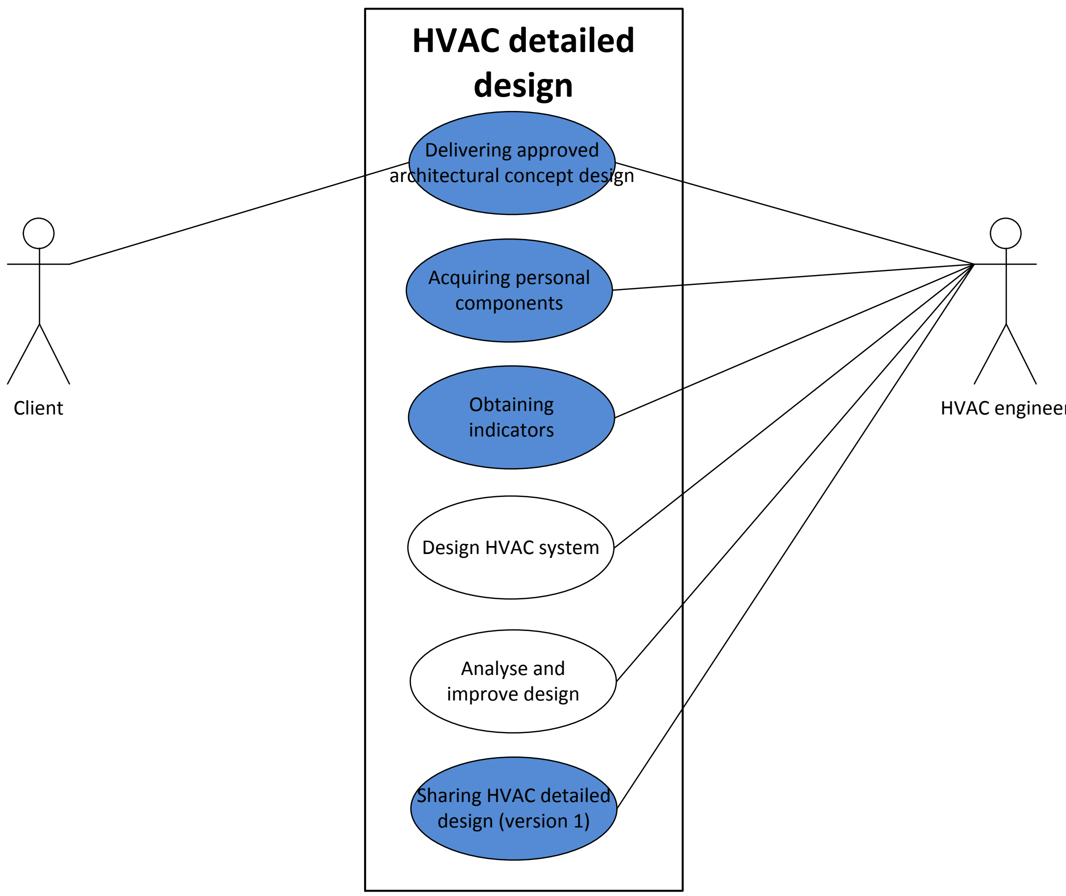

Figure A.18 Use case model for approval of the concept design

A.4.1.1 Information exchange requirements: acquiring the personal components catalogue

Project Stage	31-20 20 11: Detailed design phase
Exchange Disciplines	34-20 11 31: HVAC engineer
Description	• Purpose: the HVAC engineer accesses the components from the personal catalogue to design the HVAC system • Content of the exchange: the personal component catalogue • Detailed exchange data: - HVAC Component - Construction cost - LCC - BACS equipment • Possible tools to create data: BIM HVAC Design and simulation tool • Possible format for data exchange: IFC • One way exchange
Related Exchange Models	• Approved architectural concept design • Indicators

Table A-8 Information exchange requirements for the personal components catalogue

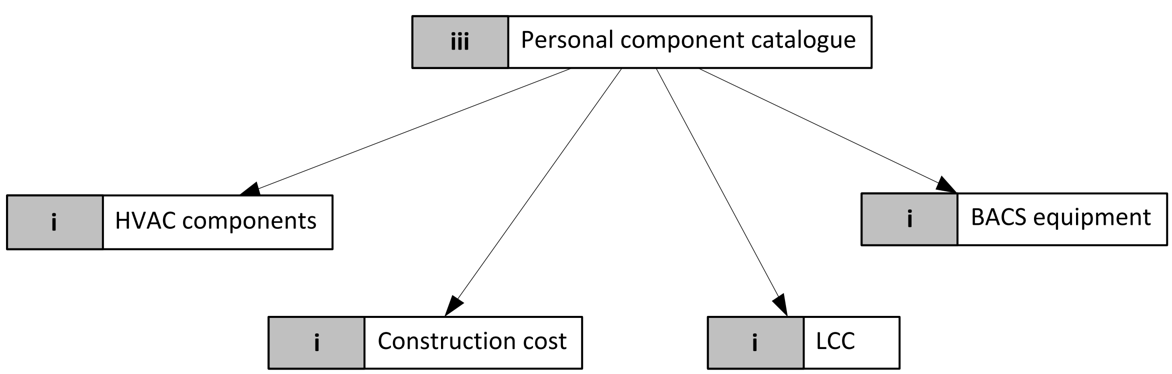

Figure A.19 Exchange objects for personal component catalogue

A.4.1.2 Information exchange requirements: obtaining HVAC indicators

Project Stage	31-20 20 11: Detailed design phase
Exchange Disciplines	34-20 11 31: HVAC engineer
Description	• Purpose: to obtain HVAC related indicators for the HVAC engineer in order to use them in the HVAC design for the comparison and validity of the HVAC design and analysis. • Content of the exchange: HVAC related indicators • Detailed exchange data: - Energy performance/building - LCC - Energy performance of the HVAC System (heating, cooling, air conditioning and ventilation) - Cost estimation of the HVAC system • Possible tools to create data: BIM HVAC Design and simulation tool • Possible format for data exchange: IFC, gbXML, CSV • One way exchange
Related Exchange Models	• Approved architectural concept design • Personal component catalogue • Detailed design BIM models

Table A-9 Information exchange requirements for obtaining indicators

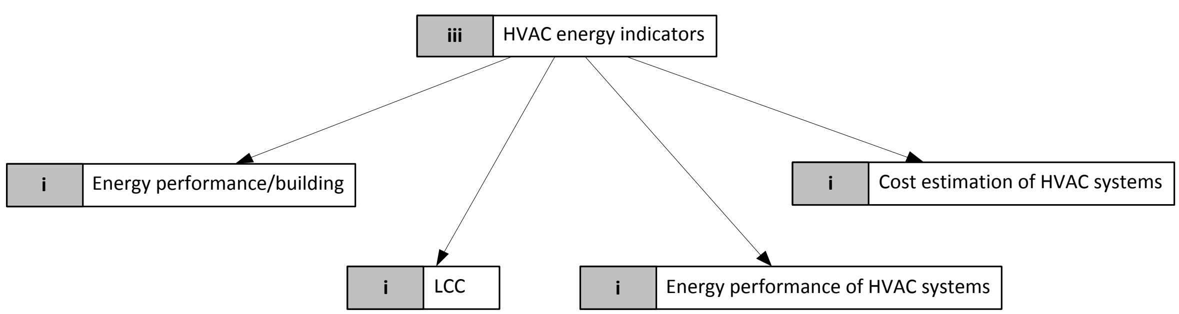

Figure A.20 Exchange objects for obtaining HVAC indicators

A.5 Final design, design review

In this stage will be carried out an integrated review of the whole design. Thus, each designer will have access to the other designer´s models via the virtual collaborative workspace. With this data, each designer will run a clash detection analysis to understand how their designs interact with each other and introducing changes in case of been required. The energy expert will have a chance to check the energy performance with the latest version of the model while the client will compare the performance simulation results against the project brief to approve or suggest changes in the design.

The key activities for this stage are:

- Each designer analyses his/her design against other disciplines.
- The energy expert puts together each design to runs a comprehensive performance simulation.
- The client compares energy results with the brief and project objectives to ensure whether the design fulfils their requirements.

Figure A 21 shows the process workflow for the integrated design review stage.

Combined analysis and clash detection: each designer will develop clash detection and combined analysis via virtual collaborative workspace to access to complementary design solutions produced by other specialists.

Integrated performance simulation: with the latest version for the detailed design, the energy expert will be able of test a new simulation to check how the latest changes affect the design performance.

Holistic matching energy analysis: with the results of the performance simulation, the energy expert will check the energy matching at the neighbourhood level to ensure that the energy option selected are the most appropriated.

Review design performance with the project brief: the client will take the detailed design BIM models and energy performance results to compare them against the project brief and determinate if the final design meets the client requirements.

For an easy representation, the use cases have been defined for each designer (architect, MEP engineer, electrical engineer and other disciplines), and then the process flow will be entirely explained by each designer from beginning to end.

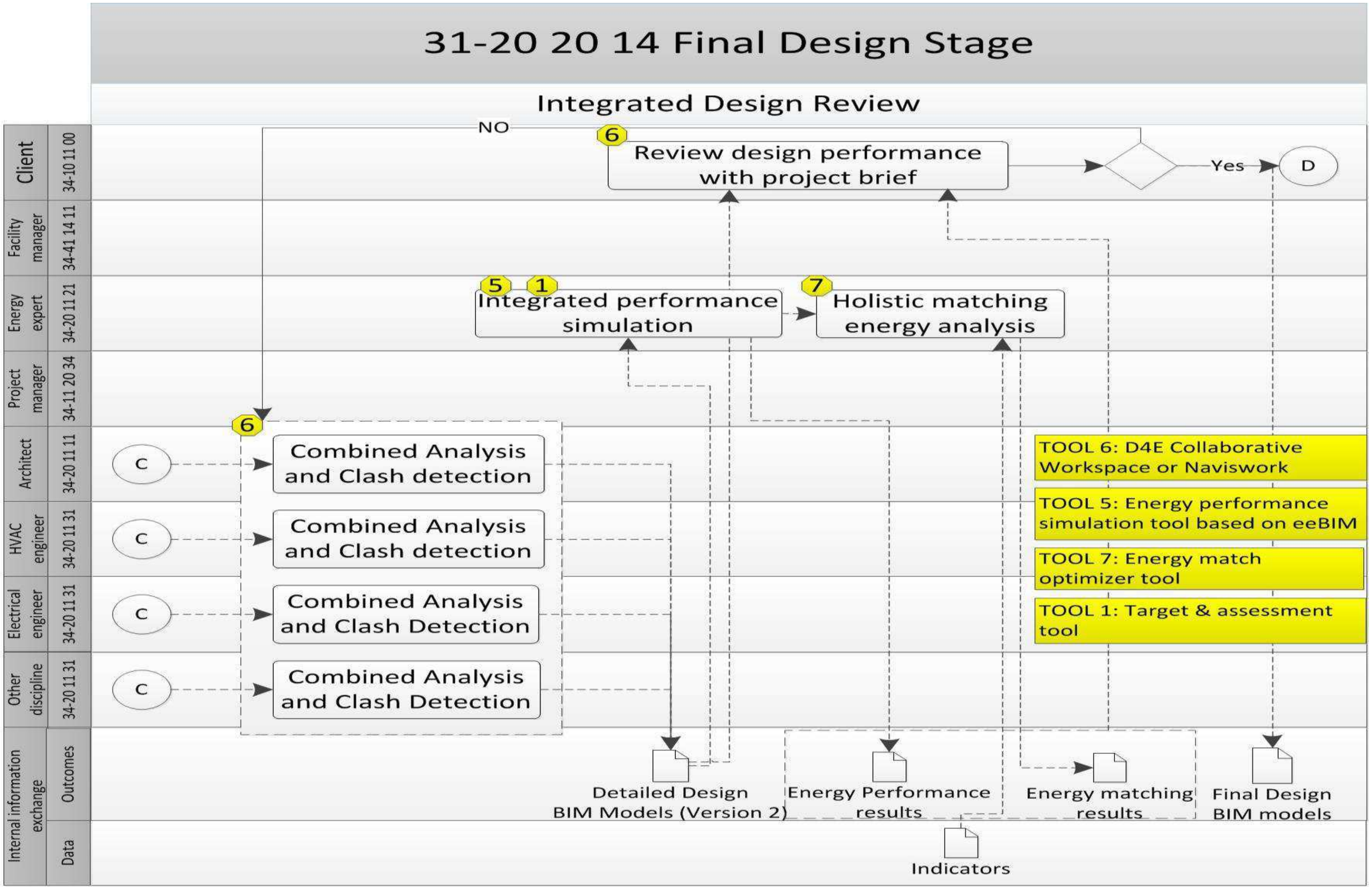

Figure A.21 Process model for final design, integrated design review

A.5.1 Use case model for integrated design review (HVAC)

Figure A 22 shows the use case and information flow for the integrated design review in HVAC design. It starts with the HVAC engineer combining the HVAC model with BIM models to identify any problem and correct it. The modified designs are passed to the energy expert to carry out a performance simulation. The results will be shared with the client to ensure that the changes in the HVAC design meet the project brief requirements.

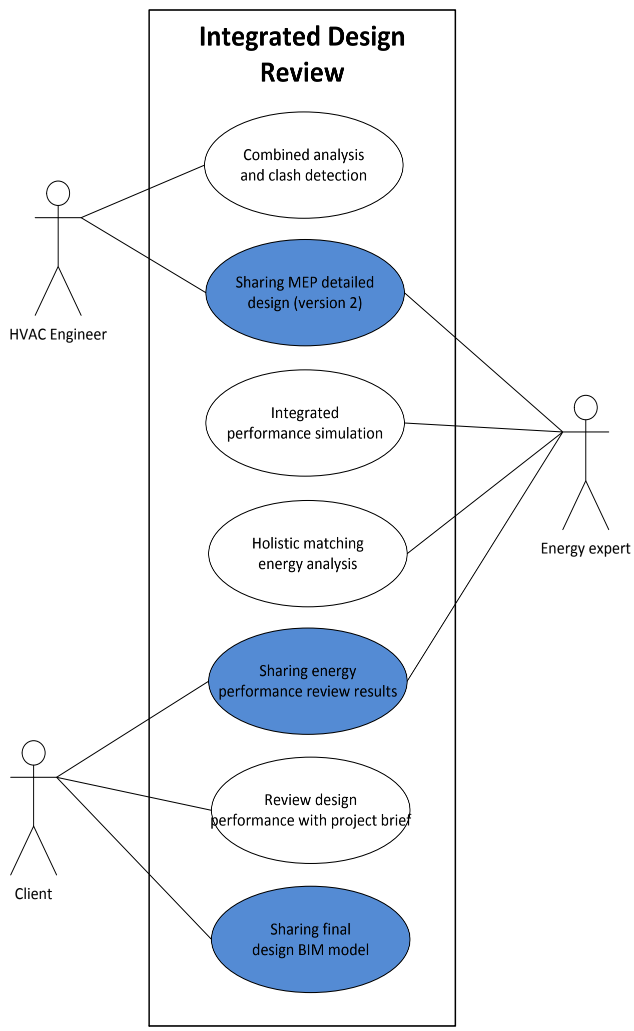

Figure A.22 Use case model for integrated design review

A.5.1.1 Information exchange requirements: sharing energy performance simulation results of the HVAC design

Project Stage	31-20 20 14: Final design phase
Exchange Disciplines	34-20 11 21 – 34-10 11 00: Energy expert - client

Description	• Purpose: to share the performance results of the HVAC design with the client to review the results against the project brief
	• Content of the exchange: energy performance results of HVAC design
	• Detailed exchange data:
	  ○ Energy Performance/building
	  ○ LCC
	  ○ Energy performance of the HVAC System (heating, cooling, air conditioning and ventilation)
	  ○ Cost estimation of the HVAC system
	• Possible tools: Energy Performance Simulation tool and target and assessment tool
	• Possible format for data exchange: IFC, gbXML, CSV
	• One way exchange

Related Exchange Models	• Detailed design BIM model • Final design BIM model

Table A-10 Information exchange requirements for energy performance simulation results

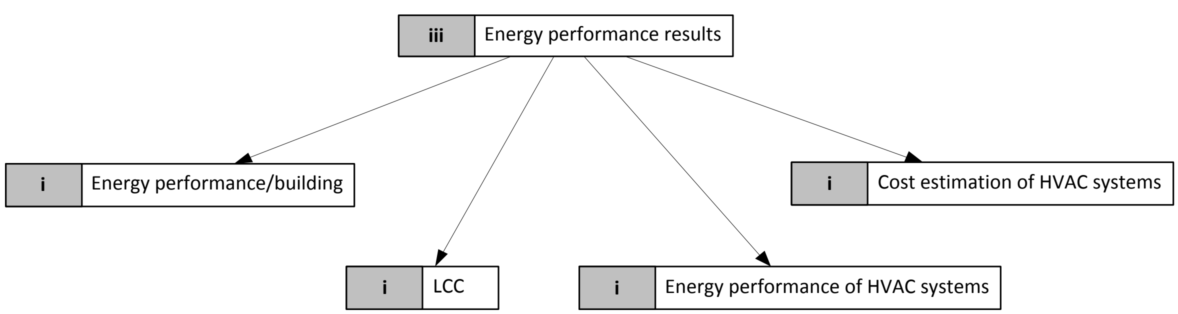

Figure A.23 Exchange objects for energy performance simulation results of the HVAC design

A.5.1.2 Information exchange requirements: sharing the final HVAC design

Project Stage	31-20 20 14: Final design phase
Exchange Disciplines	34-10 11 00: Client

Description	• Purpose: to share in the collaborative workspace the latest version of the HVAC design
	• Content of the exchange: final design BIM model
	• Detailed exchange data:
	  ○ IFC equipment for heating
	  ○ IFC equipment for cooling
	  ○ IFC equipment for ventilation
	• Possible tools to create data: D4E Collaborative Workspace
	• Possible format for data exchange: IFC, gbXML, CSV
	• One way exchange

Related Exchange Models	• Detailed design BIM model • Energy performance review results

Table A-11 Information exchange requirements for sharing the final HVAC design model

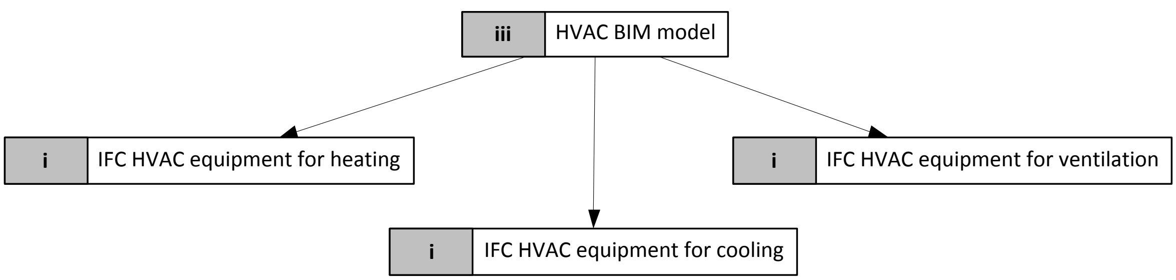

Figure A.24 Exchange objects for the final design BIM model

A.5.2 Use case model for the integrated design review (electrical)

Figure A 25 shows the use case for the electrical design. The electrical engineer combines his/her model with the other ones to check and correct any problem into the design. The modified design is shared with the energy expert to run a performance simulation for the electrical design. The results will be checked by the client to ensure that they meet their requirements.

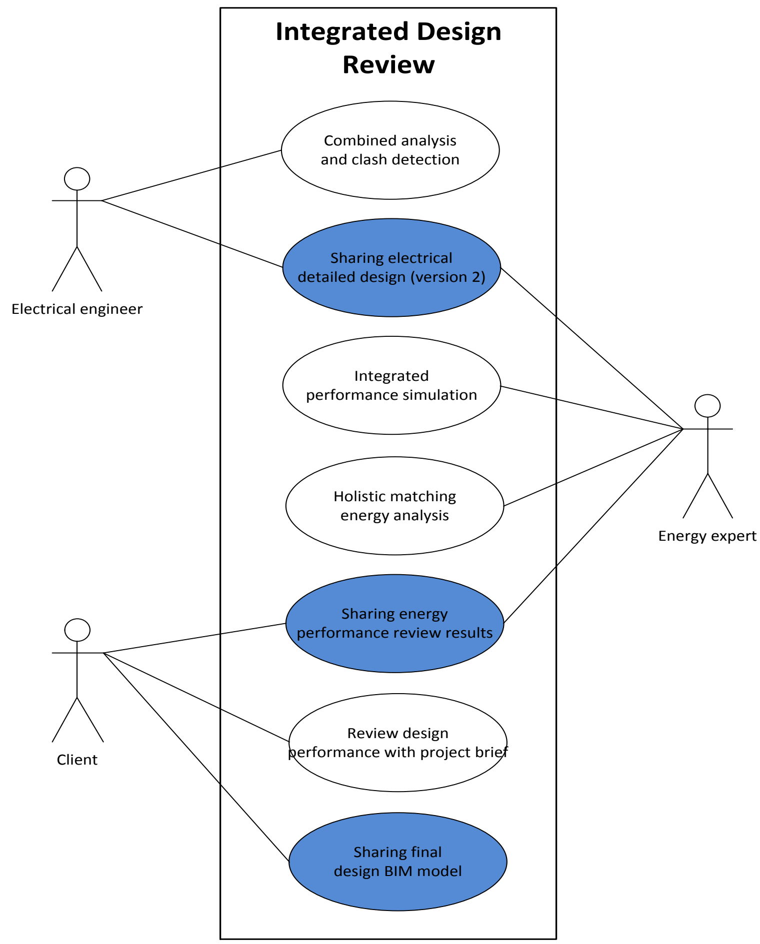

Figure A.25 Use case model for integrated design review for electrical design

A.5.2.1 Information exchange requirement: sharing the final electrical design

Project Stage	31-20 20 14: Final design phase
Exchange Disciplines	34-20 11 31 – 34-20 11 21: Electrical engineer - energy expert
Description	• Purpose: the electrical engineer shares the latest version of the electrical design via the collaborative workspace for further analysis by the energy expert and client. • Content of the exchange: Electrical detailed design • Detailed exchange data: - IFC exterior luminaries, IFC photovoltaic panels - IFC interior luminaries, IFC cable trays • Possible tools to create data: D4E Collaborative Workspace, • Possible format for data exchange: IFC, gbXML, CSV • One way exchange
Related Exchange Models	• Energy performance review results

Table A-12 Information exchange requirements for sharing the electrical design

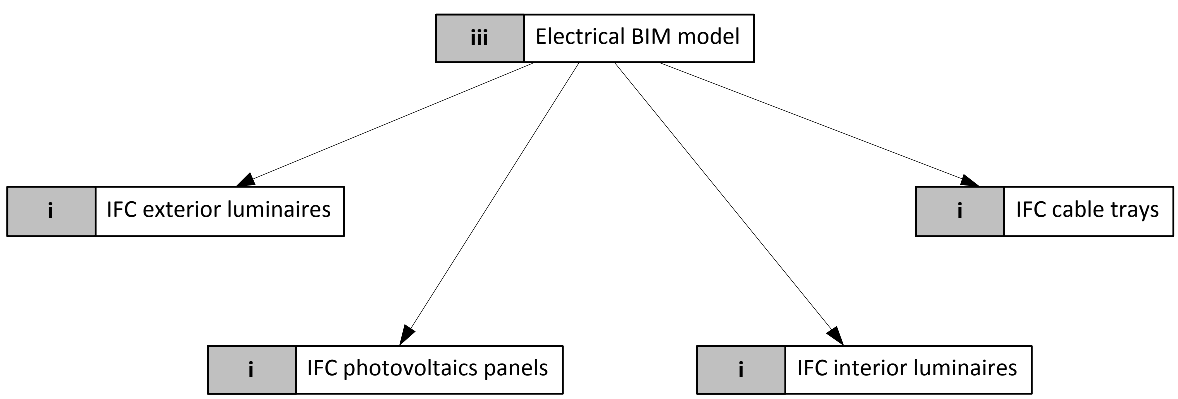

Figure A.26 Exchange objects for detailed electrical design BIM model

Appendix B , Model View Definitions

In the previous appendix has been developed the exchange objects according to the IDM methodology described in chapter 5. In this chapter, those exchange objects are used and translated in technical language using MVD methodology described in chapter 6.

The number of MVD illustrated in this appendix is a result of a rationalisation process that looked at reducing the number of exchange objects from 183 to 67. From these 67 exchange objects were selected three exchange objects from each scenario to develop the MVD, the idea behind this selection is to represent different types of information, then were chosen solid elements, documents, cost data, library objects, and information objects.

B.1 Needs identification and feasibility studies

B.1.1 MVD # 01, lifecycle cost

The first exchange object to describe will be ´Lifecycle cost´ in the information exchange ´Key criteria´ in the first scenario. In figure B.1 is shown the MVD for lifecycle cost, it is described through three entities:

- **ExternalReferenceRelationship:** it makes reference to external database (libraries, documents) when the information source is not explicitly represented in the model. Because of the lifecycle cost does not represent a particular element into the model, and then it will need to use ExternalReferenceRelationship.

- **AppliedValue**: it captures a value driven by a formula, defined by unit basis and valid data range.

- **AppliedValueSelect:** it calculates a value within a formula defined by value and units.

BuildingSMART suggests using CostValue to detail the amount of money in a situation such as annual rate return, bonus, contract, estimated cost, maintenance, material, overhead, profit, purchase, rental, repair, replacement, and whole life.

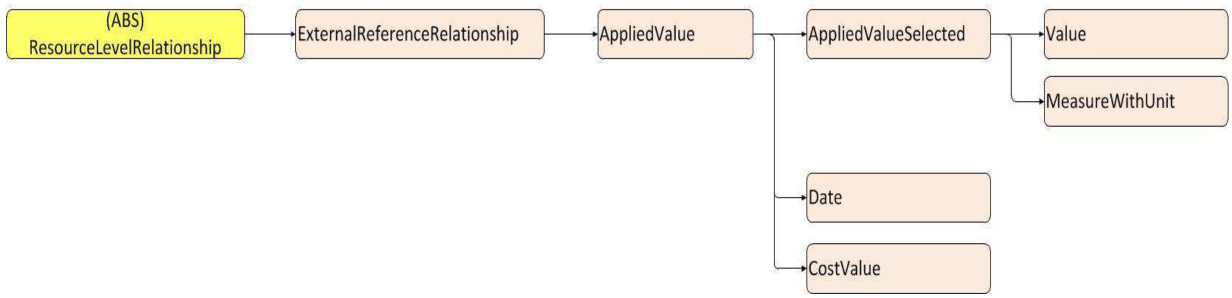

Figure B.1 Lifecycle cost

B.1.2 MVD # 02, usage indicators

The second exchange indicator from the first scenario to describe is ´usage indicator´. This MVD is described by (fig B.2):

- **The root attributes**: it defines a singular element using Globally Unique Identifier (GUID) and specific name.

- **The generic definition**: it is used to generate a property set for usage indicators. This entity set is defined by **PropertyDefinition** and **PropertySet**; they are useful to generalise multiple properties contained into **Pset_BuildingCommon** and **ePset_BuildingEnergyTarget**. The first entity defines all instances of IfcBuilding, in this case, it will be used to capture carbon footprint and indoor satisfaction, while the second property defines the energy instances to evaluate in the building.

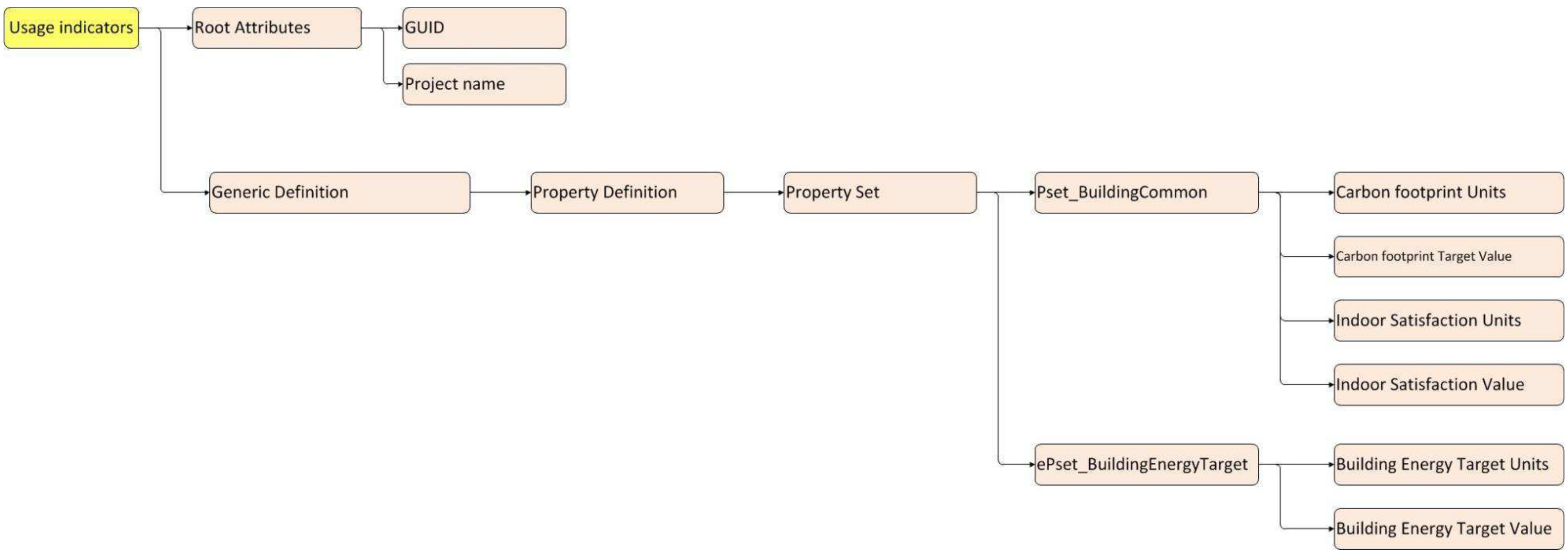

Figure B.2 Usage indicators

B.1.3 MVD # 03, self-efficiency rate

The last exchange object to describe in the first scenario is ´self-efficiency rate´. It is described in figure B.3 for the below entities:

- **The root attributes:** identifies a particular element using Globally Unique Identifier (GUID), and specific name.

- **The generic definition**: is used to generate a property set for self-efficiency rate. This entity set is defined by **PropertyDefinition** and **PropertySet**; they are useful to generalise multiple properties contained into **ePset_BuildingEnergyTarget**. This property defines the energy instances to evaluate in the building (units and value).

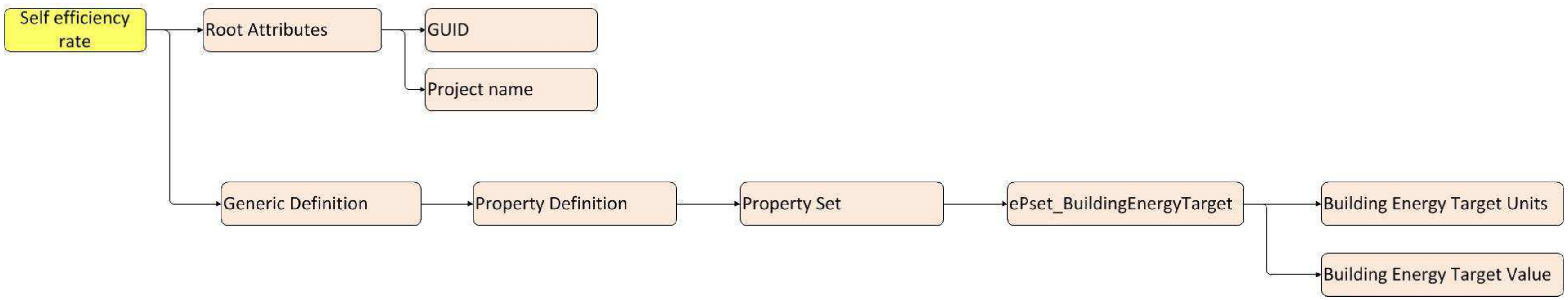

Figure B.3 Self efficiency rate

B.2 Concept design, design and simulation

B.2.1 MVD # 04, Site potential and features

This MVD describes the site potential to be considered in the second scenario, in figure B.4 is illustrated a detail for the entities into this MVD:

- **Root attributes:** these entities identify a singular element 'site' using Globally Unique Identifier (GUID), BIM owner object, BIM owner and specific name.

- **Type identification:** it identifies a product without being already inserted into a project structure without having a placement, and not being included in the geometric representation context of the project.

- **Generic object placement**: it defines the relative placement of the element site in relation to other elements.

- **Shape representation**: it represents the geometry of the site.

- **Generic containment:** it comprises all elements that are part or could be embedded into a site.

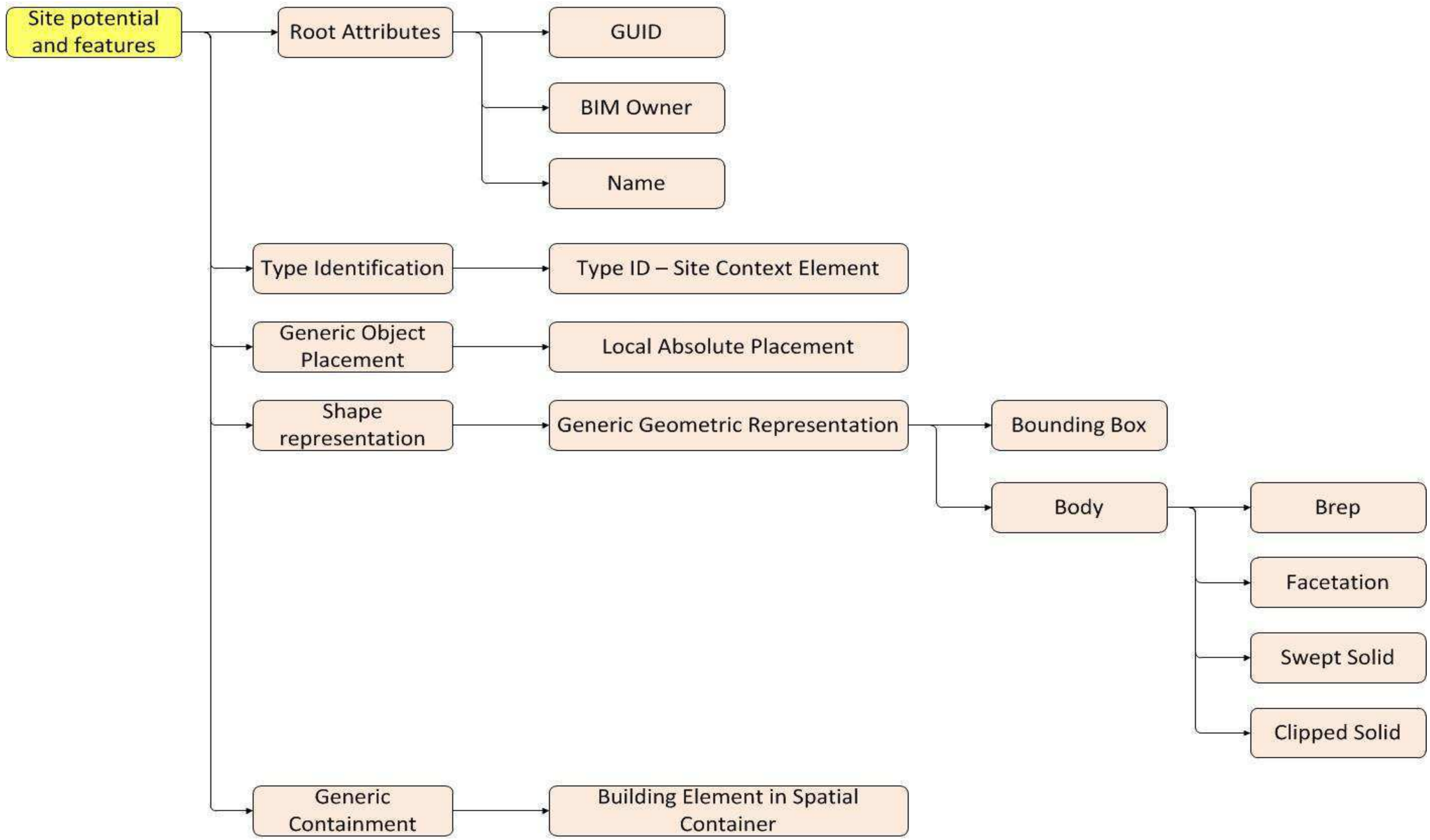

Figure B.4 Site potential and features

B.2.2 MVD # 05, U-Value

The U-Value is described in figure B.5, for below entities:

- **The root attributes**: defines a singular element using Globally Unique Identifier (GUID), and specific name.

- **Relationships:** it allows defining the thermal properties for a generic material describing the relationship between a material and element. To do so are used the follow sub-entities: **RelAssociates** to access to internal or external data (library, document, approval, constraints, or material); **RelAssociatesMaterial** to define a relationship between a material and element that will be applied the definition; **MaterialDefinition** to define any material by layer, profile or constituents; **Material** defines the units and transfer heat that will have the material to be used.

- **The generic definition:** it is used to define the thermal properties in walls, slabs, windows and doors. This entity set is defined by **PropertyDefinition** and **PropertySet**; they are useful to generalise multiple properties contained into Pset_WallCommon, Pset_SlabCommon, Pset_WindowsCommon, Pset_WindowsCommon.

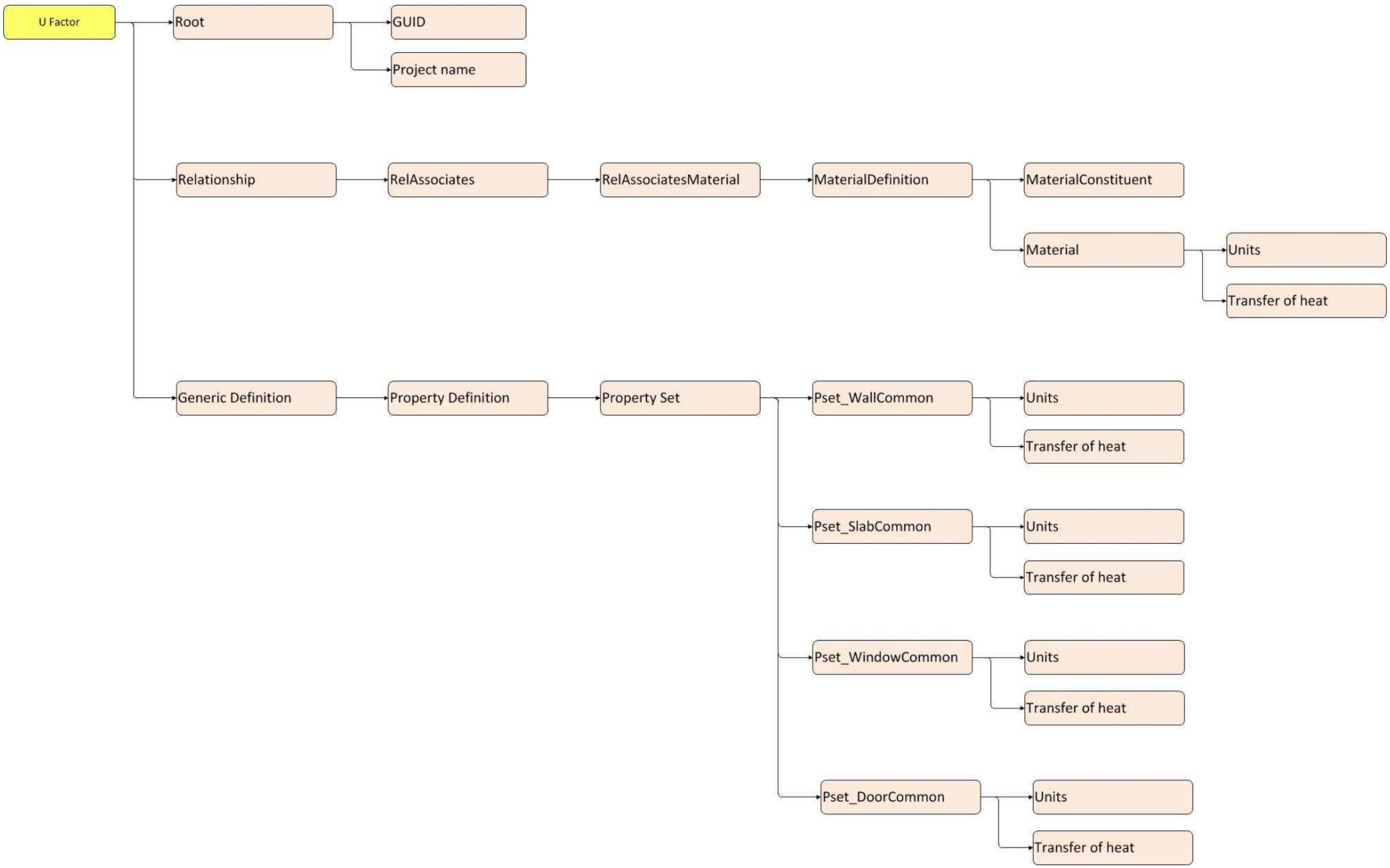

Figure B.5 U-Value

B.2.3 MVD # 06, new material slabs

This MVD describes how will be added new materials into the element slab, the entities defining this MVD are described below (fig. B.6):

- **MaterialDefinition:** it is used to create libraries allowing making an external reference, it defines all material related information items in IFC that have common material properties. This entity is defined by **Material**, **MaterialLayerSet** and **MaterialLayer. Material** defines the material to be used in each element, in this case into the slab; **MaterialLayerSet** enables to express the relative position of each layer in a multilayer element; **MaterialLayer** defines a single part of an element built by layers.

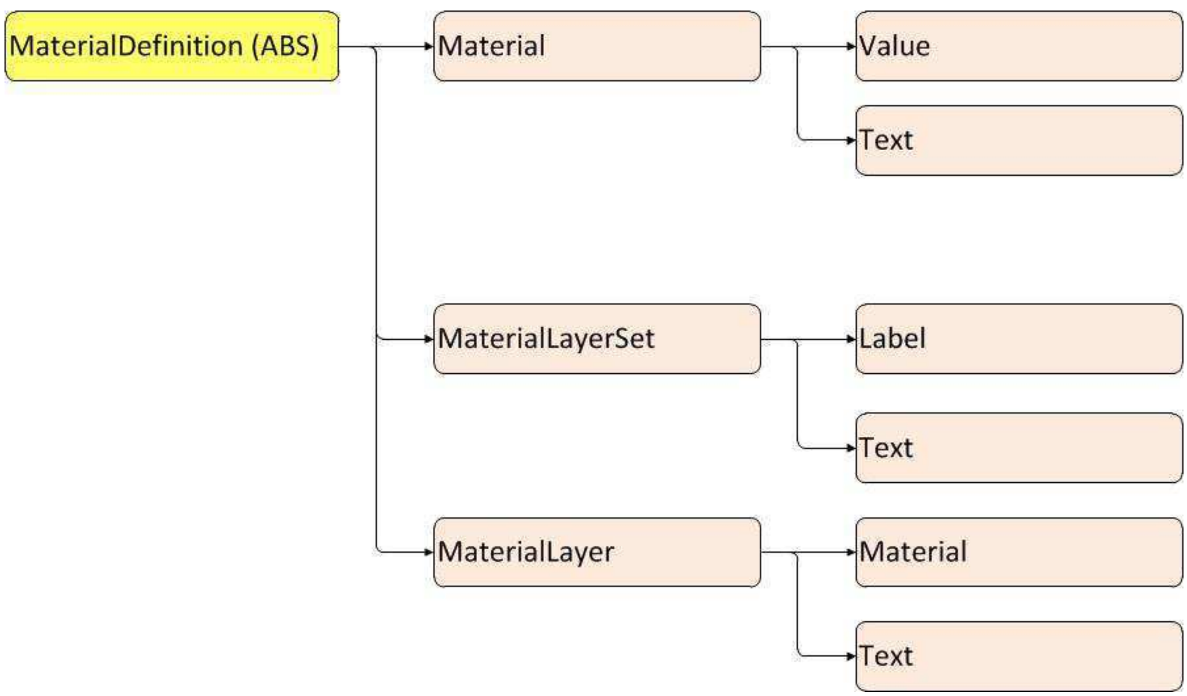

Figure B.6 New material slabs

B.3 Concept design, energy matching

B.3.1 MVD # 07, walls

Figure B.7 illustrates the MVD for a wall using eight different entities lines, below are described the objective of each line:

- **Root attributes:** the first group of entities is focus on identifying a particular element ´wall´ using Globally Unique Identifier (GUID), BIM owner object, and specific name.

- **Generic definition:** it is focused on explaining in a generic way the type of wall that the element might be e.g. it could be internal or external, or different types of walls according to the transmittance properties that the wall could have.

- **Generic association**: this group of entities define each material to consider in the element ´wall´. Also, these entities consider the existence of multiple layers including the entity Material in the material layer.

- **Generic object placement**: it defines the relative placement of the element wall in relation to other elements.

- **Shape representation**: it represents the geometry of a wall

- **Generic voiding:** it defines if the wall can host a void into it, e.g. void by cutting, drilling or milling.

- **Generic containment:** it comprises all elements that are part or could be embedded into a wall

- **Space boundary:** it defines the connection that a wall will have with another element e.g. contact by edge, face or node.

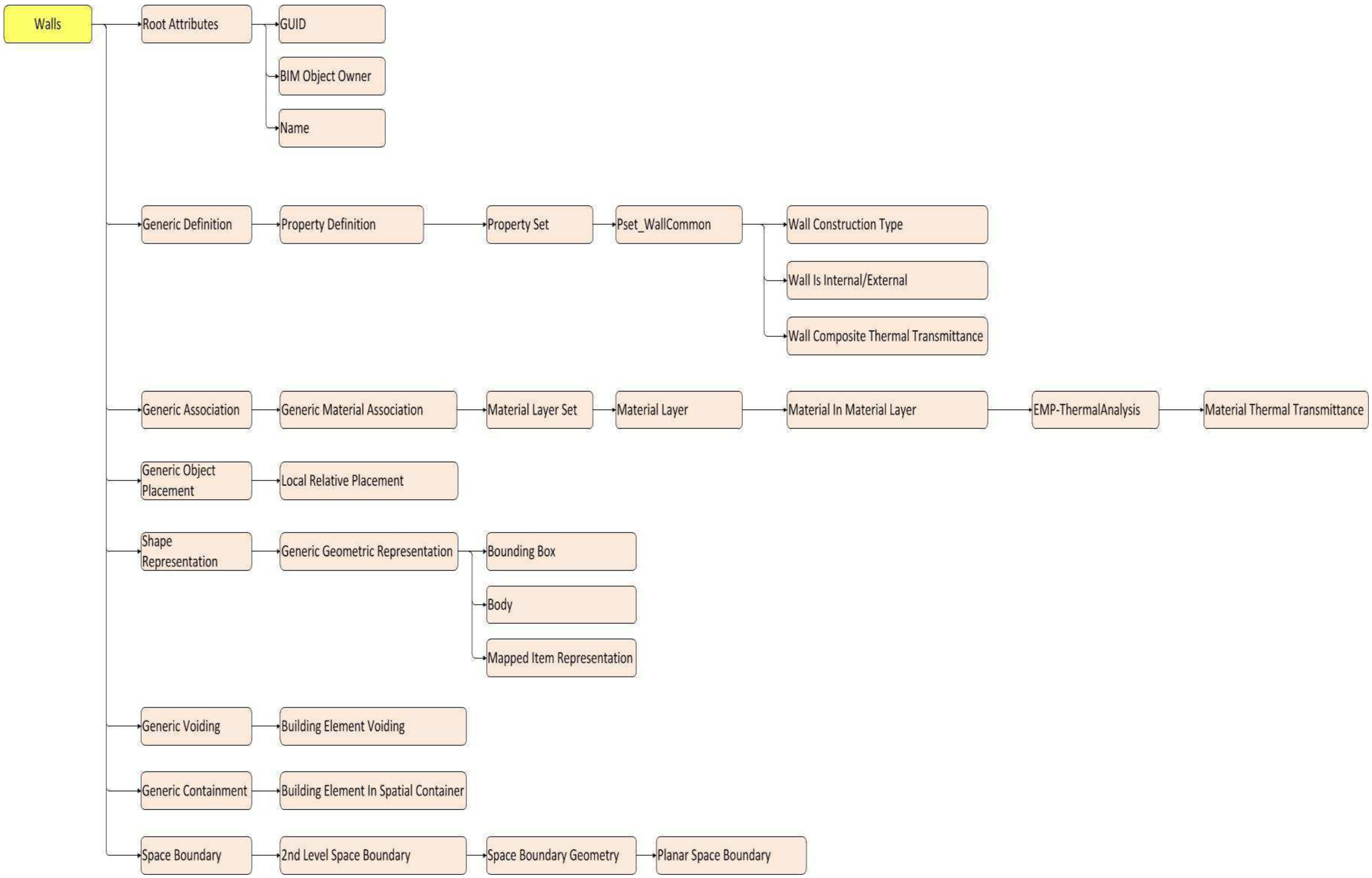

Figure B.7 MVD Walls

B.3.2 MVD # 08, columns

Figure B.8 illustrates the MVD considered for a column, below are described the objective of each line:

- **Root attributes:** the first group of entities is focus on identifying a particular element ´column´ using Globally Unique Identifier (GUID), BIM owner object, and specific name.

- **Generic definition:** is focus on explaining in a generic way the type of column that the element might be e.g. it could be internal or external, or different types of columns according to the transmittance properties that the column could have.

- **Generic association**: this group of entities define each material to consider in the element ´column´. Also, these entities consider the existence of multiple layers including the entity Material in the material layer.

- **Generic object placement**: it defines the relative placement of the element column in relation to other elements.

- **Shape representation**: it represents the geometry of a column.

- **Generic voiding:** it defines if the column can host a void into it, e.g. void by cutting, drilling or milling.

- **Generic containment:** it comprises all elements that are part or could be embedded into a column.

- **Space boundary:** it defines the connection that a column will have with another element e.g. contact by edge, face or node.

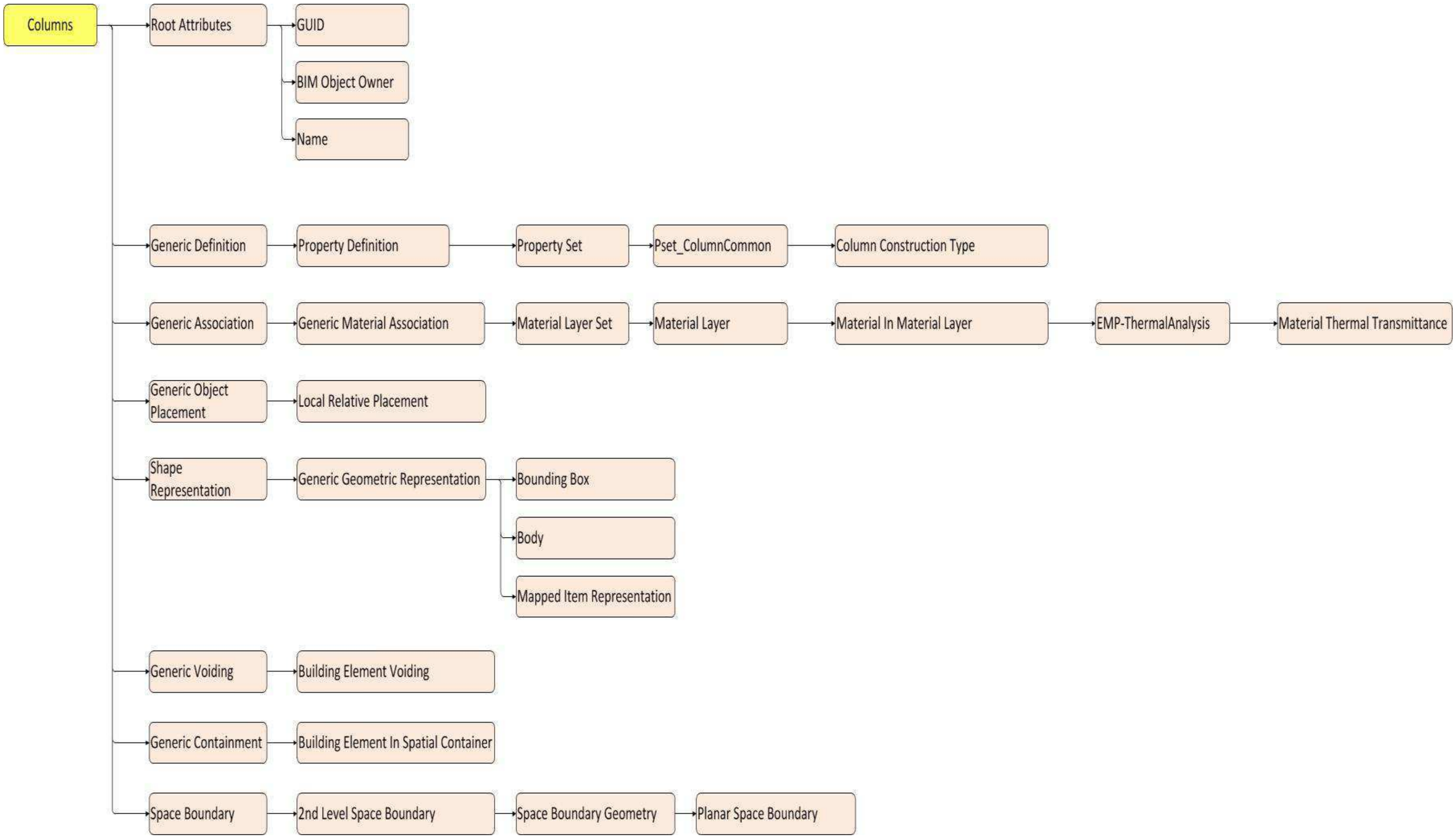

Figure B.8 MVD columns

B.3.3 MVD # 09, slabs

The MVD for describing a slab has the same structure used in walls and columns (fig B.9), below are described the objective of each line:

- **Root attributes:** the first group of entities is focus on identifying a particular element ´slab´ using Globally Unique Identifier (GUID), BIM owner object, and specific name.

- **Generic definition:** it is focused on explaining in a generic way the type of slab that the element might be e.g. it could be SlabStandardCase (prismatic shape), SlabElementCase (slab with decomposition rules) or Slab (slabs with changing thickness or non-planar).

- **Generic association**: this group of entities define each material to consider in the element ´slab´. Also, these entities consider the existence of multiple layers including the entity Material in the material layer.

- **Generic object placement**: it defines the relative placement of the element slab in relation to other elements.

- **Shape representation**: it represents the geometry of a slab.

- **Generic voiding:** it defines if the slab can host a void into it, e.g. void by cutting, drilling or milling.

- **Generic containment:** it comprises all elements that are part or could be embedded into a slab.

- **Space boundary:** it defines the connection that a slab will have with another element e.g. contact by an edge, face or node.

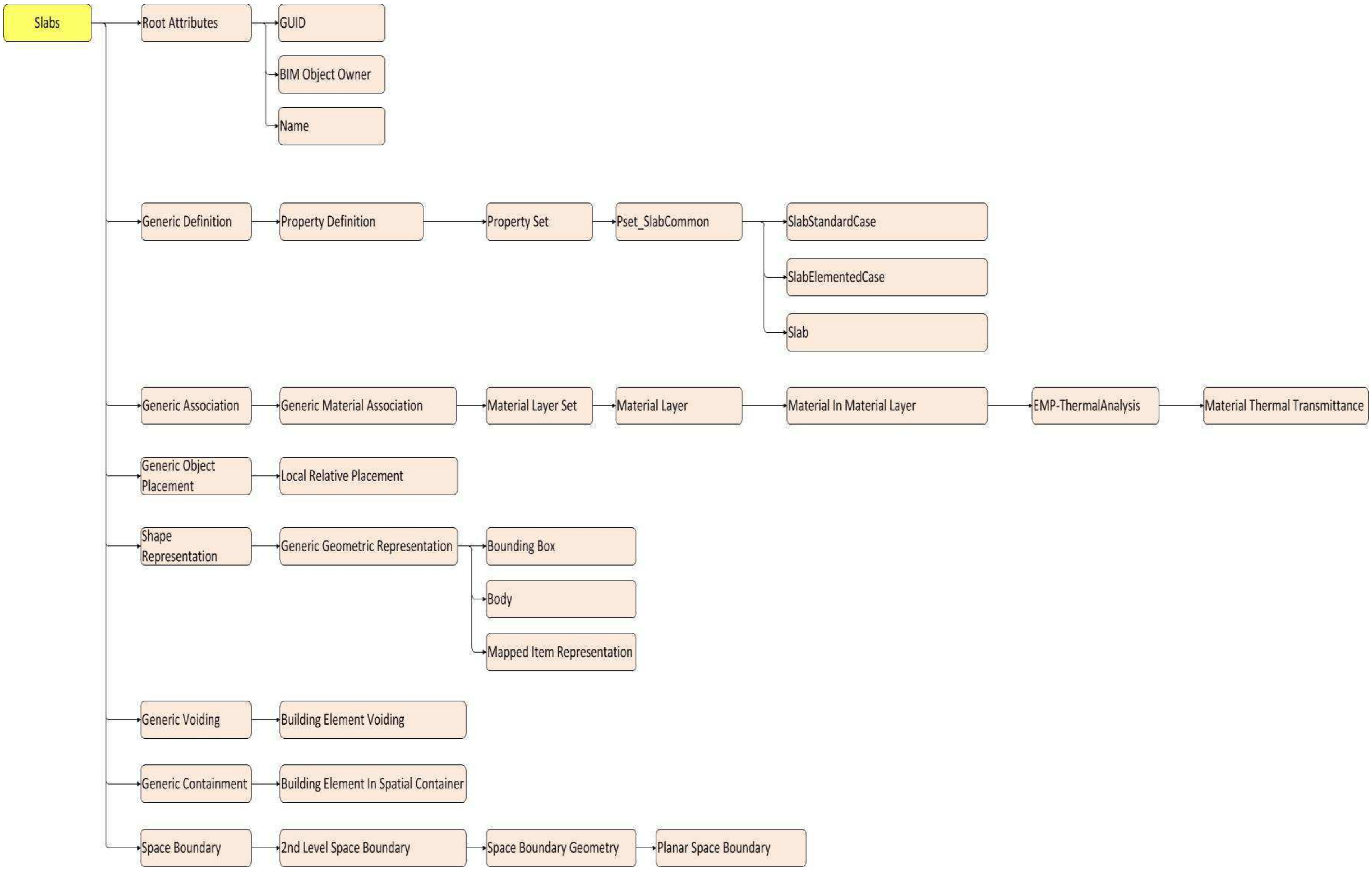

Figure B.9 MVD slabs

B.4 Concept design, energy matching

B.4.1 MVD # 10, HVAC components

Figure B.10 illustrate the required entities to define an HVAC system:

- **Port**: defines a means to connect each element (sensors, equipment or components) in an HVAC system. This **Port** is defined by **RelConnectsPortToElement**, **DistributionElement**, and **FlowMovingDevice.** **RelConnectPortToElement** is the relationship that defines the link between **Port** and **DistributionElement.** **DistributionElement** is a generalisation of all elements involved in the HVAC system. **FlowMovingDevice** defines the occurrence of a device (compressor, pump or fan) used to distribute, circulate or perform conveyance of fluids.

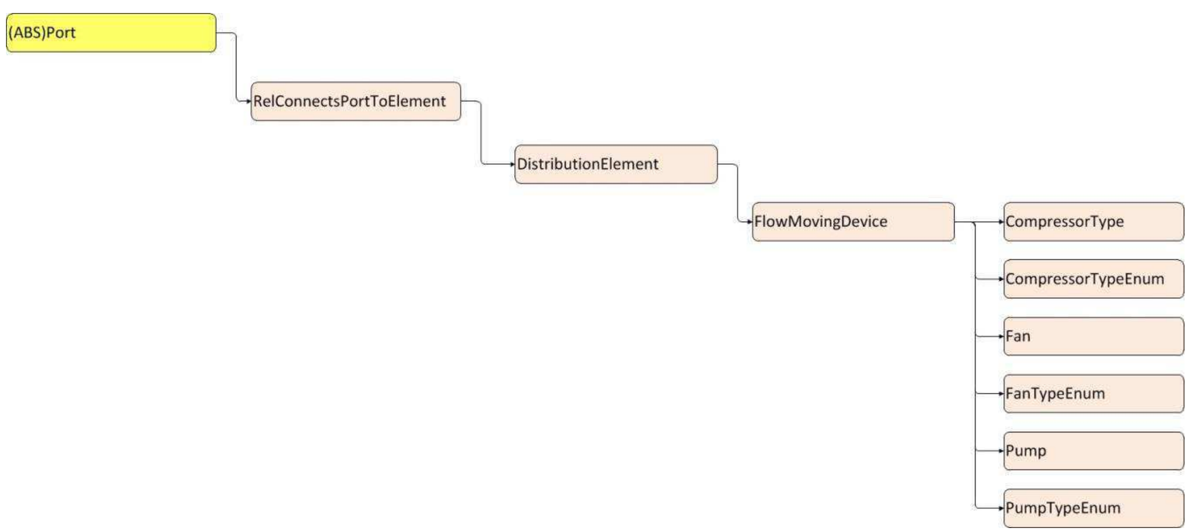

Figure B.10 HVAC system

B.4.2 MVD # 11, BACS components

This MVD describes how the different entities will be considered and linked to define a BACS (fig. B.11)

- **Port**: defines a means to connect a sensor with a system, creating a Building Automatic Control System (BACS) able to measure the different conditions into the building and send a signal in case they get out of a set range. The port may be connected with multiple IfcProducts, then it is possible to connect with carbon dioxide, electrical conductance, defect fire, light, movement alarm for say a few. The **Port** is defined by **RelConnectsPortToElement**, **DistributionElement**, and **DistributionControlElement. RelConnectPortToElement** is the relationship that defines the link between **Port** and **DistributionElement. DistributionElement** is a generalisation of all elements involved in the BACS. **DistributionControlElement** details the elements in a BACS used to maintain variables such as temperature, humidity or pressure. In this case had been considered a controller to monitor inputs and outputs in a BACS.

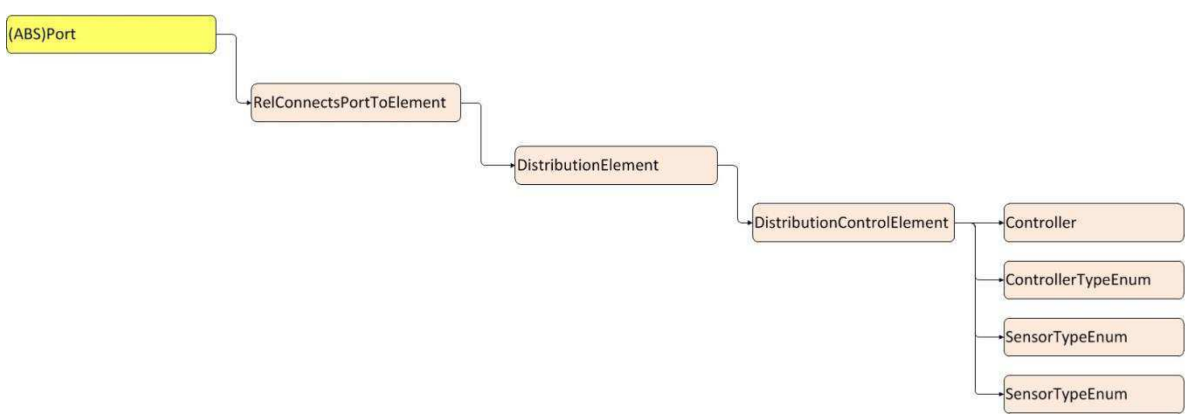

Figure B.11 BACS components

B.4.3 MVD # 12, energy performance of HVAC

This MVD defines how will be dealt the energy performance of the HVAC system in the IFC structure, in fig. B.12 are shown the entities considered:

- **Property:** it is a generalisation for all types of properties that can be associated with IFC objects. This **Property** is defined by **SimpleProperty** and **PropertySingleValue. SimpleProperty** is a generalisation for **PropertySingleValue,** and this last one allows defining a property object with a single value (numeric or descriptive).

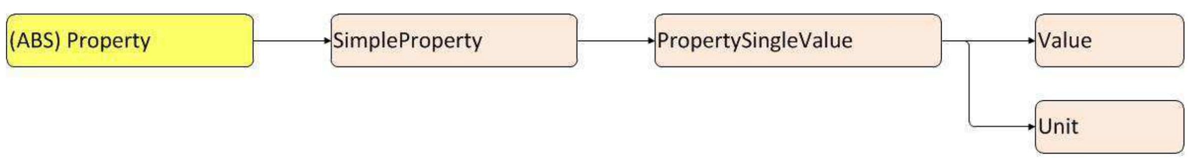

Figure B.12 Energy performance of HVAC

B.5 Concept design, energy matching

B.5.1 MVD # 13, cost estimation of HVAC systems

This MVD deal with the cost estimation of HVAC components, in figure B.13 is a detail of the entities considered:

- **ResourceLevelRelationship:** is an abstract base entity to define the relationship between resources and entities. This entity is defined by ExternalReferenceRelationship and AppliedValue. The first sub-entity enables to objects from ResourceObjectSelect being tagged by external references. While AppliedValue captures a formula result with additional data such as value, data and cost value.

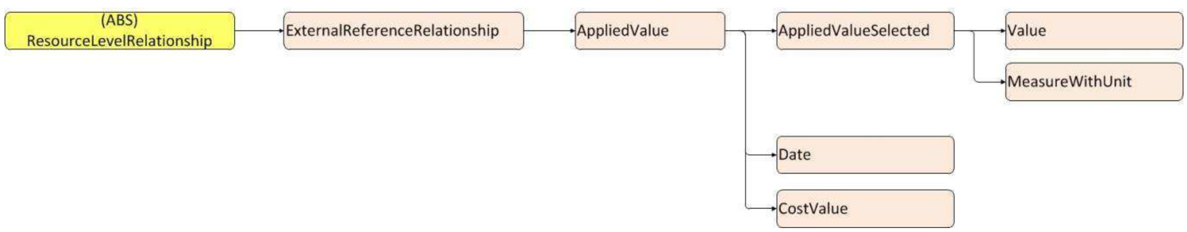

Figure B.13 Cost estimation of HVAC systems

B.5.2 MVD # 14, HVAC equipment for cooling

This MVD describes the cooling equipment considered into HVAC system (fig. B.14):

- **Port**: defines a means to connect HVAC equipment with sensors, allowing to measure and control the different operating conditions of the system. The **Port** is defined by **RelConnectsPortToElement**, **DistributionElement**, and **EnergyConversionDevice. RelConnectPortToElement** is the relationship that defines the link between **Port** and **DistributionElement. DistributionElement** is a generalisation of all cooling equipment considered into HVAC system. **EnergyConsersionDevice** defines the occurrence of devices used in energy conversion or heat transfer such as **CoolingTower** or **Engine**.

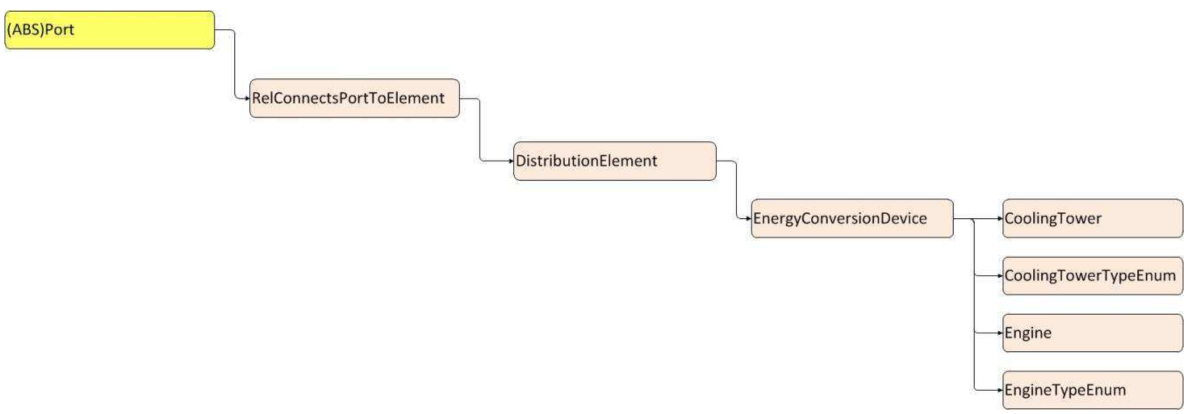

Figure B.14 HVAC cooling equipment

B.5.3 MVD # 15, photovoltaic panels

This MVD describes the elements considered for the photovoltaic panel system (fig. B.15):

- **Port**: defines a means to connect the different items in a photovoltaic system. The **Port** is defined by **RelConnectsPortToElement**, **DistributionElement**, and **EnergyConversionDevice. RelConnectPortToElement** is the relationship that defines the link between **Port** and **DistributionElement. DistributionElement** is a generalisation of all cooling equipment considered into HVAC system. **EnergyConsersionDevice** defines the occurrence of devices used in energy conversion or heat transfer such as **SolarDevice** and **Transformer**.

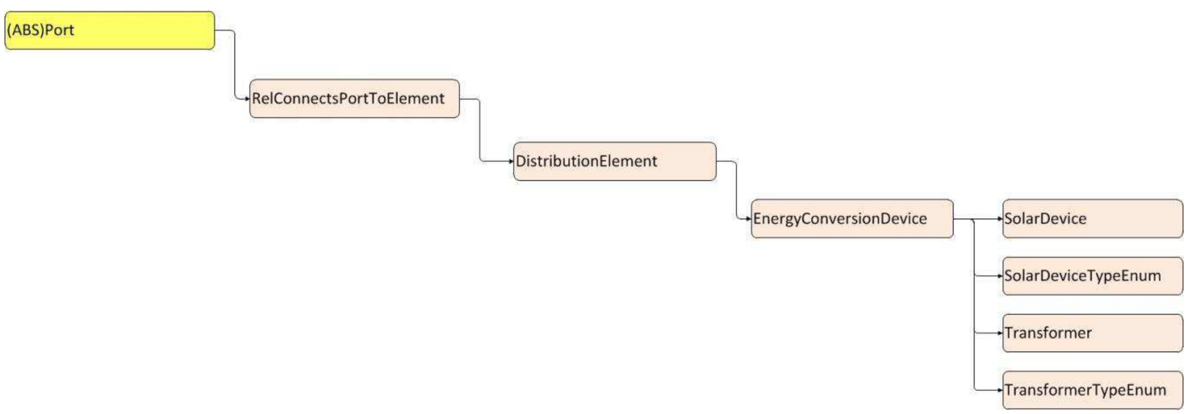

Figure B.15 Photovoltaic panels

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