Interoperability Specification Development for Integrated BIM Use in Performance Based Design

Abstract: Interoperability in BIM is low and the focus is on 3D coordination. Despite the available standards including IFC and IDM, there is still no clear guidance how such standards can be effectively used for performance based design. Thus, early collaboration is discouraged and performance analysis is conducted as late as possible to minimize the number of information exchanges, leading to difficulties and costly changes in design that is almost completed.

Aim is to propose an interoperability specification development approach for performance based design through the Design4Energy case study project. Findings show that the design process had increased flexibility, shared understanding between stakeholders about what information nuggets should be provided from whom to whom, at what stage, using which tool and data model.

It can guide for the integrated BIM practice and help developing BIM execution plans for Level 2 BIM while paving the way for Level 3 BIM.

Keywords: Energy efficiency, performance based design, interoperability, Building Information Modelling, Information Delivery Manual, Model View Definition, Design4Energy

1. Introduction

Digital tools are used in the architecture, engineering and construction (AEC) industry for the last 30 years. Nonetheless, the attention of the industry has been captured strongly in recent years by the irruption of new tools and methods for improving information management over the project lifecycle (Hetherington et al, 2010). The most important of these contemporary trends is Building Information Modelling (BIM), which encapsulates a group of tools, processes and technologies able to manage information for a building, its performance, planning and operation (Eastman et al., 2011; Arayici, 2015).

There is a consensus in the literature about the need to achieve performance based design via Integrated BIM use (Paryudi, (2015; Krygiel & Nies, 2008; Hemsath, 2015; Levy, 2012; Jeong and Kim, 2016). Building Performance Simulation (BPS) for performance based design is an area allowing the architect to create and explore different design alternatives and to select the lower energy consumption alternatives. Unfortunately, the full potential of BPS has not been achieved yet because of a lack of integration that prevents collaborative relationships among team members throughout the project lifecycle (Jeong and Kim, 2016; Wong et al, 2014; Aouad and Arayici, 2010; Deutsch, 2011). This is due to lack of clear guidance or low level of BIM use. Mainly, BIM use in practice is at Level 1 and rarely at Level 2. As consequence of low level of BIM use and lack of integration, designers are only using BPS tools to check energy codes after the design is mostly finished, instead of using it to support early design decisions to improve the energy performance (Eastman et al., 2011; Jeong and Kim, 2016).

Many building performance simulation (BPS) tools to support stakeholders 'decision-making during a building's life cycle have evolved separately from one another. These BPS tools allow design professionals and practitioners to analyse and evaluate their building projects (Arayici, 2015). Traditionally, architects and engineers have found it difficult to effectively use BPS tools because their processes are based on 2D manually-created drawings. This characteristic is necessitated by the lack of integration among the tools and between design models and building energy models ((Jeong and Kim 2016).

Based on literature, the energy simulation tools are not architect friendly and they are too complex for the architects besides the tools are not compatible with architects' working methods and needs (Paryudi, 2015; Jeong and Kim, 2016). This fact causes the limited benefits from the energy simulation tools by architects during early design stage. Not to mention is another fact that architects are novices in the energy simulation field. Therefore, they lack simulation know-how (Paryudi, 2015). This weakness impedes architects from using energy simulation tools regularly, leading to the most architects preferring simple energy simulation tools without collaboration (Jeong and Kim, 2016; Asmi et al, 2015) even though it is critical for performance based design.

The major issue with the implementation of performance based design is how effectively integrate different technologies that exist across multiple domains and provide comprehensive building performance analyses in the design process in a collaborative manner. For instance, the main concern with solar building design is how to integrate different technologies (e.g., building-integrated photovoltaic, solar thermal, and daylighting) into a coherent combination and effectively use those diverse tools and data for building performance analysis during the design phase (Jeong and Kim 2016). Therefore, a holistic and integrated approach to performance based design is needed to efficiently provide energy performance analysis based upon multiple domain simulations with a lifecycle perspective at the early design phase. Such an integrated building performance analysis would require the integration of the multi-domain actors (Jeong and Kim 2016; Arayici, 2015), including client, architect, facility managers and energy experts.

Currently, the design integration is addressed in two ways: the standalone approach and the integrated approach. In the standalone approach (Figure 1a) all the actors are working together on the same platform, while they can still use different software to create their own data that will be readable by the other users that have access to the same platform. However, this approach is not applicable to a whole project because there is not a single platform that is able to support the data created across the whole lifecycle of a project. Thus, it will be necessary to use other tools to add different data (Smith & Tardiff, 2009; Laakso & Kiviniemi, 2012).

On the other hand, the integrated approach (Figure 1b) uses a translator tool to convert the proprietary format into open data readable by any software that supports this standard (Eastman et al., 2011; Elvin, 2007). Using an open standard facilitates the collaborative work allowing any actor to exchange data with any other specialists no matter what the software was in which the data was created (Smith & Tardiff, 2009). The issue of interoperability is present in a lot of areas if collaboration, interaction and data exchange are needed. This is particularly true of the AEC (Architecture, Engineering and Construction) area, where the evolution of the practices and the uptake of the Building Information Modelling (BIM) paradigm have intensified the need for collaboration between different stakeholders across many disciplines throughout the entire building life-cycle (Asmi et al 2015; Jeong and Kim, 2016).

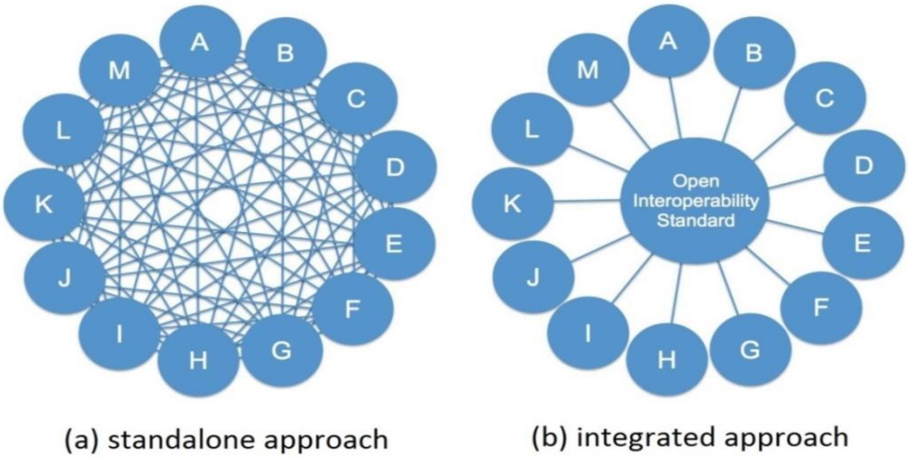


Figure 1: Information exchange view (Laakso & Kiviniemi, 2012)

The integration via open standards is critical in providing the information exchange throughout the AEC/FM project lifecycle; nonetheless the open standards need to be improved to ensure a correct data exchange no matter what tool is used to produce or read the data (Kymell, 2008). Currently, the integration for BIM models is addressed using two formats: Industry Foundation Classes (IFC) and green building XML (gbXML). The IFC format is a schema widely accepted by the AEC industry to exchange BIM models. It uses four layers (resources, core, interoperability and domain) to describe the geometry information, the material properties and the relationships in a BIM model (Smith & Tardiff, 2009). The gbXML schema facilitates the exchange of data between BIM and BPS tools (Jeong and Kim, 2016).

Despite both formats being used by the AEC industry, its adoption does not ensure a data exchange free of problems. The IFC schema does not capture the ways how information is created and shared by practitioners (Weise et al., 2009; Asmi et al 2015). In other words, what specific information at what granularity should be included in the exchange cannot be automatically invoked by the IFC schema unless there is a clear procedure and shared understanding amongst the actors about what information nuggets should be encapsulated in the IFC schema. Otherwise, some specific information will be missed in the exchange process (Juan & Zheng, 2014; Weise et al., 2009). On the other hand, the gbXML format is not mature enough and has been limited to being used in simple design solutions because of its inability to read complex geometries (Bahar et al., 2013).

Thus, the emergence of standard BIM data formats does not, however, brings a definitive solution to the interoperability issue (Asmi et al 2015) without a clear guidance or specification of information sharing for the Integrated BIM use for performance based design. Therefore, this paper provides a practical approach for how interoperability can be formulated for performance based design in a collaborative nature using the IDM and MVD protocols in the Design4Energy project case study where an interoperability specification is developed and executed for the Integrated BIM practice for performance based design.

2. The Design4Energy Project

The Design4Energy (D4E) research project, funded by the European Union (EU) under the 7th Framework Programme (FP7), aimed to develop an innovative and integrated design methodology to predict the current and future energy demand of buildings (both at the individual and neighbourhood level). Predicting energy consumption would allow operators to manage demand to off-peak times, to reduce the energy costs, to minimise outage frequency and duration and to simplify the interfacing of renewable energy sources with the system decreasing the carbon liabilities (Azhar et al, 2011).

The design methodology proposed by the D4E project asks for early collaboration, integrated processes and stakeholders with the objective of supporting informed decisions to optimise the energy performance at building life cycle level including operation and maintenance. A key point in the success of the project is the monitoring of the carbon dioxide emissions (CO_2) of buildings to ensure that the design criteria are met in practice and to collect data that enable the better decisions making (Motawa & Carter, 2013). Therefore, it is necessary to describe the information exchange that will allow a smooth information flow between applications.

What are observed and experienced in the Design4Energy project have also confirmed what is reviewed and said in the literature. There were architects from Spain, UK and Germany and energy experts and engineers from Finland and Portugal. There was no coherent understanding between them about how BIM based collaborative design can be possible and information sharing and exchange can be executed using available standards such as IFC for performance based design development and beyond. Simply architects can do BIM modelling but they had no understanding of what information and when they should share any relevant information with the client and energy experts. This was indicating that there was a need to develop an interoperability specification that would coherently picture the collaborative design process to be executed amongst themselves. Furthermore, similar confusion and lack of understanding amongst the technical team even though they were all expert in BIM and offered various BIM tools developments for data modelling and filtering, interoperability execution for the integrated BIM practice. Therefore, it was needed to develop an interoperability specification that would pull all the patches together into a coherent picture by addressing human, process, technology and data aspects for the Integrated BIM practice. Figure 2 shows the scope of the interoperability specification required in the project.

It defines the interoperation between the various systems such as the IFC-based BIM components library, the BIM information filtering system, the BIM authoring tools, the performance simulation tools, the decision support tools for early design and retrofit planning and the Collaborative Virtual Design Workspace running across the cross-organizational integrated building lifecycle processes.

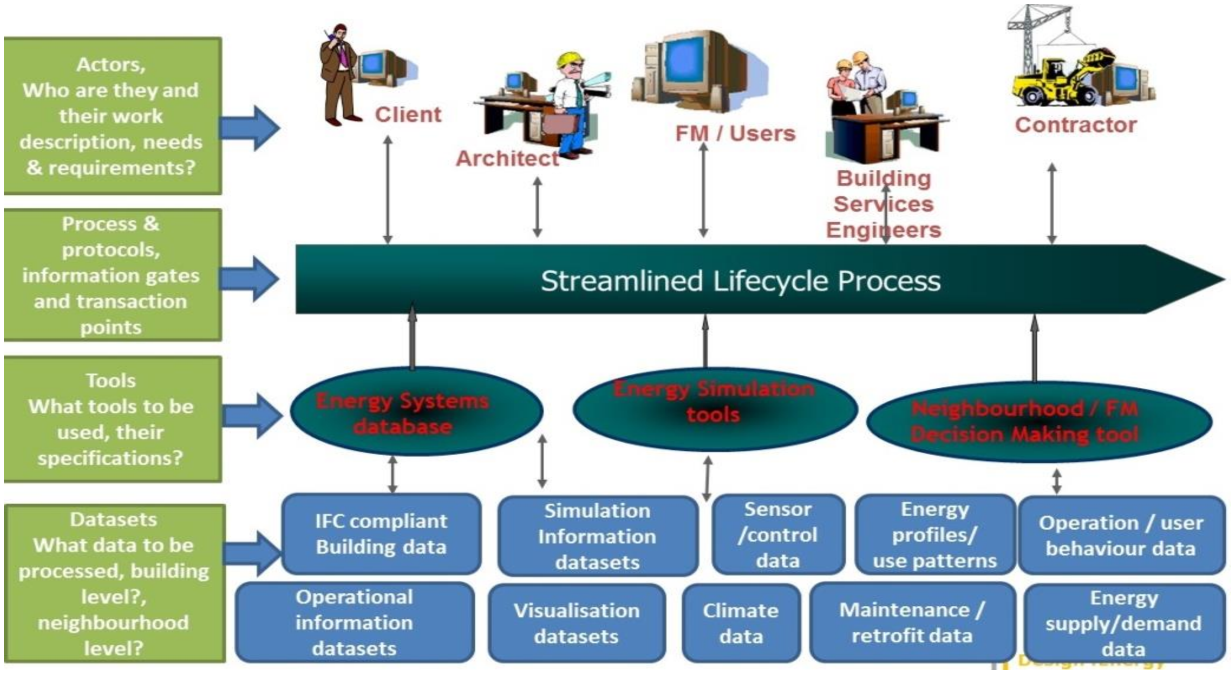


Figure 2: Interoperability vision for the Design4Energy Collaborative Workspace

The interoperability specification should clearly describe how the user requirements and needs, tasks and activities for the performance based design can be coherently dealt with by the various stakeholders using different BIM tools and technologies. The next section explains the research methodology for the development of the interoperability specification

3. Research Methodology

This paper aims at developing an interoperability specification to promote early collaboration in looking at energy simulations in addition to predicting current and future energy demand and the impact of such demands upon carbon emissions. Because such an approach does not exist in the literature (Motawa & Carter, 2013; Paryudi, 2015), the research methodology needs to support the development of new knowledge in the area where the existing theory is insufficient. Thus, this paper adopts the Design Science Research (DSR) methodology, which facilitates the spread of new ideas through the use of models, methods, constructs, instantiations and theories (Hevner and Chatterjee, 2010), social innovations, new or previously unknown properties of technical/social/informational resources, new explanatory theories, new design and development models and implementation processes or methods (Ellis & Levy, 2009). The DSR methodology uses the cycles below to create new knowledge (Figure 3):

- **Relevance cycle**: this first cycle explains the application domain, in which the research will take place. Defining the application domain will need the identification of the research requirements such as the problem/opportunity to be addressed, the people involved and the organisational and technical systems that interact towards achieving the goal. The research requirements allow for building a specification or model to address the organisational problem. This specification will be tested and the result will indicate whether additional iteration of the relevance cycle is needed (Peffers et al, 2012).

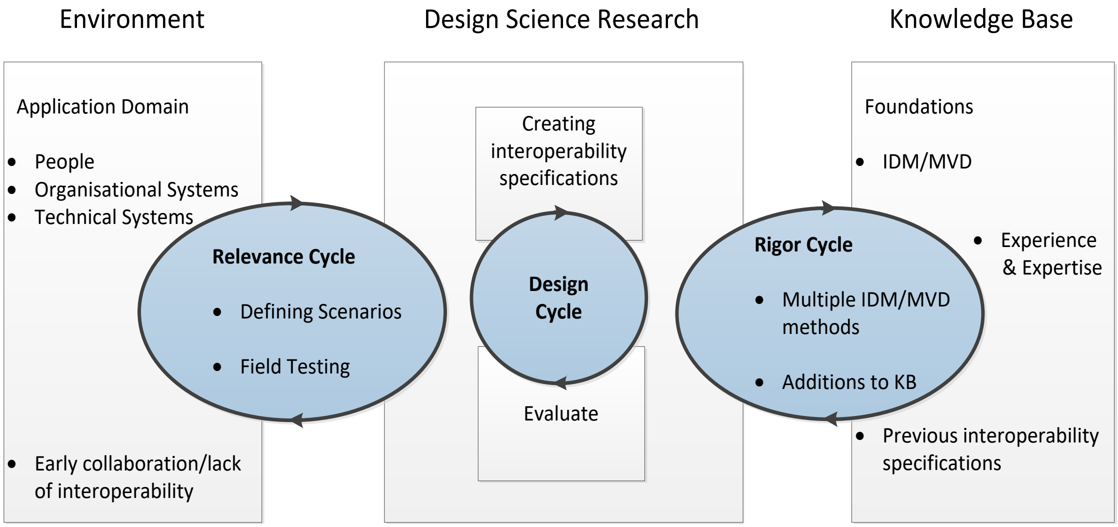


Figure 3: DSR oriented research methodology of the paper

- **Rigor cycle:** This cycle will create the foundations, in which the research will be based, ensuring that the research contains new knowledge and that it is not routine design based in a well-known process. The knowledge base will take elements from scientific theories, methods and previous experiences (Peffers et al, 2012).
- **Design cycle**: In this cycle, most of the DSR is undertaken. The research artefacts coming from the relevance cycle are built and evaluated. Based on the results from this cycle, it will be possible to modify the specification until achieving the requirements set in the relevance cycle. Knowledge gained in this cycle will be added in the rigor cycle to improve the foundations of the research (Peffers et al, 2012).

In this research, the relevance cycle will capture a sequence of expert activities. These data are described by the application domain (Figure 3) identifying people (who), organisational systems (how) and technical systems (what), which are involved in the problem. Understanding the context of the research will deliver a better grasp of the interoperability challenges and problems in different the design scenarios. On the other hand, the knowledge base will be built on IDM/MVD. The knowledge generated is used to develop the interoperability specification for the design scenarios from the application domain. Evaluation of completeness and efficacy of the interoperability specification is demonstrated via phases from the parent processes (Figure 4).

3.1. Relevance cycle (Application domain)

Figure 2 introduced the interoperability scope envisioned for the Design4Energy research project. Based on that, it is possible to state that the specification to be developed must show the user requirements, tasks and activities through the different life cycle stages and must also show the relationship between the different stakeholders and tools. To understand the relationship of the multiple elements throughout the lifecycle, it is required to develop an integrated process that provides a coherent picture of performance based design practice. The process will need to define hierarchic levels to divide the entire process into small sections and facilitate the interoperability development as shown in Figure 4 (Wix et al, 2009; Eastman et al, 2010).

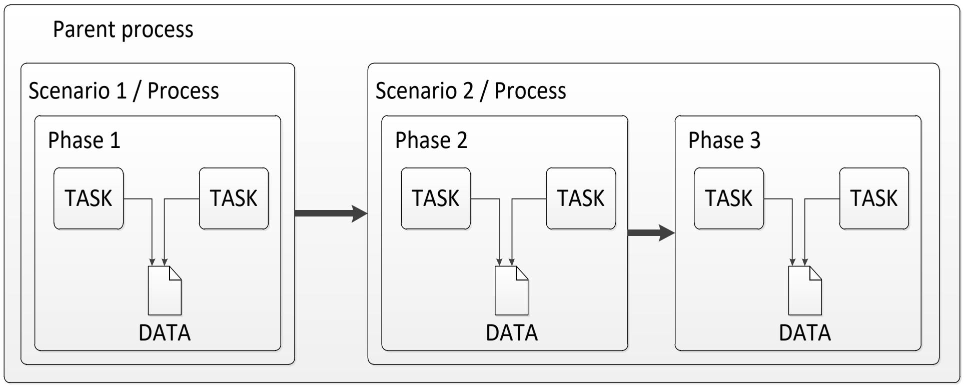


Figure 4: Hierarchy levels for cross-organisational business processes

- **Parent process**: a process that contains sub processes within its boundaries.
- **Scenario/process**: a sequence of activities in an organisation with the objective of carrying out work.
- **Phase or Stage**: a period in the duration of a project identified by the overall character of the tasks which occur within it.
- **Task:** an atomic activity that is included within a process.
- **Data**: a mechanism to show how data is required or produced by tasks.

Based on the scope of the interoperability (Figure 2) and the hierarchy levels (Figure 4), three scenarios were developed in the Design4Energy project to comprise user activities, user requirements and the functional requirements of the key stakeholders such as the client, the architect, the energy expert and the HVAC designer. These scenarios are:

- **Scenario 1**: **district energy trading context in building design**: This scenario illustrates how an energy efficient building or a group of buildings and its neighbourhood can be analysed and holistically optimised throughout the whole life cycle. This is performed by using an appropriate supportive technology platform during the design phase and the adaptation of new business models to overcome current limitations.
- **Scenario 2**: **holistic design for energy optimisation**: Focusing on a new build, the scenario illustrates how advanced simulation tools and modelling techniques can improve current practice at an early design phase. Through this scenario, multi-disciplinary design teams can explore various energy design solutions collectively and individually in an interactive virtual workspace to achieve optimum energy efficiency at a building level.
- **Scenario 3**: **use of operational and maintenance data in retrofit**: This scenario illustrates how members of the design team can simulate and evaluate design retrofit alternatives based on historical, monitored and structured data to make better design decisions.

Each of the scenarios corresponds various phases of the building life cycle (Figure 5):

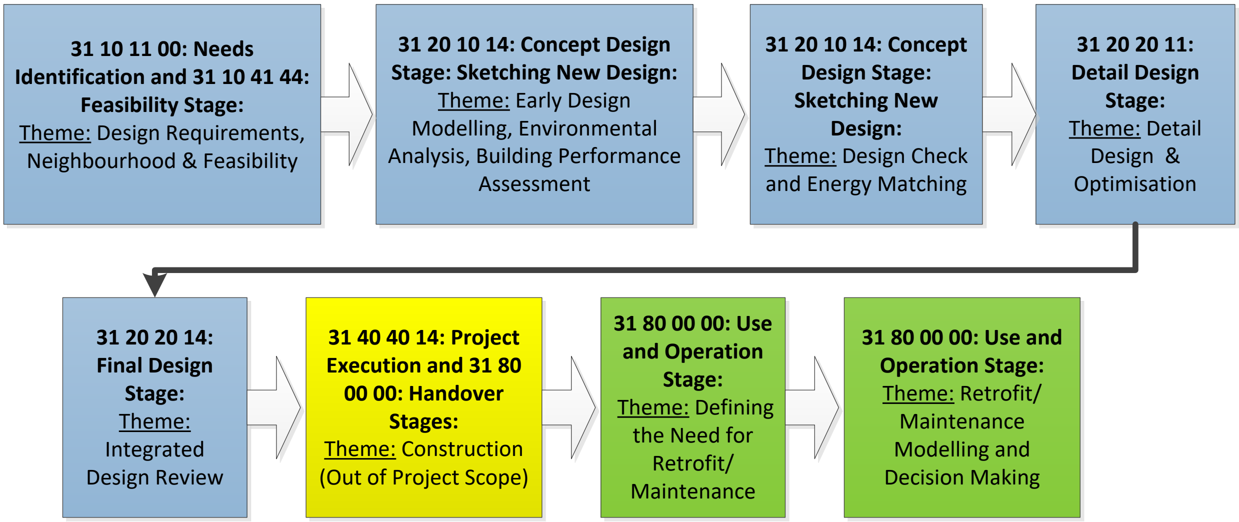


Figure 5: Integrated Building Lifecycle Processes with scenarios and Omniclass classification

- **Scenario 1:** contains the needs' identification and feasibility phases. During these phases, the design requirements, neighbourhood and feasibility studies are developed.

- **Scenario 2:** includes the concept design, the detailed design and the final design phases. The concept design phase develops early design modelling, an environmental analysis, a building performance assessment, a design check and energy matching. The detailed design phase will optimise the design. The final design phase will integrate the design for a review.

  The construction execution phase is outside the current project's scope.

- **Scenario 3:** considers the BIM handover and facility management (operation) phase, including defining the needs for retrofit or maintenance, retrofit modelling, environmental analysis, building performance assessment, retrofit check and energy matching for maintenance.

In the research, the interoperability specification is developed for the whole building life cycle process encapsulating these three scenarios. However, in this paper, the interoperability specification development for scenario 2 is explained as it is succinct enough to demonstrate how the interoperability specification is developed including soft and hard aspects shown in Figure 2.

3.2. Rigor cycle (Knowledge Base: Information Delivery Manual (IDM) & Model View Definition (MVD))

The industry has addressed the interoperability issue utilising multiple initiatives. A glance at the literature might be confusing because of the number of organisations that have, over recent years, developed standards in this field (Smith and Tardiff, 2009; Pinheiro et al 2015). For example, two BuildingSmart initiatives to tackle interoperability issues are Information Delivery Manual (Eastman et al, 2010; Asmi et al, 2015) and IFC Model View Definition (Muhic and Krammer, 2015). The objective of both methods is to develop interoperability, yet from a different point of view; while IDM defines interoperability at user level capturing processes and exchange requirements (Pinheiro et al, 2015; Eastman et al, 2010), MVD sets interoperability at a technical level defining specific IFC configurations (Asmi et al, 2015).

Both IDM and MVD methods have been amalgamated into a combined one and called "*An integrated process for delivering IFC based data exchange*" by BuildingSmart. It starts with the user requirements' capture for exchanges using the IDM methodology. It is then translated into technical schema such as the IFC schema via the MVD method. However, this procedure brings problems relating to the blurred boundaries between IDM and MVD in assigning the users the responsibility for developing a technical solution such as exchange requirement models. In other words, the lack of requirement rationalization can lead to the incurrence of similar exchange models, which need to be reduced to avoid the number of repetitiveness in MVD modelling. For example, a BIM model improves progressively throughout the design process phases, in which the same information exchange model can be shared more than once even if the values would be different in each exchange. Therefore, it is critical to identify the repetitive exchanges of the same BIM model information in the development of the MVD based technical schema. This would help to:

- make information exchanges between project participants more reliable.
- improve information quality.
- improve decision making.
- undertake a BIM project far more effectively.

The steps in the IDM method for the interoperability specification development include process modelling, information exchange and functional parts. Both IDM and MVD are explained in the following sections on the Early Design Modelling, Environmental Analysis, Building Performance Assessment themes in the *DesignCheck&EnergyMatching* Process Phase in Figure 5.

3.2.1. Information Delivery Model (IDM)

IDM (ISO, 2016) proposes a systemic method to capture (and progressively integrate) business processes whilst, at the same time, providing detailed user defined specifications of the information that needs to be exchanged at particular points within a project. A set of reusable modular functions that handle the basic information ideas in AEC/FM are used to assist the development of further user defined information exchange specifications.

Process Modelling: This is the initial step to describe the flow of activities within the boundary of a particular topic and the roles played by the actors involved, together with the information required for those activities. A process map sets the boundary for the extent of the information contained within the process, establishes the activities within the process, and shows the logical sequence of the activities and administrative information about the exchange requirements (Weise et al., 2009). *Business Process Modelling Notation* (BPMN) is used for the process modelling and mapping the flow-oriented representations of business processes (Quyang et al., 2009). It helped to identify the Exchange Models (EMs) in the Design4Energy project and provided a base to identify the content of each information exchange package.

Information Exchange Requirements: Based on the process modelling, a set of information exchange requirements are defined for the interoperations throughout the process. Exchange Models (EMs) are utilized to provide the purpose of the exchange, content of information exchanges between users and/or software applications. As shown in table 1, a standard template is used for all the information exchanges in the specification for the three scenarios.

Functional Parts: It is necessary to identify the information categories and sub-categories until a sufficient level of granularity is achieved so that information can be referred to as an individual attribute or a function or action within an information category. At this low level, these information items or nuggets are called functional parts as shown in figure 6. Each functional part provides a detailed technical specification of the information that should be exchanged in an action. Since that action may occur within many exchange requirements, a functional part can be bound to one or many exchange requirements. Therefore, they should be specifically defined to be reusable within several exchange models.

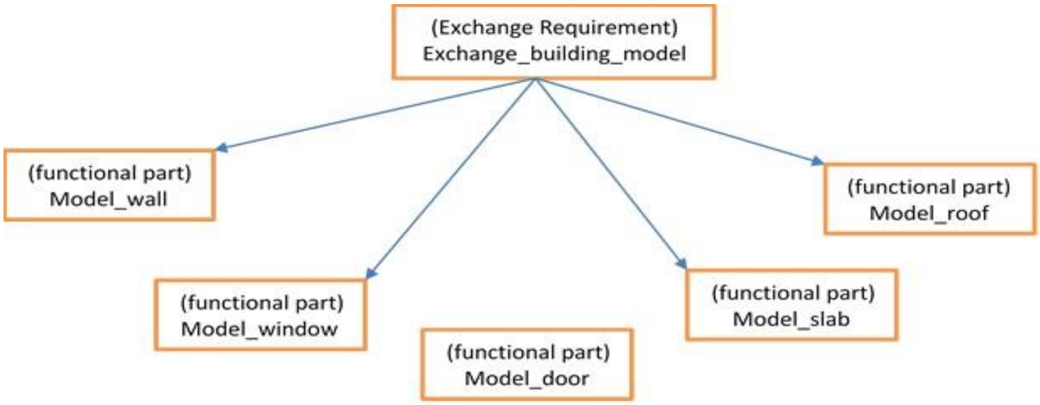


Figure 6: Functional parts in an exchanged requirement

3.2.2. Model View Definition (MVD)

A Model View Definition (MVD) sets the interoperability at software level translating IDM outputs in a readable language schema such as IFC (Asmi et al, 2015) as shown in Figure 7.

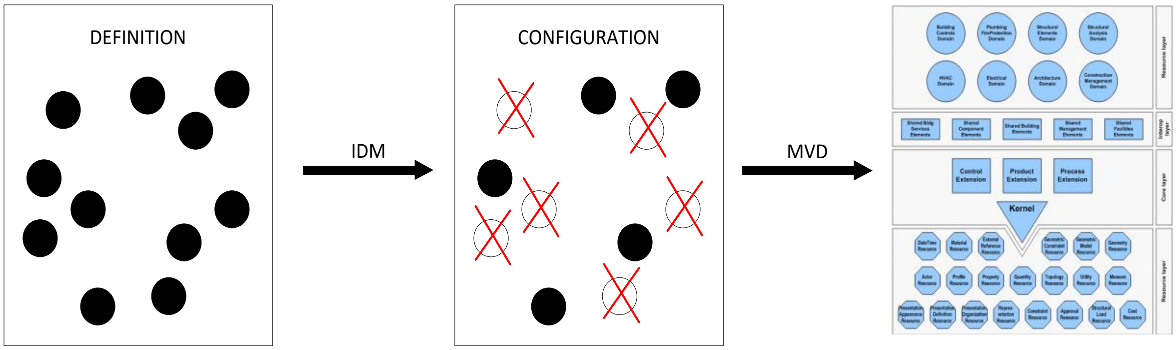
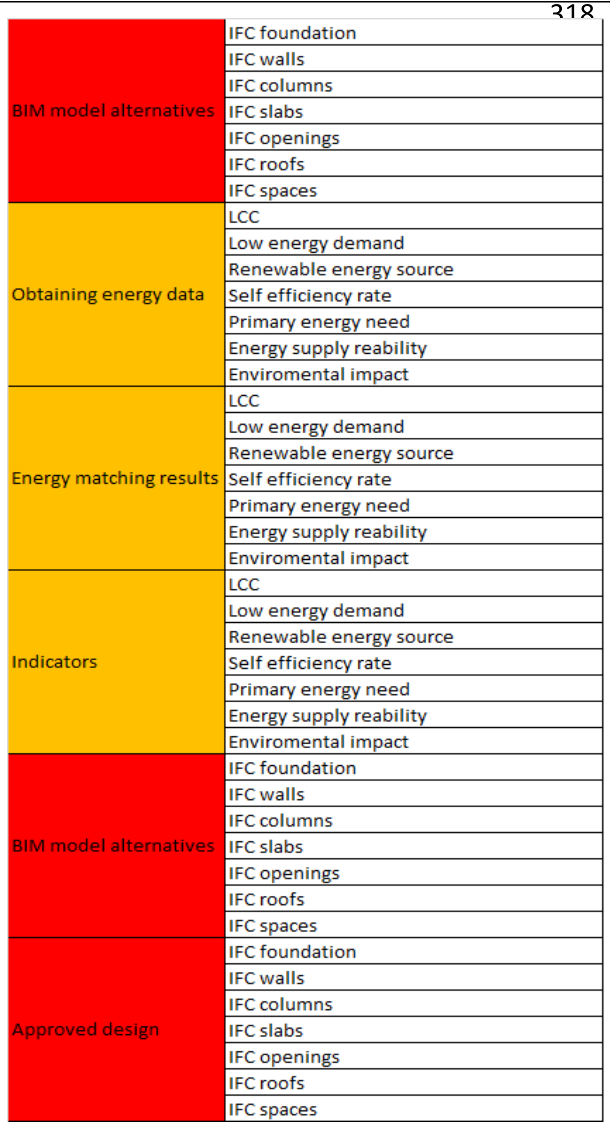


Figure 7: IDM and MVD processes

The IDM outputs, such as BPMN process modelling, Exchange Requirements and Functional Parts, will help developers to understand the interoperability required by the users between BIM applications (Berard and Karlshoej, 2011; Belsky et al, 2014). With this data as a guideline, the developer will set the interoperability from a technical point of view. Thus, each of the exchange elements are translated into a readable language schemasuch as IFC.

The first step to develop an MVD will be the rationalization of the functional parts to decrease the number of MVDs to develop and to avoid duplicity. Figure 8 summarises the outputs or functional parts developed for scenario 2 (Figure 5); the left-hand column groups the exchange requirements (ER) while the details for each of them is shown in the right-hand column.



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 8. Summary of output from design check and energy matching in scenario 2

A review through the left-hand column identifies that the functional parts are the same structure and parameters even if they belong to different ERs taking place at different times. For example, the ER highlighted in red (*BIM model alternatives and approved design*) contains the same parameters and the ERs highlighted in orange (*obtaining energy data, energy matching results and indicators*) can have the same parameters even if the information nuggets or values assigned to these parameters are different in the various ERs.

Thus, there is no need to develop repetitive or duplicate MVDs for different ERs that can have the same structural parameters. As a result, it is possible to identify equal data and to reduce the number of MVD development. In the case of scenario 2, depicted in Figure 5, the rationalization of the functional parts allowed reducing the number of MVDs to be developed from six to two.

Implementation of the data exchange requires adopting a data schema such as IFC or XML to describe and store each functional part (Figure 8) in a database readable for any tool that supports the schema (Murata et al., 2005). BuildingSMART suggests using XML as the exchange protocol. This format has been widely used as a standard for data exchange given its ability to manage small amount of data and to facilitate the exchange over the web

(Combi & Pozzi, 2005; Eastman et al., 2011). However, this schema is not adequate because it is not able to describe the relationship between elements in the schema. Thus, the geometries dealt by this schema are very simple (Abanda et al., 2013). Although BuildingSMART developed a property called MVD-XML, they recognize the weakness of the format to include data from IFC file (Paryudi, 2015; Pinherio et al, 2015). As a result, the format proposed by BuildingSMART fails to translate the 3D geometry from BIM models. Because of this drawback regarding the XML schema, this research will use the IFC schema for the interoperability.

3.3. Design cycle (Interoperability Specification Development in Design4Energy)

The interoperability specification prescribed for the performance based building design, which incorporates the BIM tools and technologies used by the stakeholders through engaging with the data models. These are elaborated below.

3.3.1. Process modelling

The purpose of the process map is to describe the flow of activities in scenario 2, the roles played by each actor involved and the information used or created by each of them. Figure 13 shows the main components of the process model for the *Concept Design Phase: Sketching a New Design Within a Neighbourhood Context: Design Check & Energy Matching*, which is the third stage/phase in Figure 5 and part of scenario 2. The process models are produced for each stage of the building lifecycle process in Figure 5.

The process model uses rows to categorize activities with different functional capabilities. The rows identify the actors involved in the exchange while the columns show project phases. In the cells of the rows, it is possible to represent activities as white rectangles and the data to be exchanged is shown as corner folded blocks (Eastman et al., 2011).

The process model illustrated in Figure 9 is one of the nine process models indicated in Figure 5 and focuses on matching the design alternatives with the district energy requirements. The proposed workflow starts with the client reviewing the energy options for each alternative produced in the previous Early Design Sketching phase. From these design options, the client and architect will choose few options in a collaborative manner.

The selected options will be available for the energy expert, who will add energy data such as energy price, energy potential maps and energy production components to match the design proposed for the district. The results of this analysis will be passed to the architect via the Design4Energy virtual collaborative workspace. These results will help to make some corrections and improvements in the design alternatives. Finally, the design alternatives are shared with the client, who will select an alternative through a comparative review of the alternatives with indicators.

Yellow boxes in the process model in Figure 9 indicate what tools are used for which activity in the process. This was requested by the users, mainly architects in the project. The main tools used in this process are coded as Tool 1: Target Assessment Tool, Tool 5: Energy Performance Simulation Tool, Tool 6: Collaborative Workspace and Energy Match Optimizer Tool.

The process model helps in showing the functional requirements and describes how the information exchange should work between the client, architect and the energy expert for the energy matching theme at the neighbourhood level in the *DesignCheck&EnergyMatching* phase of the building lifecycle process is shown and it reflects which exchange should take place between which stakeholders conducting consecutive activities. The key activities in this process are explained below.

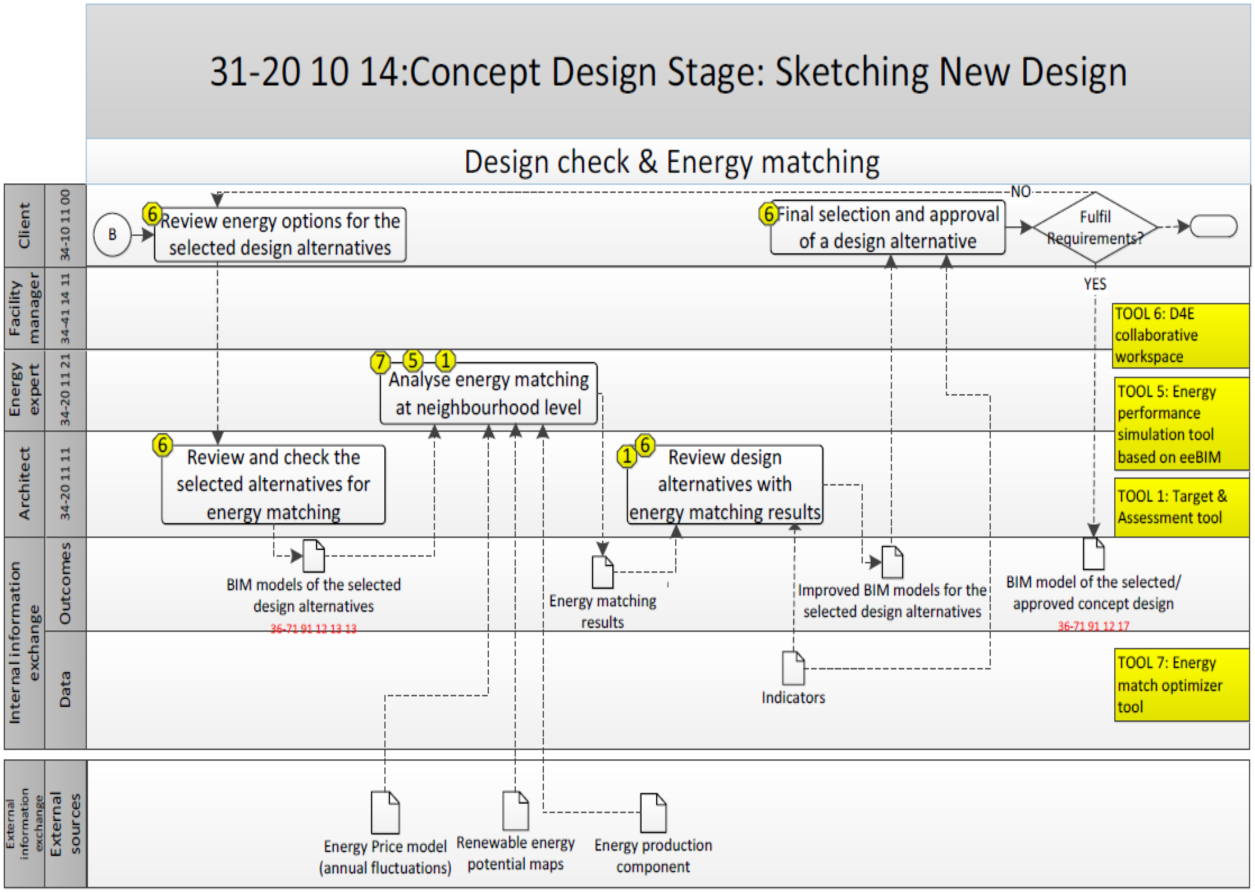


Figure 9: Process map of design check & energy matching in scenario 2

- **Review energy options for the selected design alternatives:** client receives the design alternatives and energy performance simulation results from the energy expert to choose the most suitable proposals for economic and aesthetic needs.
- **Review and check the selected alternatives for energy matching:** design alternatives chosen previously will be checked by the architect and then these models will be analysed for energy matching through the virtual collaborative workspace.
- **Analyse energy matching at the district level:** the energy expert runs a new analysis to determine how the proposed design should be fitted into the district energy requirements.

- **Review design alternatives with energy matching results:** the architect obtains the results from the energy matching analysis and applies some changes to optimize the proposed design.
- **Final selection and approval of a design alternative:** the client will analyse the BIM models being developed to select the most appropriate option for economic, functional, energy efficient and aesthetic needs. The selected alternative is shared via the virtual collaborative workspace.

Main actors at this *DesignCheck&EnergyMatching* phase are the Client from Manchester, Energy Expert from Helsinki and the Architect from Dresden. Following the scenario development and process modelling studies in the project, there were clear understanding and agreement between them for how they should interact and share information amongst them. This then helped further granulation for the interoperability specification. Similar process modelling is also carried out for the other stages of the cross-organisational processes shown in Figure 5.

3.3.2. Information Exchange Requirements

The next step is to specify the information exchange and its content with the Information Exchange Requirements template that represent the link between process and data. It contains the relevant data to ensure the correct exchange of data between two actors and their corresponding tasks in the integrated process (Berard and Karlshoej, 2011; Belsky et al, 2014). Table 1 shows the BIM model exchange between architect and energy expert that is one of many exchanges in Figure 9.

Project Phase	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 architect to energy expert. • Content of exchange: BIM models of design alternatives (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 and Energy performance simulation tool • Possible format for data exchange: IFC • One-way exchange
Related Exchange Models	• Energy price model • Renewable energy potential maps • Energy production components

Table 1: Information Exchange Template for sharing BIM models for design alternatives

The information exchange template encapsulates the information nugget to be exchanged between the architect and the energy expert in this instance and the business process phase is highlighted in the header section while the overview section gives the aim and content of the exchange requirement explained in the user requirements. In this instance, the aim of the exchange is to pass the BIM models of design alternatives from the architect to the energy expert (which should encapsulate building components such as IFC Foundation, IFC walls, IFC columns, IFC slabs, IFC openings (internal/external), IFC roof and IFC space). This exchange would take place from a BIM authoring tool used by the architect to the energy performance simulation tool used by the energy expert. Finally, related exchange models are the preceding and succeeding exchanges, which would set the expectation for the correct wrap of information in the exchanges.

3.3.3. Functional parts

The functional part focuses on detailing the information encapsulated in an information model to be exchanged. Each exchange requirement provides a series of functional part to be exchanged as a result of an activity. Since that activity may be part of many exchange requirements, a functional part can be bound to one or many exchange requirements. The granularity in this case is defined by practical reasons, the BIM model alternatives (Figure 10) could be represented in a very coarse functional part e.g. by floor or area, but in doing so will lead to develop MVDs that contains a large amount of non-reusable data. On the other hand, a fine granularity will lead to disintegrate the BIM model alternatives from its components e.g. IFC foundation, walls or columns could be divided in even small data such as materials, cost, manpower and so on.

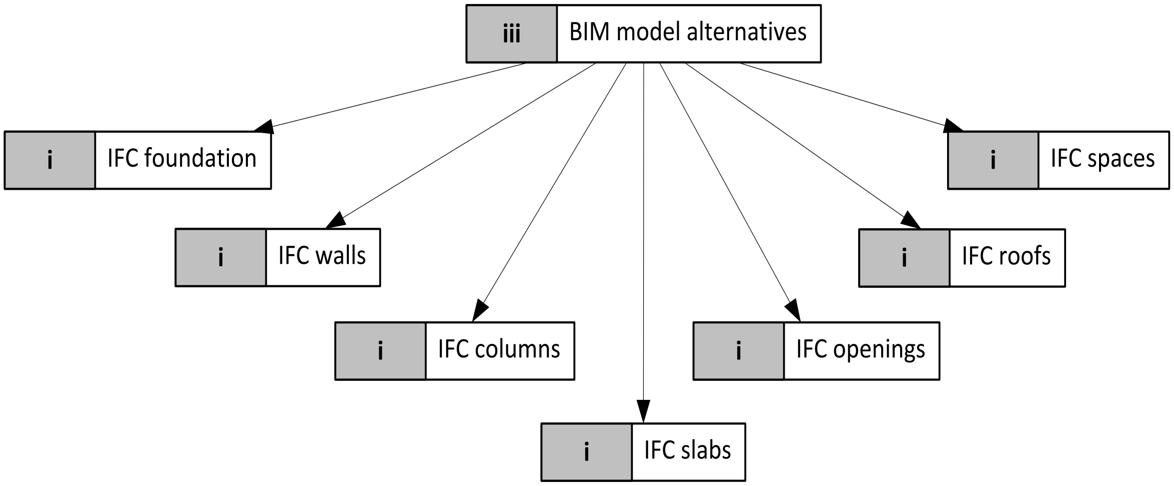


Figure 10: Functional parts for the exchange requirement in table 1

Each exchange requirement in functional parts is considered sufficient such as constructive elements (foundation, walls etc) and allowing to re-use the data in an MVD into another.

3.3.4. MVD examples

Having discussed the procedure to develop interoperability via IDM/MVD, this section will introduce instances for Model View Definition in Design4Energy. Those instances are walls, U-value and HVAC system components chosen because their relationship in energy simulation.

The MVD schema shown in Figure 11 represents a generic wall for various parameter definitions in the technical schema.

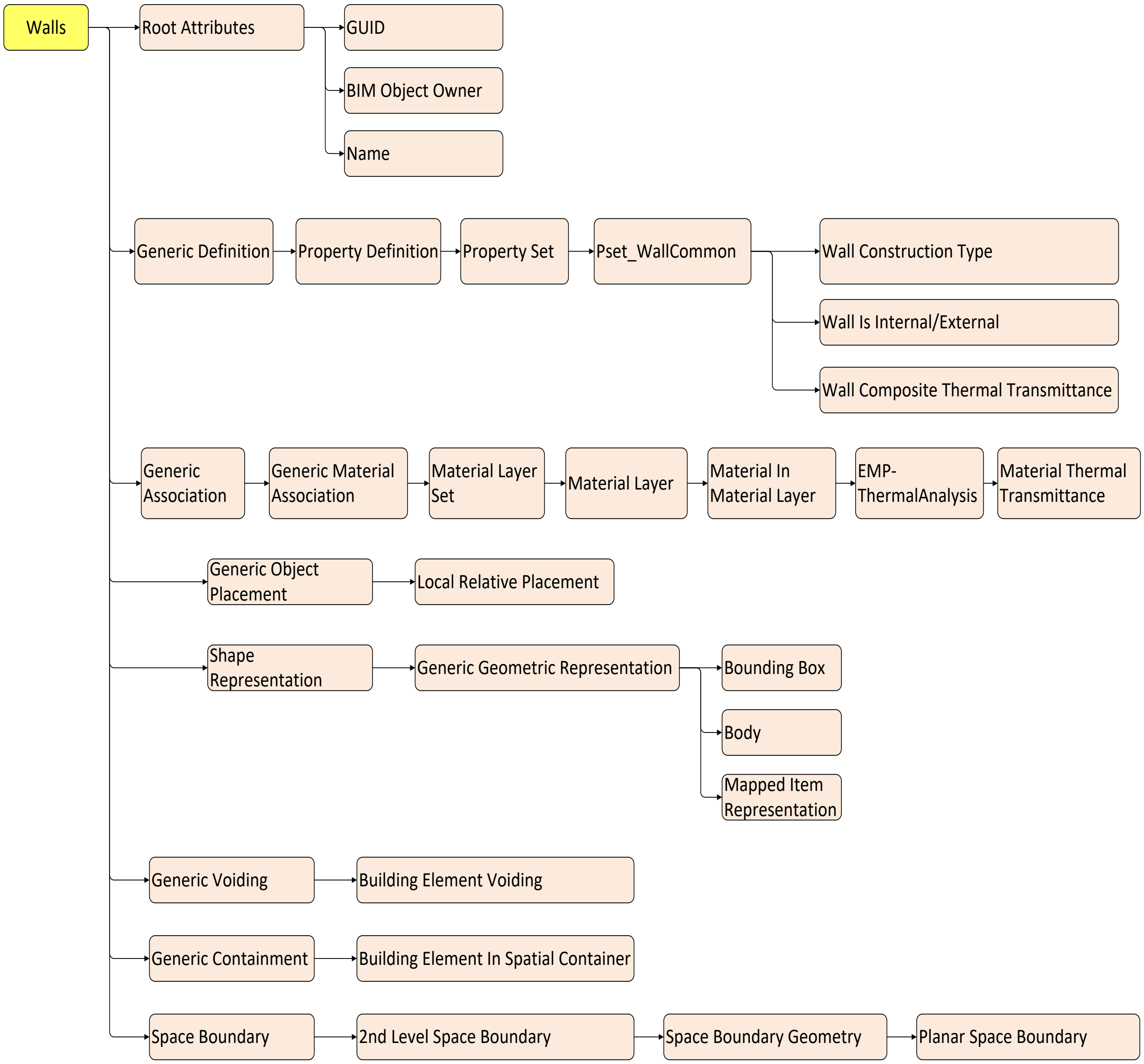


Figure 11: MVD for generic IFC Wall

- **The root attributes** define a singular element using a Globally Unique Identifier (GUID), a specific name and identifies the element creator.
- **The generic definition** is used to generate a property set for a generic wall. The properties to be included are wall type, internal or external and thermal transmittance.
- **The generic association** is related to the material definition for the wall object that contains a number of layers, e.g. a cavity wall with brick masonry and an air gap.
- **The generic object placement** defines the position of a generic wall to the other elements.

- **The shape representation** details the geometry used for a generic wall being able to set three alternatives: bounding box or simplistic 3D representation; 3D body such as wireframe, surface or solid; mapped item representation.
- **The generic voiding** defines the relationship between building elements and their openings.
- **The generic containment** connects walls with the spatial container where they are placed.
- **The space boundary** is a closed shell limited by planar walls; this space boundary describes the materials contained in the boundary walls.

The U-Value is described in Figure 12 for the following entities:

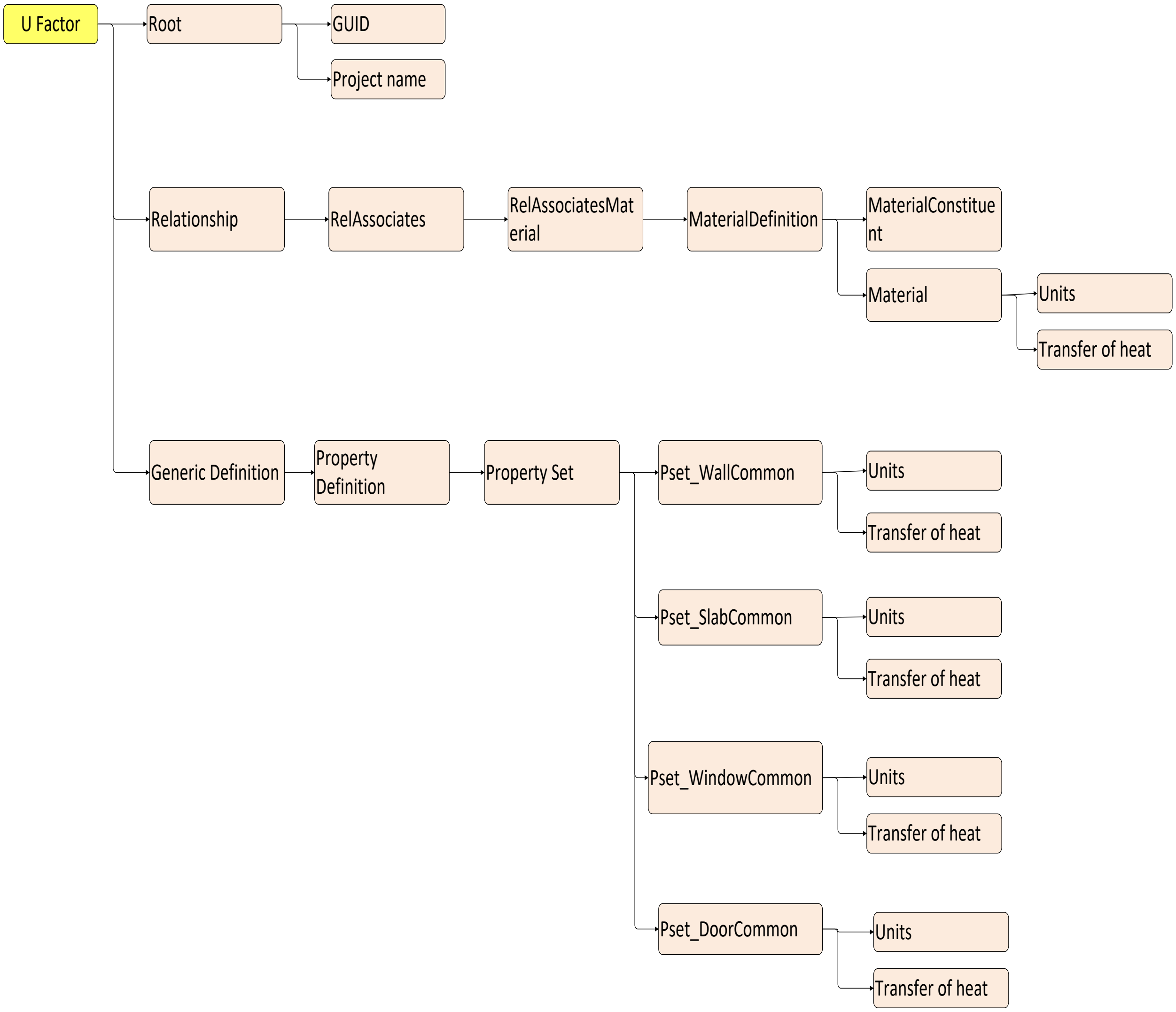


Figure 12: MVD for IFC U-value

- **The root attributes**: define a singular element using a Globally Unique Identifier (GUID) and a specific name.
- **Relationships:** allow for defining the thermal properties for a generic material describing the relationship between a material and an element. To do so, the following sub-entities are used: **RelAssociates** to access internal or external data (library, document, approval, constraints, or

material); **RelAssociatesMaterial** to define a relationship between materials and elements; **MaterialDefinition** to define any material according to its layer, profile or constituents; **Material** defines the units and transfer heat of the material to be used.

- **The generic definition:** 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 generalize multiple properties contained in Pset_WallCommon, Pset_SlabCommon, Pset_WindowsCommon, Pset_WindowsCommon

Figure 13 illustrates the required entities to define a HVAC system:

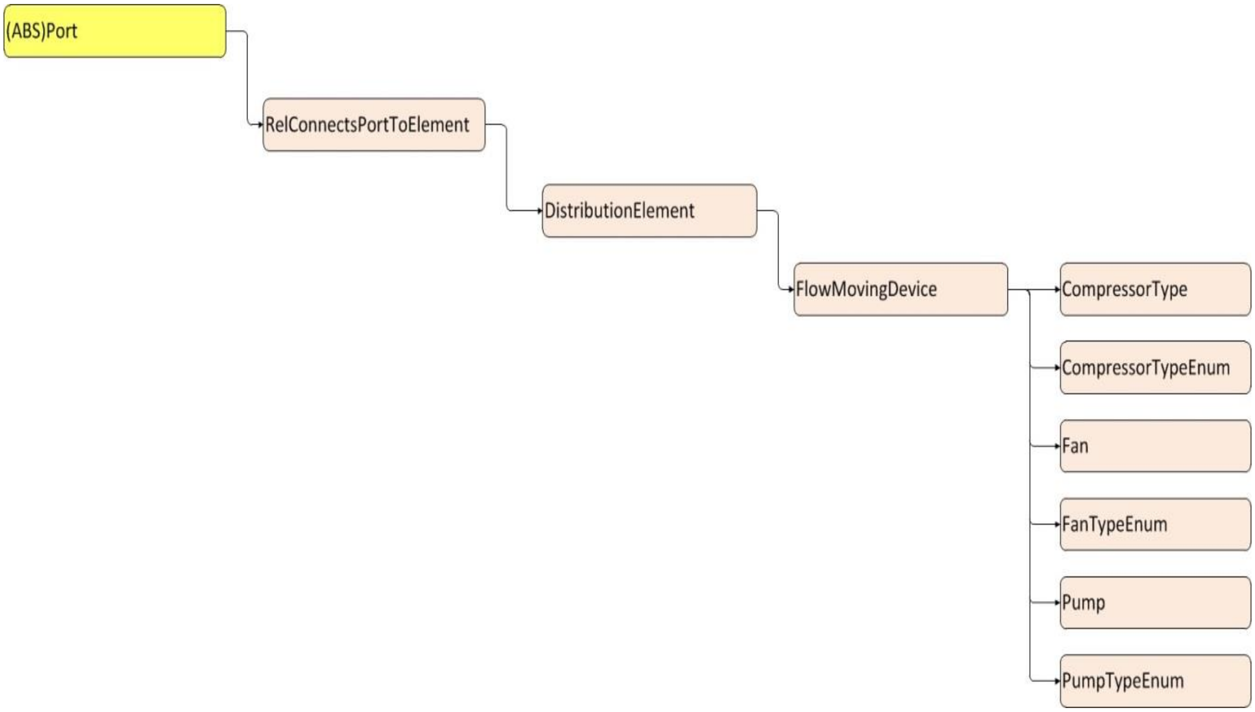


Figure 13: MVD for IFC HVAC system

Port: defines a means to connect each element (sensors, equipment or components) in a HVAC system. This Port is defined by **RelConnectsPortToElement, DistributionElement** and **FlowMovingDevice. RelConnectPortToElement** is the relationship that defines the link between **the Port and DistributionElement**. DistributionElement is a generalization 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 the conveyance of fluids.

4. Discussion

There are seven process models covering the phases in Figure 5 for the integrated cross-organisational business process workflow incorporating the three scenarios. In the research, 37 Exchange Requirements, 61 Functional Parts covering only scenario 1 and scenario 2 were produced. In addition, 30 technical schemas with MVD models including life cycle cost, usage indicators, a self-efficiency rate, site potentials and features, U-value, walls, columns, slabs, HVAC components, BACS components, the energy performance of HVAC, a cost estimation of

HVAC systems, HVAC equipment, for cooling, photovoltaic panels were produced in the research, which are comprising of the interoperability specification for the Design4Energy system. In this paper, it was only possible to represent one from each IDM and three MVD examples.

The interoperability specification helped to develop the virtual collaborative workspace, in which how information exchange between whom at what stage in the process using which data model encapsulating what information nuggets are defined and eventually the specification is used through the demonstration of the virtual collaborative workspace that interacts a number of BIM tools. Without the development of the specification in the Design4Energy project, it was not possible to build the coherent picture of the whole building lifecycle or understanding amongst the stakeholders about how the integrated BIM practice would be possible for performance based design and retrofit including the neighbourhood parameters. For example, the process model diagram illustrated in Figure 9 represents the main functional parts of the process stage: ***design check and energy matching*** within a district context. The main set of tools required is: D4E Collaborative Workspace Tool (Design Review Tool), Energy Match & Optimiser Tool, Energy Performance & Simulation Tool and Target Setting & Assessment Tool, as shown in Figure 14.

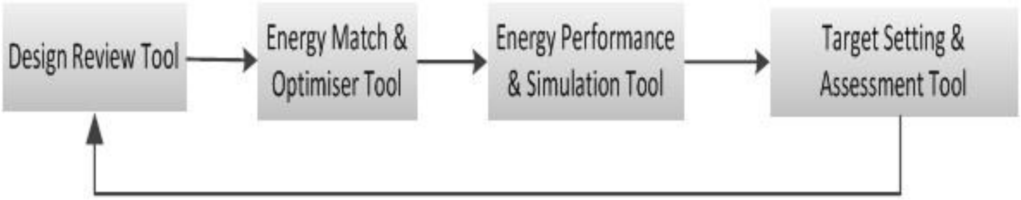


Figure 14: Tools interacting in the design check & energy matching

In this interaction in Figure 14, interoperability specification helped the technical teams in the project to understand and configure their tools for what data specifically should be filtered from a BIM tool to the other. Figure 15 shows the outcomes of the interactions from figure 14, representing the case study example of design check and energy matching demonstration and its outcomes using the D4E Collaborative Workspace that executed the interoperability specification between the tools in Figure 15 by the architects, client and the energy experts in Design4Energy.

The workflow process of the information exchange and activities related to the design alternatives with various energy options can be viewed and shared by the stakeholders for the performance based design in developing prosumer buildings. It should also be noted that BuildingSmart initiated IDM and MVD techniques as originally issued are mainly data and technology oriented and have less emphasis on human and process aspects and complicated with the technical jargons that confused both user partners and the technical partners. That is why, in Design4Energy, interoperability specification development started with the scenario developments that are then translated into the specific process models, which are heavily discussed and agreed by both technical and user partners. Following that, the process models are delved into the further details for exchange models and functional parts and the MVD structures, which are used by the technical team to develop their tools for successful communication and interactions with other tools in the whole Design4Energy system. Therefore, it is recommended that further issues of the IDM and MVD techniques by BuildingSmart should also consider the user-friendliness, flexibility aspects. In other words, human and process dimensions of the interoperability for the wider use and straightforward implementation of them in the interoperability specification development, which may vary from projects to projects since each project has its own goal, scope, priorities and features

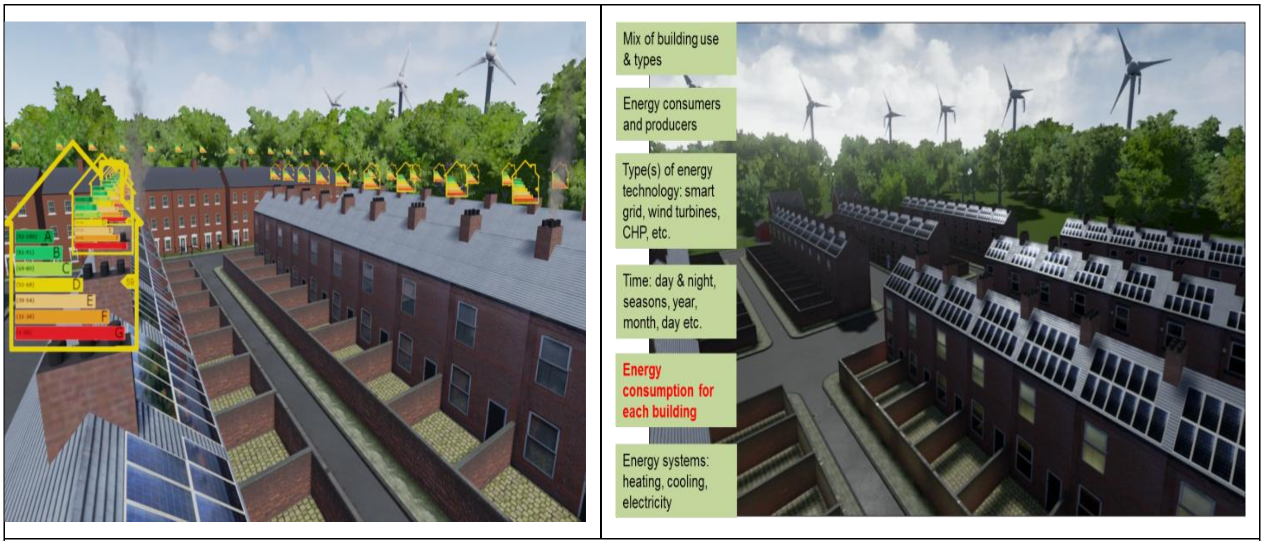


Figure 15: D4E system for design check & energy matching via the interoperability spec.

That means that there is no one-fit-for-all solution for interoperability despite the available standards. In this paper, the detailed examples from the interoperability specification are given and the paper prescribes how it is practically developed using with the IDM and MVD protocols by addressing project specific scope and priorities. Thus, the paper demonstrates an approach for how interoperability specifications can be practically and systematically developed for integrated BIM use by considering human, process, technology, data models and information dimensions together.

The interoperability specification framework, shown in Figure 16, in this research brings together the three scenarios (district, holistic building design and retrofit), reflecting the Design4Energy project scope and it prescribes how each of these scenarios can be integrated into a coherent process workflow, where stakeholder definitions, tools and technologies for data manipulation and processing, information exchange requirements models and technical schemas are specified at the various stages of the integrated process workflow for the performance based design, not only for a passive design but also for an energy producing building design through a BIM-enabled collaborative virtual workspace. The interoperability framework shown in Figure 16 is the rationalised version of the interoperability vision given in Figure 2.

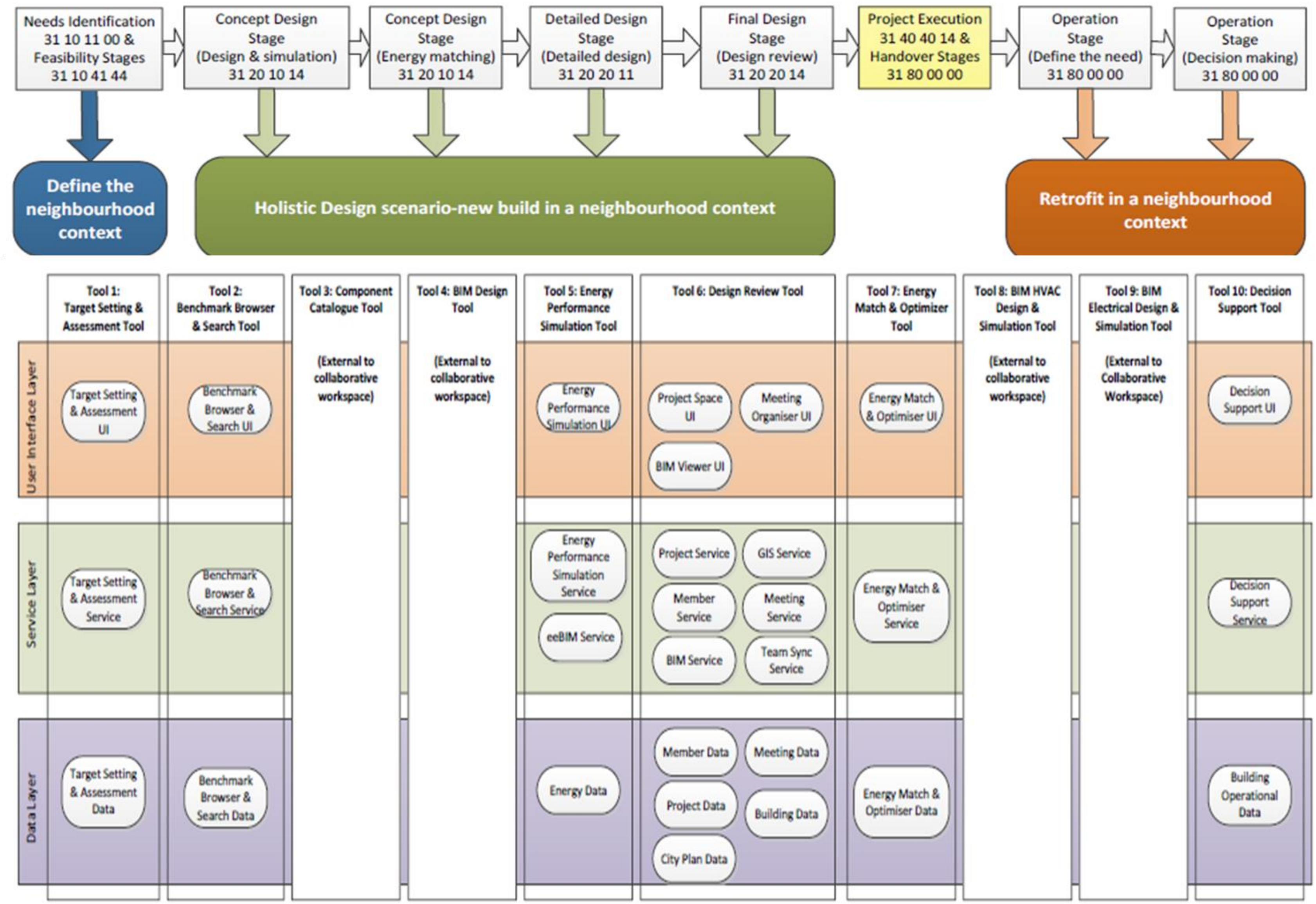


Figure 16: Interoperability specification for the Design4Energy system

In Figure 16, the higher-level building life cycle stages are defined based on the international Omniclass classification and for each stage, an integrated process model is developed for the corresponding scenarios (scenario 1: district; scenario 2: holistic design; and scenario 3: retrofit).

For stage three (Concept Design Stage: Energy matching), the process model is shown in this paper in Figure 9. Tools are mapped into the framework in accordance with their use in the process while the information exchange and data structuring is laid out within the system architecture perspective including the User Interface Layer, the Service Layer and the Data Layer of the Collaborative Workspace of the Design4Energy project. This indicates that the integration of design knowledge base and interoperation of building modelling for effective lifecycle information management for performance based design is critical and only possible via the Integrated BIM practice.

The interoperability specification in Figure 16 represents a novel approach and contributes to knowledge in literature and practice to understand the key aspects to consider for the interoperability requirements and proposes a practical approach for the interoperability developments for the Integrated BIM use for the prosumer building projects.

The interoperability specification development also reflects a forward-thinking approach to address the interoperability challenges in a practical way for the BIM implementation at Level 2 and Level 3, which is already promoted by the UK Government's policy agenda in leading the UK construction industry towards sustainable design and FM through the Integrated BIM practice. Finally, the proposed interoperability specification development approach also provides the theoretical basis for the effective development of BIM execution plans in practice for energy efficient prosumer building design and construction.

5. Conclusion

The performance based design requires a holistic design approach that entails multiple stakeholders interacting with a lifecycle perspective and requires considering neighbourhood level aspects and the use of various BIM applications. This leads to a significant need for the integration of multi-domain performance simulation and analysis. Furthermore, traditionally, architects and engineers find it difficult to effectively use performance simulation tools because their processes are based on 2D manually-created drawings. This characteristic is necessitated by the lack of understanding of interoperation and the lack of integration between design models and building energy models. To overcome this challenge, in the Design4Energy Project, an interoperability specification is developed for the effective and efficient data and process integration, which is also executed by the Design4Energy collaborative workspace system for the Integrated BIM use.

This paper explained the development of an interoperability specification for the Integrated BIM-practice for the Design4Energy system that executes the interoperability specification for collaboration and the information exchange between the stakeholders for performance based design. It provides a solid foundation for developing a holistic and coherent picture of cross-organisational business processes, which reflects an integrated supply chain for energy efficiency, not only for a passive design but also for an energy producing building design through a BIM-enabled collaborative virtual workspace.

The cross-organisational business process modelling and the interoperability specification development have adopted IDM recommended by BuildingSMART, which was, however, focusing on more data and technologies than people and processes. Therefore, it was difficult to adopt it initially in the Design4Energy project without addressing the people and process aspects.

The research work described here is the very first of its kind utilising the integrated process modelling using IDM for energy efficient design development by bringing energy databases, simulation and collective knowledge exploration through an integrated supply chain. The main achievements of the research in this paper are listed below:

1. Interoperability specification pulls together three scenarios to bring the district context and energy trading into a holistic energy efficient building design for new and existing buildings.
2. A complete integrated process workflow for new building design is developed and implemented based on scenario 1 and scenario 2, Information Exchange requirements and functional parts of the information exchange models. Thus, it is now possible to state what tools by whom would manipulate which data model by processing what information at which phase of the integrated design process from a very high level to a very detailed level.
3. It coherently pulls together all the research and development from all the users and technical partners in the Design4Energy project.
4. The ongoing iterative cycle of development, namely the interoperability specification development within scenario 2 is approved by the end users from Spain, UK, Finland and Germany and it is extended towards scenario 3. The interoperability specification formed a pivotal position in the Design4Energy project for the performance based design development.
5. IDM and MVD methods are difficult to use without addressing the human and process dimensions that the paper addresses the user-friendliness and usability of IDM and MVD methods and discusses in-depth about the interoperability issues of the Architecture, Engineering and Construction (AEC) area from a performance based design perspective addressing the human and process aspects in addition to the technology and data aspects for the Integrated BIM practice.
6. The interoperability specification development approach in the paper can help for the development of successful and practical BIM Execution plans for the Integrated BIM practice.

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