AMERICAN UNIVERSITY OF BEIRUT

UNDERSTANDING THE GENERATION AND COMMUNICATION OF DESIGN: DYNAMICS, METRICS AND BIM DASHBOARD

by
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AN ABSTRACT OF THE DISSERTATION OF

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The design phase of construction projects is a crucial step that impacts the entire project's lifecycle. Shape, constructability, serviceability, functionality, as well as the maintainability of the facility are all decided at this phase. Inadequate management of the design phase; however, leads to suboptimal design solutions, disrupted information flows, rework, reduced value, design errors and omissions, as well as cost and time overruns in both the design and construction phases.

Meanwhile, the construction industry is witnessing an increasing use of Building Information Modeling (BIM) as a work platform to run and manage design projects. While the full potentials of BIM are yet to be realized, BIM has proven to be a game changer in the way design information is being generated, coordinated, and shared among involved stakeholders. In this regard, several studies have addressed the use of BIM during the design phase aiming to enhance the overall project's performance.

However, a formerly under-explored perspective of BIM workflow during the design phase is the one that correlates between stakeholders' interactions and BIM model dynamics. To bridge the gap, this study approaches design workflow at the interaction of social, process, and product aspects of BIM-based design projects. First, an agent-based simulation model is developed to understand the development dynamics of real BIM-based design projects; second, a visual dashboard is designed to correlate between design development and BIM model dynamics, and third, an ontology-based framework is developed to standardize the representation of BIM-based design projects at both the product and process levels. In this context, case studies and illustrative examples are employed to showcase and test the application of developed frameworks.

The results of the study show how: (a) the client's knowledge about his/her project's value, the ability of involved AE teams to address and shape this value, the process setup, as well as the quality of design planning affect the time, cost and quality performance of BIM-based design projects; (b) design dynamics leave imprints at the level of BIM model's content that can be traced to enhance the monitoring and control of BIM-based design projects; and (c) standardizing the representation of BIM projects can help designers better link BIM model's content to design activities, reduce domain-related gaps, increase shared understanding and promote collaboration among them.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The design phase of construction projects is a crucial step that impacts the entire project's lifecycle. Shape, constructability, serviceability, functionality, as well as the maintainability of the facility are all decided at this phase; hence its crucial importance. Inadequate management of the design phase; however, leads to suboptimal design solutions, disrupted information flows, poor coordination among disciplines, rework, reduced value, design errors and omissions, as well as cost and time overruns in both the design and construction phases (Li and Taylor 2014, Said and Reginato 2018).

What was simply known as "arkhitektōn" in Greek roots, or the Master Builder, is now divided into a big list of experts including architects, structural, civil, mechanical, and electrical engineers; as well as interior designers, environmental consultants, facades' specialists; not to forget contractors and construction managers, and all involved disciplines and trades that you may think of. Therefore, deciding on building shape, services, construction methods, operation, and maintenance routines is now a collective effort that requires decisions to be made at several levels and at different stages among involved stakeholders.

The complexity of construction projects is basically caused by the increasing sophistication of clients' demands, the augmented size and scope of projects, and by the increased number of expertise involved in the project's delivery process (Nicholson and Naamani 1992). In this context, the design phase of construction projects seems to have the biggest influence on the entire project's life cycle as argued by El. Reifi & Emmitt (2013) and Sacks et al. (2009). Nonetheless, the design phase is a major cause of issues arising during the construction phase, as well as a major contributor to waste generated during execution (Koskela, Huovila and Leinonen 2002, Gamage, I.S.W., Osmani and Glass 2009, Osmani , Glass, J. and Price, A. D. 2008). Therefore, a proper understanding of design dynamics and the influence of stakeholders' actions on design development is crucial to enhance the management of the design phase.

Understanding the nature of design and the structure of the design process is essential to improve the management of design projects as well as to increase the value of design products. On one hand, design is an iterative and ill-structured process that has a complicated network of workflows within and across disciplines (Simon 1984). On the other hand, design takes place in a social context that includes several stakeholders with different backgrounds and interests (Cross and Cross 1995). These two major characteristics, along with the absence of adequate managerial tools, complicate the management of the design process and affect its performance.

Although construction projects share some common characteristics, every project is unique in terms of its design challenges (Berard 2012). Designers work with different clients having different needs, under different budget and time limitations, under different topography conditions, and with different design specialty consultants that are sometimes spread across continents. The uniqueness of design projects is a major barrier that faces design management standardization efforts. As stated by Rittel & Webber (1973), although designers benefit from their previous experiences, they do not have a template to follow when tackling a new design problem.

In this context, generating and communicating design intent is a major issue encountered during the design phase of construction projects. Design intent is linked to the intent of the architects' and consultants' drawings, to the corresponding specification, and to the intended functionality and operation of the facility (Abdelmohsen 2011). With the involvement of several parties, the increased complexity of projects, and the density of information dependencies, generating and communicating design intent is becoming a collective effort that needs to be nurtured throughout the entire process.

In this regard, several management practices have been developed to support, enable, and realize coordination among involved parties (Hartmann 2010, Berard 2012, Hammond, et al. 2000). However, these efforts are in general practically oriented, and lack of strong theoretical backing (Koskela, et al. 2016), which make them sensitive to project's specific environment. Koskela et al. (2016) shed lights on multiple theoretical concepts that strengthen the theoretical background of management in general and of design management in specific. For instance, terms like "shared understanding", "common grounds", "boundary objects", and "situational awareness" started to gain more attention from researchers and practitioners due to their great importance in the context of design management.

Meanwhile, the AEC industry is witnessing an increasing use of Building Information Modeling (BIM) as a work platform to run the design process. BIM is an n-dimensional compilation of parametric data into central or combined local models. If properly used, BIM can enhance coordination among disciplines in a 3D environment and can increase the quality of design deliverables (Barlish and Sullivan 2012, Hartmann 2010, Staub-French and Khanzode 2007). Managing the BIM process is not fully established, and experiences differ according to BIM maturity levels, involved stakeholders, and specific project context (Miettinen and Paavola 2014). However, BIM is doubtless a game changer in the way design is being conducted and design intent is being communicated. The question is how to transform BIM from a segregated "information generation" process spread among disciplines, to a collective "shared understanding" process.

To formalize the development of BIM models, research and industry efforts are trying to establish a set of regulatory rules and specifications to control the share and use of information (BIMForum 2018, The American Institute of Architects 2013). The Level of Development (LOD) concept was created to enhance and control the communication of design intent among different involved stakeholders. LOD, as defined by the American Institute of Architects (AIA), defines the minimum content requirements for a model element and its authorized uses at five progressively detailed levels of completeness. Current classification systems range from LOD 100 to LOD 500, specifying the minimum graphical and non-graphical information an element should hold at each level, and its possible authorized uses (The American Institute of Architects 2013). Therefore, LOD is used as a communication language among designers to manage the modeling process, assign responsibilities, set modeling requirements, and control the share and use of information. Note that current LOD definitions are descriptive and they are not clearly linked to the design context where elements pass through different design steps before reaching each LOD milestone.

Accordingly, managing a BIM-based design project comprises, on one hand, the management of design as a collective thinking process, and on the other hand, the management of BIM as a modelling and collaboration process. Although these two processes overlap and intermingle throughout the development of design, each process has its uniqueness. While design is a thinking process that aims to address client's needs and values under a set of constraints and limitations, BIM is a 3D model-based process that aims to formalize the development of design information among involved stakeholders. Note that design can be conducted without BIM, but BIM is not defined without the design process. Moreover, BIM by itself cannot ensure better design solutions; however, BIM has the potential to improve the quality of design if properly tailored to the characteristics of the design process.

Because the boundaries are not clearly set between the BIM process and the design process, management efforts are sometimes directed towards managing BIM without giving enough attention to the underlying design course. Therefore, a bias focus on managing BIM can cannibalize the multi-disciplinary design process, instead of supporting it. It is assumed that managing the BIM process automatically means managing the design process; but this is not always the case. In this regard, it is highly crucial to notice that the BIM process and its deliverables are a surrogate system of a collaborative design thinking process happening among involved stakeholders. In this context, an appropriate mapping between design thinking and the underlying BIM process can enhance the management of BIM-based design projects.

Practically speaking, design managers seem to face serious barriers while trying to plan and monitor design projects regardless of the platform used. Even the adoption of BIM does not alleviate the causes behind these barriers that originate from the iterative and vague nature of design projects. Accordingly, the ill-structured nature of design, especially at early phases of project definition, prevent design managers from following a clear and a standardized design management approach, even on BIM platforms. In this context, supporting BIM models with appropriate design related metrics is expected to reap the full benefits of BIM when used for design product development. This can result in an overall enhancement of the design process as well as an increase of the value of generated design deliverables.

In this regard, the use of BIM in the design phase captured researchers' interests in the construction industry especially that the adoption of the new technology is continuously growing among Architecture Engineering and Construction (AEC) practitioners. Part of the related studies tackles the advancement brought by BIM at the level of the design product manifested in better project 3D visualization (Azhar 2011), enhanced geometry control (Ku, et al. 2008), more accurate cost estimates (CRC Construction Innovation 2007), better design product quality achieved through continuous clash detection (Hartmann 2010), code compliance checking (Eastman et al. 2009) and reduced error propagation (Al Hattab and Hamzeh 2016).

Another part of these studies addressed the enhancement brought by BIM at the design process level manifested by reduced design hours and better 3D-based collaboration (Azhar 2011), enhanced information flow among design parties (Al Hattab and Hamzeh 2013), as well as better design change management (Juszczyk, Tomana and Bartoszek 2016). Nonetheless, researchers studied the impact of the BIM social configuration on information flow among design parties (Al Hattab and Hamzeh 2018) and other studies addressed the evolution of the BIM product during design (Poirier, Staub-French and Forgues 2015) and the modeling effort required for different levels of development (Leite, et al. 2011).

However, a formerly un-explored perspective of BIM workflow during the design phase is the one that correlates between stakeholders' interactions across the design phase and the resulting dynamics at the BIM product and process levels. To bridge this gap, this study approaches design workflow at the interaction of social, process, and product aspects of design projects conducted over BIM platforms. The research employs agent-based simulation modeling and case studies to investigate the effects of designers' and clients' actions on design workflows and BIM model dynamics. Accordingly, a better understanding of the dynamics occurring in BIM-based design projects is realized and employed to enhance the reliability of early design planning. Moreover, the study develops new measures to assess the actual design maturity of BIM models in addition to LOD concept. These measures are expected to increase situational awareness among design stakeholders and to raise the trust in model's embedded information. The study also develops a visual dashboard to monitor the dynamics of BIM model's content and tries to correlate between these dynamics and related design activities. Finally, an ontology-based framework is suggested to standardize the representation of BIM-Based Design tasks. The study is expected to enhance the reliability of design planning, increase stakeholders' awareness of process dynamics, standardize the mapping between design process activities and BIM content development, and improve the traceability and control of information flow during design generation.

1.2 Research Process

A research process is a roadmap set out to guide the dissertation development from initiation to completion. It serves as a systematic strategy to identify problematic issues and limitations around the study, formulate and answer a set of research questions, develop and achieve the study objectives through a well-developed research methodology, and provide solid conclusions backed by different sources of evidence.

The first step of the study process presented in Figure 1.1 involves a revision of available literature related to BIM and design management to highlight the current challenges faced by the industry and the research gaps in the body of knowledge. The second step is to outline the study motivation and to develop the objectives of the research based on the identified gaps and limitations surfaced in the first step. The third step comprises the formulation of specific research questions inspired by research objectives. The fourth step deals with the design of research methodology based on the nature of the identified research questions. The fifth step initiates the experimental design, data collection, and model validation and verification as guided by the developed methodology. The sixth step presents, analyzes, and discusses the results of the study, while the seventh step presents study contribution and recommendations.

1.3 Dissertation Organization

The organization of the dissertation is presented in Figure 1.2. Chapter 2 provides the background research of the topics tackled in this study; mainly Design Management, Building Information Modeling, Agent Based Simulation and Ontology. Chapter 3 highlights the industry challenges and research gaps that ignite the motivation behind this study. Chapter 4 explains the developed research methodology and used methods. Chapter 5 investigates the influence of design process dynamics and stakeholders' interactions on BIM model development and design workflows. Chapter 6 presents the development of BIM dashboard that aims to increase situational awareness among design stakeholders and improve process control. Chapter 7 presents the development of a Top-Level BIM Ontology the representation of BIM-Based design tasks. Chapter 8 concludes and inspires future works.

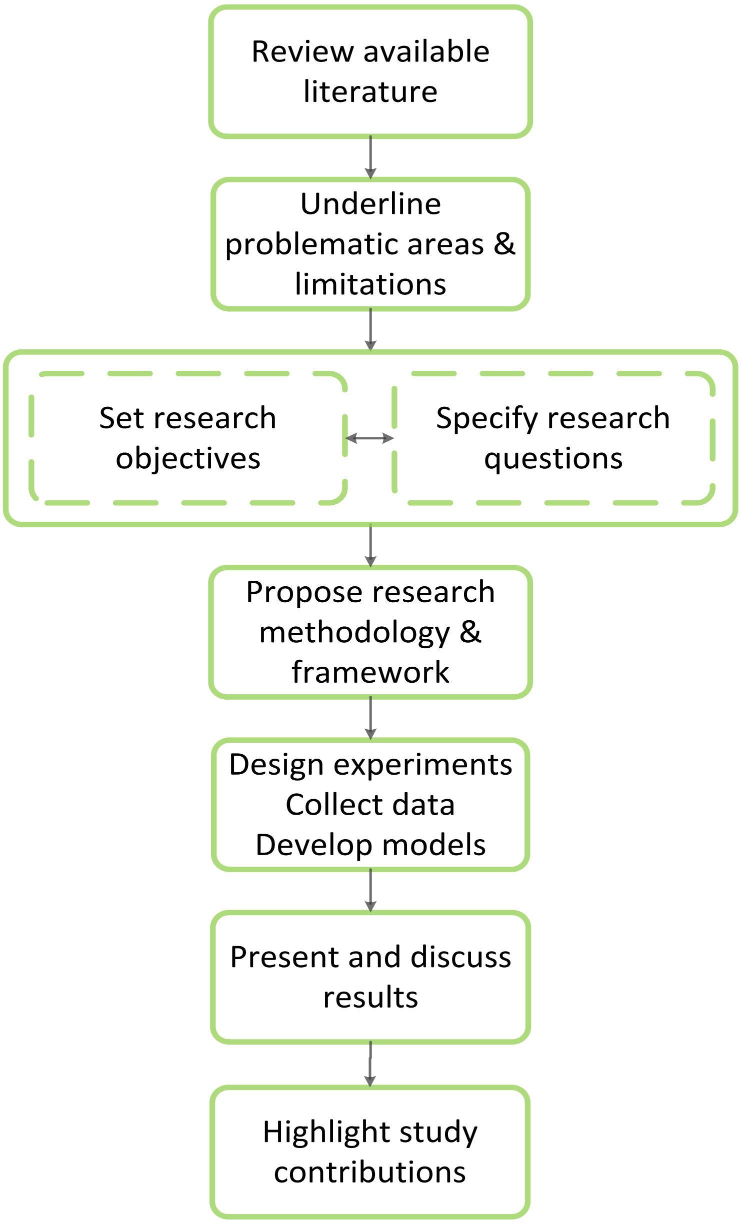

Figure 1-1: Process for Research Design

Chapter 1 Introduction	•Introduction to the study •Research Process •Dissertation Organization
Chapter 2 Research Background	•Design Management •Building Information Modeling •Ontology
Chapter 3 Research Motivation and Questions	•Problem Statement and Motivation •Research Objectives •Research Questions
Chapter 4 Research Methodology and Methods	•Research Methodology •Research Methods
Chapter 5 Design Planning	•stakeholders's characteristics and project's setup •Agent based Simulation Modeling •Analysis and Discussion
Chapter 6 Design Monitoring and Control	•BIM Visual Dashboard •Case Study Application •Analysis and Discussion
Chapter 7 Design Standardization	• Top Level Ontology for BIM • Example on Ontology Use • Analysis and Discussion
Chapter 8 Study Contribution and Future Works	•Comprehensive Study Conclusion •Future Works

Figure 1-2: Dissertation Organization

CHAPTER 2

RESEARCH BACKGROUND

2.1 Preface

This chapter reviews the relevant body of knowledge that has influenced the study and it is divided into three main sections. Section 1 presents the research background of design management. Section 2 highlights the research related to Building Information Modeling, while section 3 reviews ontology and its current uses.

2.2 Design Management

2.2.1 Nature of Design

Design, as a general term, aims to fulfill client's needs by finding ways to overcome the obstacles that undermine client's satisfaction (Cross 1984). Similarly, building design aims to fulfill client's needs and values by solving the design problem in a multidisciplinary environment. Although designers work on meeting the client's value preposition for a project, the final outcomes of the design phase remain vague at early stages. If design outcomes were perfectly predictable early on, the design phase would not be a value adding process (Ballard 2000).

In this regard, iterations in the design process are inevitable and are essential for both the designers and the client to build an understanding of their project and to improve the corresponding design solution. The iterative loops witnessed during the design process are caused by the ill-structured nature of the design problem. As defined by Simon (1984), ill-structured problems are problems that have so many unknowns associated with the problem definition on one hand, and so many unknowns associated with its solution’s means and methods on the other hand (Simon 1984). In the contrary, well-defined problems have clear goals that are already prescribed and apparent, where their solution requires the search of suitable methods (Rowe 1987). For instance, later design stages that comprise design development and analysis can be considered as well-structured and defined design problems.

Other researchers go further and approach design problems as wicked problems. In addition to being ill-structured, wicked problems share a set of characteristics that distinguish them from other regular problems as defined by Rittel & Webber (1973). In this regard, a wicked problem is a problem that does not have a definitive formulation, where understanding and defining the problem depends on the approach adopted to solving it. In other words, the problem and its solution are co-dependent and evolve together.

Accordingly, solving a wicked problem has no stopping rule where the designer can always reach a better solution if more investment in understanding the nature of the problem is performed. Hence, designers stop working on solving a design problem not for reasons inherent in the logic of the problem, but for external considerations like running out of time, money, or even patience. Based on that, design solutions can only be approached as good or bad solutions, not true or false. In other words, two design teams equally equipped, interested, and entitled to solve a certain design problem would provide two different solutions based on their specific value sets (Rittel and Webber 1973).

In this regard, Buenano (1999) argues that “facts, beliefs, ideas, discrepancies, causes and consequences continuously interplay” while defining the design problem.

Accordingly, accepting that design problems evolve in different directions throughout the design process, and that they are framed differently by project stakeholders, leads us to accepting the wicked nature of the design process (Buenano 1999). Whelton and Ballard (2002) further investigate the wicked nature of design using exploratory research through three case studies. They compared the characteristics of wicked problems as stated by Rittel (1973) to the process of defining the design problem in these cases. They conclude that wicked problems in project definition are a function of the complexity of project's variables as well as stakeholders' needs and values (Whelton and Ballard 2002).

In a different direction, some researchers tried to deal with design as a scientific method and this approach goes back to the start of the 20th century as science gained increased value and esteem among design researchers. In this context, Gregory (1967) noted that science is a pattern of problem-solving behavior employed to uncover the nature of what exists, while design is a pattern of behavior employed to invent things of value which do not exist yet. "Science is analytic, design is constructive", (Gregory 1967). Thus, although design involves problem solving techniques employed to surpass the encountered constraints, the design method could not be entirely approached as a scientific method.

In this regard, Cross et al. (1981) believe that putting design under the umbrella of science tries to bring scientific values like objectivity, rationality, neutrality and universalism to the design method. However, since major characteristics, like subjectivity, hinder design from being totally scientific, they introduced a new definition that approaches design as a technological activity; in which design is the application of scientific and non-scientific knowledge to practical tasks achieved by social systems that involve people and machines (Cross, Naughton and Walker 1981).

With the absence of clear and systematic design procedures, designers developed various strategies to overcome encountered design obstacles. In this regard, several researchers investigated the cognitive behavior of individual designers while performing design tasks (Kruger and Cross 2006, Cross 2004). They have differentiated between various cognition strategies including: problem driven, solution driven, information driven, and knowledge driven design strategies. They also related each strategy to corresponding design outcomes. Researchers have also investigated design cognition in a team environment by directly measuring the quality of team mental models while the design is unfolding (Dong, Kleinsmann and Deken 2013). Moreover, researchers have addressed creativity issues in design and have related it to the corresponding design quality (Dorst and Cross 2001). These efforts increase the understanding of the nature of design and form a theoretical background for developing practical design management procedures and tools.

2.2.2 Communication of Design Intent

Due to the ill-structured and iterative nature of design, managing the generation and communication of design intent is a major issue encountered in the design phase of construction projects. Design intent is linked to the intent of the architects' or consultants' drawings, to the corresponding specification, and to the intended functionality and operation of the facility (Abdelmohsen 2011). Some researchers define design intent as the rationale and reasoning performed to justify the design of a certain product or part of it (Lee and Lai 1991, Pena-Mora, Sriram and Logcher 1993). Whereas other researchers define design intent as a path of decision making and alternatives' generation that spread from an initial state to a final state (Conklin and Yakemovic 1991, Brissaud, Garro and Poveda 2003).

The issue of communicating design intent; however, dates back to the Roman architect Vitruvius, in the first century BC. He discussed the intrinsic value of using plans, sections, elevations, and perspectives to properly communicate the design intent (Morgan 1960). Vitruvius work influenced the architecture profession especially in the Renaissance era, and practitioners adopted his ways to represent their design intent until our days. In this regard, the use of 2D-CAD software to draft design projects is a replication of manual drafting procedures that apparently existed long before the invention of computers (Abdelmohsen 2011).

In the context of generating and communicating design intent, Koskela et al. (2016) refer to the preconditions and setups required for successful communication and collaboration in construction projects. They discussed several major concepts that form the basics of any successful collaboration including: "shared understanding", "common grounds", and "situational awareness" as detailed in the following sections:

2.2.2.1 Shared Understanding

Design teams spend a lot of time and effort collaborating and coordinating generated design information before they can reach a shared understanding of the design problem. In this process, involved teams must manage conflicts generated from several interpretations of ideas, concepts, and also representations (Cross and Cross 1995). Therefore, shared understanding is an overlap of understanding among different involved designers for a specific design task (Maher, Cicognani and Simoff 1996), and the lack of shared understanding is a major cause of unnecessary negative iterations

(Valkenburg 1998). Accordingly, shared understanding is not just a type knowledge; it is an ability and a reasoned dynamic action. In this regard, Arias et al. (2000) highlights the importance of focusing on the social aspects of creating shared understanding in collaborative design development (Arias, et al. 2000).

2.2.2.2 Common Grounds

"If any two people are going to have a debate, there needs to be some common ground", (Aristotle n.d.). Common ground refers to the knowledge, beliefs, and suppositions believed to be shared among corresponding speakers (Clark 1996). Nonetheless, common ground is approached as a dynamic construct mutually constructed by involved interlocutors throughout the communication process (Kecskes and Zhang 2009). In this regard, Clark and Brennan (1991) introduced the term "grounding" to highlight the dynamic nature of creating common ground. In a different study, Klein et al. (2005) studied the loss of common ground during a communication process. They found that the confusion of who knows what forms the basic reason behind loosing common ground, calling it as Fundamental Common Ground Breakdown (Klein, et al. 2005)

2.2.2.3 Situational Awareness

Situational awareness is defined as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" (Endsley 1995). In the context of collaborative design, situational awareness emerged as an important factor among involved teams to understand the dynamics of the ongoing process. Accordingly, teams who have situational awareness know the workload of other teams and understand the dynamics of the ongoing design process at its macro level (Endsley and Jones 2001).

Therefore, in a reconfiguration of Endsley's definition, "situation awareness would be the capacity to perceive and comprehend the characteristics of an environment within time and space supporting the realization of predicted futures aligned with a task or project" (Koskela et al. 2016).

2.2.2.4 Boundary Objects

"Boundary objects" (BO) is a concept introduced to describe objects used by several actors to coordinate interdisciplinary work (Star and Griesemer 1989). The term boundary reflects a shared space where two or more worlds are related to each other in particular ways. Accordingly, boundary objects are used to describe objects present in several intersecting social worlds and satisfying the informational requirements of each of them (Star 2010, Star and Griesemer 1989).

Although the definition of boundary objects differs from one researcher to another, all definitions share some common aspects. Among them, boundary objects: (a) can be of abstract nature or actual objects, (b) must be "plastic enough to adapt to local needs", (c) "robust enough to maintain a common identity across sites" (Star and Griesemer 1989)(Star and Griesemer 1989), (d) and subject to reflections and interpretive flexibility (Star 2010).

In the Architecture, Engineering and Construction (AEC) industry, boundary objects are artifacts used to facilitate coordination and collaboration among construction stakeholders. Such artifacts include plans, 3D models, schedules, as well as sketches and prototypes (Koskela et al. 2016).

2.2.2.5 Mediating Artefact

Mediating artifacts include tools, procedures, processes and accepted practices that reflect distributed cognitive structures of a group of collaborators (Macpherson, Jones and Oakes 2006). Through these artifacts, different communities from different backgrounds can represent, share, and contribute to building the ongoing “knowing” process (Ewenstein and Whyte 2009). Mediating artifacts help practitioners make informed decisions to run ongoing activities; however, they differ in some respects. Basically, the way these artifacts are presented whether in textual, visual or any other format; their degree of contextualization whether they are developed at the abstract level or contextualized; their granularity level that reflects the amount of details available in the corresponding artifact, and their structure configuration whether using organized flat vocabularies or categorized typologies (Conole 2009).

2.2.3 Design Process Models and Information Flow Conceptualization

Several models were created to describe the design process; however, most of the work done in this field can be classified under two categories: Activity Based and Phase Based models (Evbuomwan, Sivaloganathan and Jebb 1996). In the Activity Based models, design is viewed as a series of cyclic iterations of three activities: analysis, synthesis, and evaluations (Cross , Dorst and Roozenburg 1992). In the Phase Based models, design is viewed as a sequential progression of design information from less to higher detailing in terms of the amount known from the actual physical characteristics of the product to be made (Pahl and Beitz 1988).

Other researchers proposed a model that combines both aspects of previous models using a generic design process roadmap (Tate and Nordlund 1996). However, design management methods basically focus on the Phase Based aspect of the design process due to the complexity of tracking the mental activities of designers. As quoted from Suh (1995); the problem in managing the design process is that design involves synthesis.

Regardless of the model used to describe the design process, several researchers tried to conceptualize the flow of design information among stakeholders. These studies include metaphors of fluid mechanics, the flow of products in manufacturing, electrical current as well as metaphors to automotive power trains. Note that developing measures of information flow highly depends on which concept is used to approach design information flow. For instance, in the electrical current approach, metrics like Resistance is used to measure the resistance value of each design task through which the information is flowing (Ostergaard and Summers 2007). In the fluid mechanics approach, measures like velocity, viscosity, and volatility of fluids flow are suggested to use in information flow measurements (Krovi, Chandra and Rajagopalan 2003); however, these measures were not developed nor demonstrated (Tribelsky and Sacks 2010).

In a different direction, the design process is compared to the production process as far as inputs are transformed into outputs at various processing stations (Ballard 2000). While in the typical production process, workers and machines produce actual products, in design, consultants transform client's requirements into design documents. In addition to transformation, flow and value characteristics are introduced to describe the design process. In this context, design is perceived as a transformation of inputs to outputs, as a flow of information and deliverables among involved parties and as a value generating process where client's needs and requirements are ought to be fulfilled (L. Koskela 2000). Tribelsky and Sacks (2010) further elaborate on Ballard's and Koskela's models; they introduced new metrics to quantify and measure design workflows. These metrics help evaluate the characteristics of information flow such as work in process, cycle time, batching and other lean related concepts. However, these metrics do not reflect the quality of design itself nor its progress; they just reflect the characteristics of the ongoing process.

2.2.4 Design Planning and Scheduling

A simplified approach to define design management is to say that design management is about managing people and information (Emmitt and Ruikar 2013). However, the iterative and multi-disciplinary nature of design increases the complexity of design management. From a problem-solving perspective, researchers approached design as successive tasks of analysis-synthesis-evaluation (Evans, Powell and Talbot 1982), or also as divergence-transformation-convergence (Jones 1981). This understanding of design represents only its “horizontal” dimension which could not be easily formulated in administrative contexts, since it reflects individual ways of problem solving (Hassan 1996). Other researchers highlight the progress of design from concept to detail, being the “vertical” dimension, and use it to differentiate among different design phases known as Feasibility Study-Schematic/Preliminary Design-Detailed Design (Beakley and Chilton 1974, Ahuja 1984). The latter approach conforms to contractual and organizational aspects and it is well known among industry practices.

To formalize the planning of design activities taking into account their iterative nature and interdependencies, the Analytical Design Planning Technique (ADePT) was developed by Austin et al. (1999). ADePT is a Dependency Structure Matrix (DSM) tool used to plan the building design process. Design tasks are ordered in a way to reduce rework based on information dependency among them. Accordingly, better flow of information among design parties is expected. However, scheduling the design program resulting from the ADePT requires not only the sequence of activities, but also the start/end dates, durations, and resources requirements of each activity. Accordingly, the lookahead planning technique is suggested to further detail design activities, identify constraints, allocate resources and release work packages. Nonetheless, the Percent Plan Complete (PPC) was used to manage projects during the design phase as in Hamzeh et al. (2009). In this regard, DePlan was developed to integrate the planning, scheduling and control of design tasks (Hammond, et al. 2000).

DePlan enhances the use of ADePT by generating reliable weekly work plans and controlling their execution throughout the design process; similar to the use of the Last Planner system in the construction phase. However, the characteristics of the design process cannot be fully captured in this framework. For example, PPC only measures the quality of the scheduled plan not the quality of design itself. A 100% PPC does not necessarily reflect a 100% accepted design. Moreover, DePlan focuses on the flow aspect of design and gives less attention to its transformation and value characteristics.

2.3 Building Information Modelling (BIM)

Meanwhile, the construction industry is witnessing an increasing use of Building Information Modelling (BIM) as a platform for running the design process. BIM is a visual database that combines parametric design data into a centralized model. The proper use of BIM has been proven beneficial for the design process as well as the final design product (Al Hattab and Hamzeh 2016, Eastman, Lee, et al. 2009). Since BIM is object oriented, elements used in the model holds the corresponding design information either in their graphical appearance or in the corresponding attached data. Accordingly, managing the design phase using BIM defers from conventional procedures used in the case of traditional 2D-CAD processes.

The proper adoption of BIM applications is expected to improve design management. In this context, several researchers have developed evaluation metrics to quantify the benefits of BIM (Tribelsky and Sacks 2010, Barlish and Sullivan 2012, Jung and Joo 2011, Succar, Sher and Williams 2012). Some of these benefits include: savings in design hours, complex geometry control, design-construction integration, rework reduction, cost and time savings, and stream-lined information flow (Ku, et al. 2008, Li, et al. 2008). Several studies have also focused on exploring the different uses of BIM during design and construction. Clash detection, automated code checking, fabrication/ shop drawing generation, visualization, cost estimation and quantity take-offs are few of the uses that have been reported and validated by data from various case studies (Eastman, Lee, et al. 2009, Hartmann 2010).

The success of the BIM process depends mainly on the content embedded in the models. Since BIM models are object oriented where model elements are classified according to a certain hierarchy, deciding on elements' graphical and non-graphical information is a major challenge in every BIM process; an additional task absent in traditional 2D-CAD workflows. To address this new concern, industrial and organizational efforts have created the notion of Level of Development (LOD) to classify the development of each model element in terms of graphical representation and assigned information (BIMForum 2018, The American Institute of Architects 2013, VicoSoftware n.d., New York City Department of Design and Construction 2012). LOD values range from 100 to 500 describing the element's progress from lower to higher detailing levels. LOD identifies the minimum content requirements and the authorized uses an element can have.

Academic research on LOD is still in early stages but started to gain momentum. Some efforts used the LOD concept in a proposed methodology to generate BIM models with laser scanning (Li, Isele and Bretthauer 2008, Fai and Rafeiro 2014) using a different nomenclature than that adopted by AIA where LOD is only related to the graphical appearance of elements. LOD is also used in research studies addressing BIM models' content and their possible uses (Staub-French and Khanzode 2007, Hooper and Ekholm 2012). Hooper (2015) targets the understanding of the LOD concept and its use in design management, along with a proposed framework to automatically compare model's actual status to the planned LOD model progression (Hooper 2015). Chang and Shih (2013) demonstrate the use of AIA LOD definitions in modeling a project, giving insights to what the model may contain at each LOD level (Chang and Shih 2013). Choi et al. (2011) present a simplistic LOD interpretation to understand data interactions in a BIM process during the planning phase of a mega project (Choi, et al. 2011). In addition, Leite et al. (2011) analyze the modeling effort in terms of time and objects modeled ac-cording to LOD levels (Leite, et al. 2011), whereas Wood et al. (2014) use the LOD concept to assess the cost implication of alternative structural designs in residential projects (Wood, Panuwatwanich and Doh 2014). Other studies relate LOD to 4D BIM simulation in an effort to link 3D model elements to scheduled tasks (Liu and Li 2013).

2.4 Ontology Development and Use

With the gradual expansion of the use of computers and the exponential increase in the size of generated data in different areas of human life, the need to store, organize, integrate and use the generated data is rising. In this regard, one increasingly dominant strategy to store and organize generated data in a computer-friendly environment is associated with the term ontology, or ontological engineering, which is understood as a controlled vocabulary used to represent the types of entities in a given domain (Arp, Smith and Spear 2015). Once developed, the ontology would be logically understood by computers which enhances its handling by prospective users.

Ontology is a representational artefact intended to represent some combination of universals, defined classes, and certain relations between them by employing a defined taxonomy (Arp, Smith and Spear 2015). It is developed based on fundamental propositions of domain experts following clear knowledge classes and hierarchy using semantic relationships (Gruber et al. 1993).

Ontology is used in several engineering and design domains. For instance, ontology is used to represent and capture dynamic design intent in the mechanical field (Khan, Demoly and Kim 2016), to manage product design and encountered changes (Gruhier, Demoly and Gomes 2017), enhance CAD to CAD solid modelling interoperability and incorporate design knowledge into CAD systems (Khan, Demoly and Kim 2017), to describe products' relationships over space and time in integrated design (Gruhier, et al. 2016), to collaboratively develop Product Service Systems (Correia, et al. 2017). However, the use of ontology in the AEC industry is still sparse compared to other fields. For instance, ontology is used to enhance information management and sharing (El-Diraby 2013, Ruikar, et al. 2007), to model construction processes for simulation purposes (Benevolenskiy, et al. 2012), to create a bill of quantity for cost generation purposes (Xu, et al. 2016), to combine BIM and GIS data

(Le and Jeong 2016), and to enable automated compliance regulation checking (Liebich, et al. 2002).

In BIM, ontologies are used at the software level to systematically structure the IFC schemas. This implementation led to the development of the ifcOWL Ontology. IfcOWL employs a Web Ontology Language (OWL) to represent IFC data (buildingSMART 2010). It aims at avoiding inconsistencies while mapping information generated by domain experts. The ifcOWL ontology presents a semantic web representation of IFC that can be used in creating a web of building data linking many construction domains together (OpenBIMStandards n.d.).

2.4.1 Basic Formal Ontology (BFO)

BFO is an upper-level ontology originally developed to represent data generated from scientific research. BFO is purposefully designed to be very small and generic as to allow for the consistent representation of upper-level categories common to domain ontologies developed by different scientists in different fields. Accordingly, BFO does not address the terminological needs for specific scientific domains; however, it does provide a starting point for anyone trying to build a specific ontology for a corresponding domain of knowledge (Arp, Smith and Spear 2015).

BFO considers the world to be formed of entities, where an entity represents anything that can exist in any way at all. BFO categorizes these entities into continuants and occurrents. While continuants represent entities that continue to exist through time, occurrents represent entities that occur or happen as events. Nonetheless, BFO provide major sub-types for both the continuants and occurrents as highlighted in Figures 2.1 and 2.2. For instance, BFO: Continuants comprises Independent Continuants (ex: a person, a place, an object part, etc), and Specifically Dependent Continuants (ex: quality such as a color, a mass; a function such this switch turns the light on, etc.). More details about different BFO categories can be found in Arp, Smith and Spear (2015).

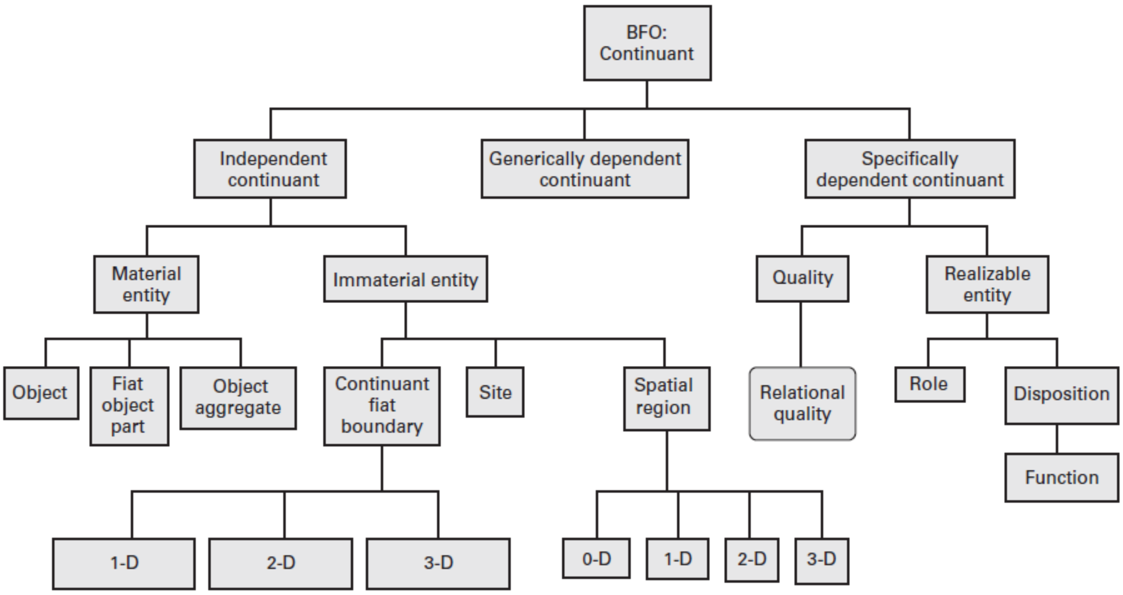

Figure 2-1: BFO Continuants (Arp, Smith and Spear 2015)

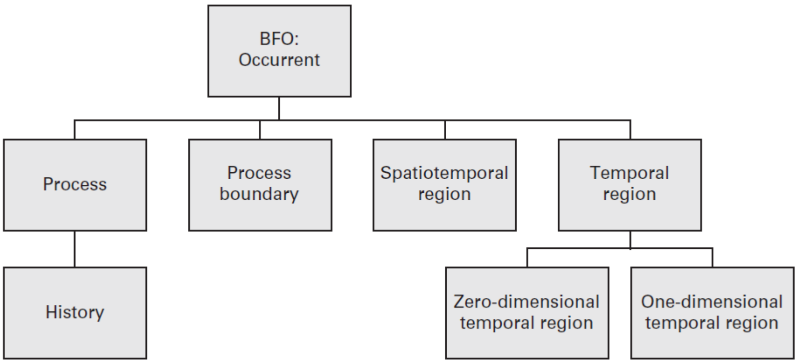

Figure 2-2: BFO Occurrents (Arp, Smith and Spear 2015)

In addition to categorizing entities under specific classes, BFO provides a set of logical relations that connect the different BFO entity types together. Without logical relations, the developed ontology cannot capture important scientific information about the corresponding domains. These relations allow for the logical reasoning in a developed ontology and they are basically divided into three types that connect universals to universals, particulars to universals, and particulars to particular. Further information about BFO relations can be found in Arp, Smith and Spear (2015).

CHAPTER 3

RESEARCH MOTIVATION AND QUESTIONS

3.1 Problem Statement and Motivation

Despite the known importance of the design phase in directing projects towards achieving their time, cost, and quality objectives; insufficient attention is given to design planning and control in the AEC industry (El. Reifi and Emmitt 2013, Choo, et al. 2004, Austin, et al. 1999, Thyssen, et al. 2008). Accordingly, many construction projects end up with unsatisfied clients and deprived value (Egan 1998). In this regard, the importance of properly managing the design phase has been shown in related literature (G. Ballard 2008, Bertelsen and Emmitt 2005, Tunstall 2006); where poorly controlled design stages seem to be a major contributor to reducing the overall performance, efficiency, and quality of the constructed artefact (Hansen and Vanegas 2003, G. Ballard 2008, Tilley 2005). This section will highlight the major problems and gaps in design management practices and related research to better understand the challenges hindering the enhancement of design process management.

3.1.1 General Gaps in Design Planning

The iterative and ill-structured nature of design makes it hard to plan and control design progress using conventional project management tools such as the Critical path Method (CPM) or PERT (Choo, et al. 2004, Bashir and Thomson 1999). With the absence of adequate tools, practitioners traditionally focused on the progress of design deliverables to plan and monitor the progress of design (ex: 30%, 60%, 90%, or 95% of complete drawings or models as per the list of deliverables developed at each phase of the design project) (Choo, et al. 2004). While this approach focuses on pushing resources to transform client’s needs to a set of design deliverables at each project milestone, it ignores other important aspects of design such as the flow and value (Koskela, Huovila and Leinonen 2002). The traditional approach inaccurately assumes that the required information is made available and properly communicated whenever needed (Choo, et al. 2004).

In this regard, researchers developed new tools that address the flow of design information to enhance the overall performance of the design phase. Among the most notable works in this area are the works of (Austin, Baldwin and Newton 1996, S. Austin, et al. 1999, Choo, et al. 2004, Hamzeh, Ballard and Tommelein 2009). The first two studies developed ADePT: a tool that employs the Design Structure Matrix (DSM) technique to reduce the amount of rework in the design process by enhancing the sequence of design tasks based on information dependency among them. The second two studies made an intervention to ADePT by employing the Last PlannerTM system as a production philosophy to improve the reliability of scheduling and controlling the execution of design tasks. A new tool called DePlan was therefore developed.

Although these techniques can be employed to enhance the flow of information among stakeholders and to reduce rework, they have major shortcomings. First, they assume that creating a model of the design process that represents all design activities and their information requirement is possible; ignoring the fact that the design process is highly dynamic and vague especially at early project phases. In this regard, defining steps to achieve a design solution cannot be pre-established realistically at a very fine level of detail (N. Cross 2008). Second, these techniques do not include necessary provisions related to important macro aspects witnessed during design projects such as the process architecture, collaboration protocols, contractual agreements, as well as stakeholders’ interactions at the social and individual levels. These aspects play a major role in influencing the flow of information and project’s value and should be further examined to enhance the reliability of design planning.

3.1.2 General Gaps in Design Management and Control

The control of design development highly depends on the means used to plan and schedule the design phase. In this regard, the metrics devised to detect the conformance of actual design progress to planned design tasks vary accordingly. For instance, Percent Plan Complete (PPC) is used along with the lookahead planning method to detect the progress of design based on the team’s ability to achieve planned tasks (Choo, et al. 2004, Hamzeh, Ballard and Tommelein 2009). PPC in this scenario reflects the planning reliability and the capability of designers to deliver the promised tasks. Accordingly, PPC does not reflect on the quality of design information generated after the execution of corresponding tasks; which is an important aspect needed to assess design progress and maturity.

Other Earned Value analysis tools are sometimes used by practitioners to assess the progress of design. For instance, design managers sometimes compare spent man-hours to the percentage of complete deliverables to assess the design progress. This approach helps design managers compare the incurred costs vis-à-vis to produced deliverables. Therefore, this method gives an idea about the teams’ overall performance; however, it does not reflect on the integrity and maturity of design information if it does satisfy client’s needs, comply with standards and regulation, and whether checked against other design disciplines or not.

With the emergence of BIM as a new platform to run design projects, the planning of design took new directions. Practically speaking, the traditional approach in planning design based on drawings' delivery is no longer appropriate in BIM where design information is shared through data rich BIM models. In this context, the industry developed new techniques to plan the generation of design information using the Level of Development (LOD) concept (American Institute of Architects (AIA); 2008). A set of LOD model requirements is set at each project stage using a table showing elements that need to be modeled, their LODs, and corresponding Model Element Authors (MEA) (The American Institute of Architects 2013). The LOD concept went popular on projects run over BIM because it gives designers an impression about model's development at a moment in the process. For instance, BIM models with higher LOD levels seems to be more stable and less subject to change (Berlo and Bomhof 2014).

However, several concerns were expressed about the LOD concept as it is currently introduced and used in the industry. At the concept level, concerns are related to the fact that current LOD classification systems are limiting the potential of the LOD concept since only five levels are used, which is insufficient to capture all the statuses witnessed by model elements during product development (McPhee and Succar 2013). At the practical level, the implementation of LOD is labor intensive and still managed outside the BIM model (McPhee and Succar 2013). Nonetheless, the kind of information that need to be embedded in the model element at each LOD level is still not clear despite the development of several LOD classification guides. This fact creates confusion among BIM stakeholders resulting in different and subjective estimation of model's LOD levels (Berlo, et al. 2012, Berlo and Bomhof 2014). Moreover, the lack of trust in model's reliability might result in disrupted workflow where teams prefer to wait for others to reach a certain LOD levels before starting their own design activities (Berlo and Bomhof 2014, Hooper and Ekholm 2012). In this regard, planning the development of BIM models using the LOD concept is closer to be a guideline approach rather than a robust planning and control mechanism.

3.1.3 Specific Research Gaps

Based on the previous sections, poor management of design projects originates from inappropriate planning methods as well as from the lack of robust control measures that can assess the actual development of design projects. In this regard, this study focuses on the following five specific gaps:

- Lack of understanding of the effects of stakeholders' characteristics and dynamics on design project development.
- Lack of understanding of the effects of process architecture and collaboration protocols on design workflows.
- Poor assessment of the actual design maturity of BIM models.
- Lack of appropriate measures and visual tools that can help design managers better monitor the progress of their projects.
- Insufficient mapping between BIM model development and corresponding design activities.

The combined effect of these limitations may jeopardize the performance of a design project which may lead to substantial delays, cost overruns, and reduced value. Starting from the planning phase, ignoring the social design context and the process architecture may result in an unrealistic project plan that does not account for negative iterations and possible risks that may arise because of stakeholders' characteristics and dynamics. Note that an unrealistic project plan is one of the major causes behind cost and time overruns witnessed in design projects (El. Reifi and Emmitt 2013, Bashir and Thomson 1999, Thamhain and Wilemon 1986).

Nonetheless, an unrealistic project plan may produce ripple effects in downstream phases where designers are working under unrealistic time constraints. The resulting urgency to meet major deadlines may affect the product's value where designers' efforts are directed towards meeting the delivery schedule to avoid delaying downstream project phases, especially in the case of fast-track projects. Also working under squeezed time periods increases the probability of making design errors which may decrease the design product quality, or in worst case scenario lead to product's failure.

Moreover, the lack of adequate measures and tools that can help design managers keep track of the work progress further affects the effectiveness of design management practices (El. Reifi and Emmitt 2013). In some situations, this issue might affect the designers' commitment to plan which is also an extra cause of disturbance in design projects (Thamhain and Wilemon 1986). This fact might push design managers to manage the generation of design in ad-hoc manner, reactively responding to ongoing process dynamics.

In this regard, this study is driven by the urging need to address these long-lasting problematic areas in the field of design management. The study will focus on aspects related to design planning, control, and standardization and will advise on improvements that can enhance the overall performance of design projects as a major phase in the construction process. At the level of design planning, the study will explore the effects of project's dynamics on the development of the design process; different stakeholders' characteristics and process architectures are examined. In this regard, a better correlation between project's dynamics and design planning are expected to be realized. At the level of design control, the study develops new measures and tools that link the development of BIM models to the actual design progress achieved through consecutive design checks and reviews. These new measures can be visually used by design practitioners to enhance the planning, tracking and control of design projects. At the level of design process standardization, the research suggests a top-level ontology to represent BIM model content on one hand and design process activities on the other. Better correlation between design activities and BIM model development is expected to be achieved, which can increase the shared understanding and transparency among involved stakeholders.

3.2 Research Goals and Objectives

The effects of stakeholders' dynamics, the governing role of the process architecture and the effects of collaboration protocols in shaping the development of BIM model's content need to be further examined in BIM-based design projects. Based on the underlined gaps, the major goal of this study is to examine, analyze, and understand the dynamics of BIM-based design projects to enhance their management at the planning and control levels. To achieve the desired goals, the study employs Agent Based Modelling (ABM) to mimic the dynamics occurring among design stakeholders as well as at the level of BIM model's content. Modeling the BIM-based process, backed by data from actual case studies, can allow researchers and practitioners better understand the characteristics of the ongoing workflows which enables them to better introduce and test improvement schemes under a controlled simulation environment.

3.2.1 Research Objectives

To achieve the major goals of the study, a list of objectives is developed to guide the development of the research as follows:

- Understand the effects of stakeholders' characteristics on design development
- Investigate the effects of process architecture on BIM model development
- Enhance the planning assessment of actual design progress
- Visualize the dynamics of BIM model content
- Standardize the representation of BIM at the product and process levels.

3.3 Research Questions

Reviewing the literature, attending international conferences that present BIM and design studies, holding discussions with design and BIM experts, in addition to my previous experience as a structural designer, have resulted in several research questions that this study aims to address. The questions outlined in section 3.3.1 are following the corresponding SMART principles:

- Specific: questions should be specific to the objectives and topics under study.
- Measurable (Assessable): answers to the questions should be qualitative, quantitative, or assessable through certain means and methods
- Achievable: resources needed should be reachable and questions should be able to be answered.

- Realistic: the purpose of the questions should be reasonable and not too broad, and methods should be practical.
- Timed: questions and methods used should have a set time span that meets the available time prospects and convenience for practical use.

3.3.1 Specific Research Questions

Accordingly, the specific research questions addressed in this study are the following:

- How do the characteristics of clients, architects and engineers affect the performance of BIM-based design projects?
- How does client's engagement in the design process and the level of design planning affect the corresponding design workflows?
- How are design dynamics and BIM model progress correlated?
- How to visualize the development of BIM-based design projects?
- How to standardize the representation of BIM-Based Design Projects??

The next chapter presents the methodology and methods adopted in this research work to answer the above questions and achieve the outlined research objectives.

CHAPTER 4

RESEARCH METHODS

4.1 Preface

Understanding the effects of stakeholders' characteristics and their corresponding interactions on design workflow is needed to enhance the overall management of design projects. In this study, the focus is on the development of BIM models and their corresponding content as a medium to generate and share design information during the design phase of construction projects. Accordingly, BIM-based design workflow is approached in this study as a flow of BIM models among involved stakeholders across different design milestones. Necessary design information is therefore assumed to be generated and shared using BIM models exclusively, and therefore all other types of design deliverables are outside the focus of this study.

Running design projects on BIM platforms significantly differs from running them using traditional 2D-CAD technologies. This difference is imposed by the object-oriented nature of BIM software where designers can represent their design intent using actual elements not lines and layers. Accordingly, when designers employ BIM during design, they create parametric elements in the model with specific graphical representation and information content. Nonetheless, these elements are classified following a certain hierarchy that relates classes to subclasses as shown in Figure 4.1. Note that this hierarchy in defining model elements imposes some sort of properties' inheritance among classes and corresponding sub-classes, which govern the definition of each individual element.

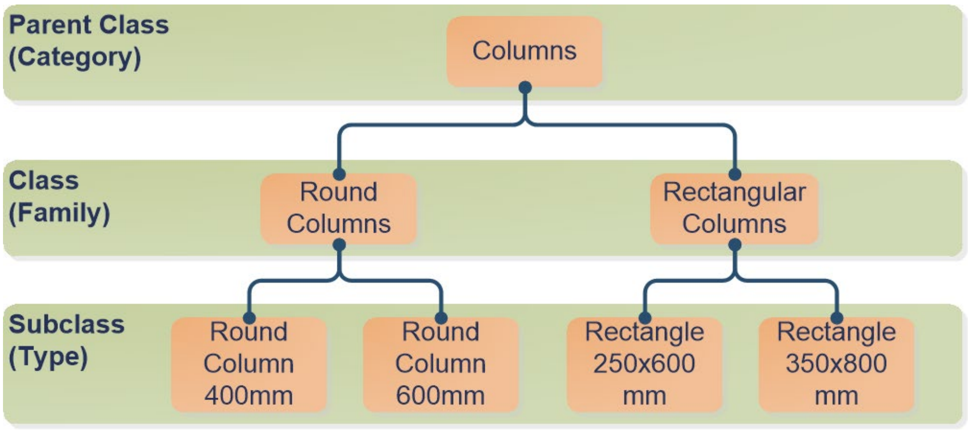

Figure 4-1: Hierarchy of Defining Elements in BIM models (adjusted from Autodesk, n.d.)

In this regard, developing the design solution across different project phases is accompanied by continuous dynamics witnessed at the level of BIM models' content. At every design iteration, new elements could be created, some elements could be further developed, while other elements could be deleted. Thus, design dynamics among stakeholders are reflected by the generation and development of model elements throughout the process. Therefore, these elements would witness continuous development at the level of their graphical appearance as well as at the level of their attached information. In this regard, following the dynamics occurring at the level of BIM model elements can serve as a good approach to better understand BIM-based design workflow dynamics.

Based on this perspective of BIM-based design workflow, this study focuses on the dynamics occurring at the level of BIM model elements to: (1) study the effects of stakeholders characteristic and corresponding interactions on design workflow and project's performance, (2) to design a BIM-based dashboard to enhance the monitoring and control of design progress by monitoring different elements' dynamics, and (3) to develop a top level BIM ontology to standardize the definition of design work packages based on the BIM elements needed to express design intent and the corresponding design tasks necessary to reach the desired design solution. The roadmap followed in this study targets the development of these three points across three different modules as highlighted in Figure 4.2.

4.2 Research Method

The research method employed in this study is Design Science Research (DSR). DSR is suitable to conduct research in the construction management field where innovative concepts and tools can be developed to address practical field problems and to add value to involved stakeholders (Rocha, et al. 2012). DSR is also known as constructive research that has two fundamental activities: (1) creating artefacts to serve human purposes and (2) evaluating their performance in use (March and Smith, 1995). In design sciences, knowledge is produced by creating and implementing solutions that can manipulate a particular phenomenon (Vaishnavi and Kuechler 2007). In this regard, DSR is inherently iterative and incremental where the testing/application steps provide essential feedback for the development of the desired artifact (Hevner, et al. 2004).

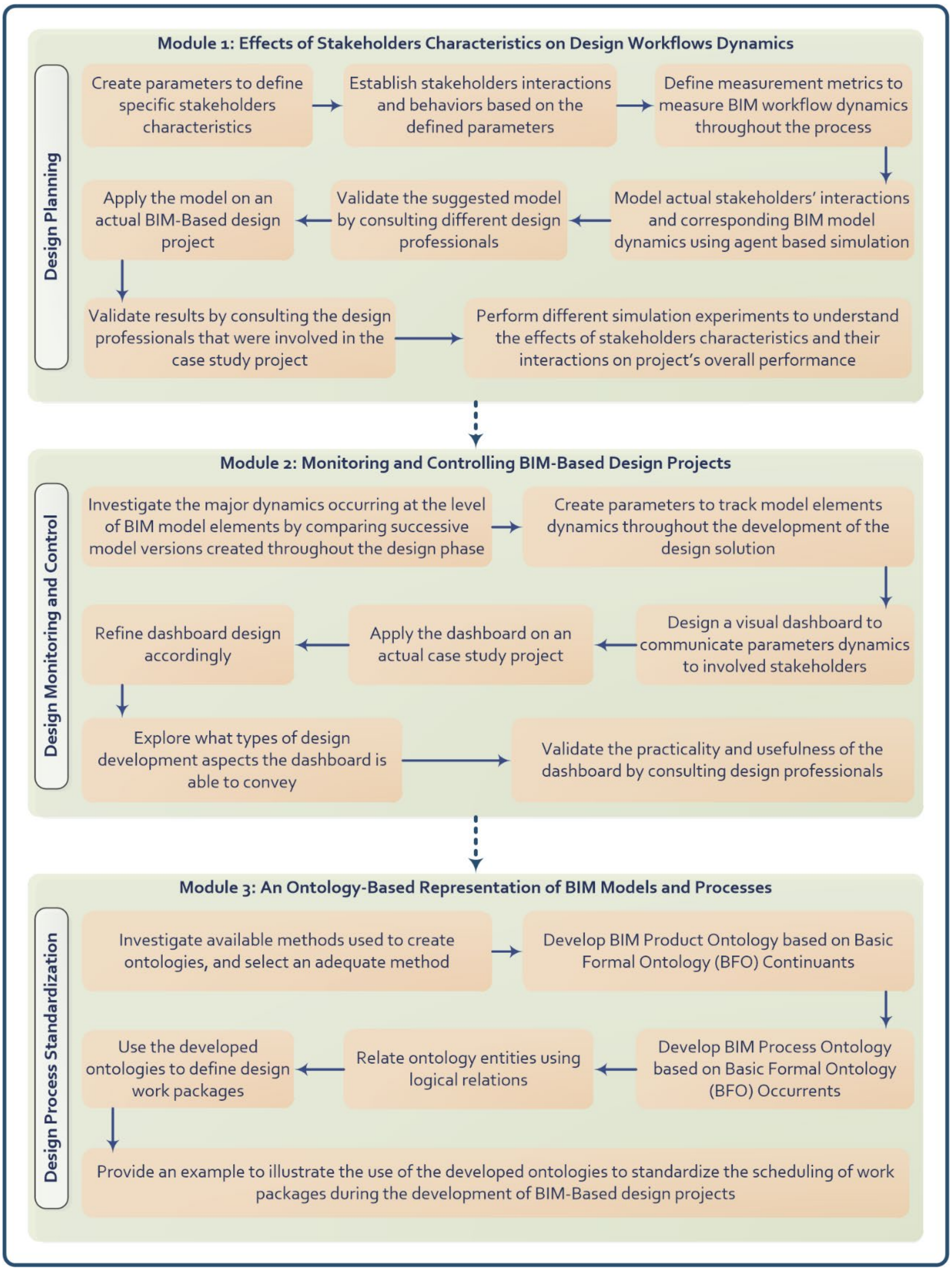

Figure 4-2: Research Roadmap

Models are among several types of artifacts that can result from a DSR research. "A model is a conceptual object that comprises constructs and associations among these constructs as a way to describe and represent some subset of real-world phenomena" (Weber 2013). In this study, several models were created depending on the corresponding research scope following the guidelines advocated by Hevner, et al. (2004). In this context, an artifact is designed, applied and tested in each module of the study to help the researchers reach specific research outcomes.

The research consists of three modules as highlighted in Figure 4.3. Each module comprises the development of a model artifact that serves the research objectives of the corresponding module. From a DSR perspective, understanding a design/research problem and its solution is acquired through the building and application of a representative artifact (Hevner, et al. 2004). Accordingly, different models/artifacts were built in each module of the study to enable the researcher to better understand the research problem and to suggest adequate solutions. The following sections will elaborate on each module separately.

4.2.1 Module 1: Effects of Stakeholders' Characteristics on Design Dynamics

Module 1 aims to understand the dynamics of design workflows resulting from the interactions among different involved design stakeholders. In specific, this module investigates the effects of interactions among the project's owner, the architect and the engineer on design workflows in the concept and preliminary design stages. For this purpose, an agent-based simulation model (ABM) is developed to mimic these dynamics. The developed simulation model serves as a representational artifact of a subset of a real-world phenomenon which is the BIM-based design process. The developed model allows the researchers to better understand the actual phenomenon's characteristics and enables them to investigate different real-life scenarios. Nonetheless, the developed model can be used as a tool to enhance the planning reliability of design projects as will be discussed in Chapter 5.

A conceptual model is first developed as highlighted in Figure 4.3. Five different types of agents are defined. The first agent type represents the project's owner which has a value that needs to be fulfilled at the end of the design phase. The role of the owner is to express its needs and requirements on one hand, and to review and evaluate the suggested design developed by the architect and engineer agents on the other. In this context, the initial perception of the project's value differs from one owner to another; it depends on the owner initial knowledge and on the complexity of the design project. For instance, a knowledgeable client is more likely to be able to define its project's value early in the design process; however, this ability decreases if the project's complexity is high where an initial accurate definition of project's value is hard. Moreover, the client has a learning model that governs the speed and extent of owner's learning ability about the project's value. This model is affected by the design process architecture as well as by the architect's and engineer's characteristics that influence the learning ability of the owner. The details about the owner agent characteristics and behavior are elaborated in Chapter 5.

The second agent type defined in the ABM model is the architect agent. The architect is responsible for the development of the architectural BIM model which represent the architectural design intent of the architect. The architect agent develops the architectural BIM model based on client value and the reviews received from the client after each design iteration. In this regard, the architect's ability to define and shape the project's value differs from one architect to another. Nonetheless, this ability affects the project's value itself and affects the client satisfaction. Therefore, architect's characteristics influence the progress of the design solution and the corresponding design workflows. The details about the architect agent are further elaborated in Chapter 5.

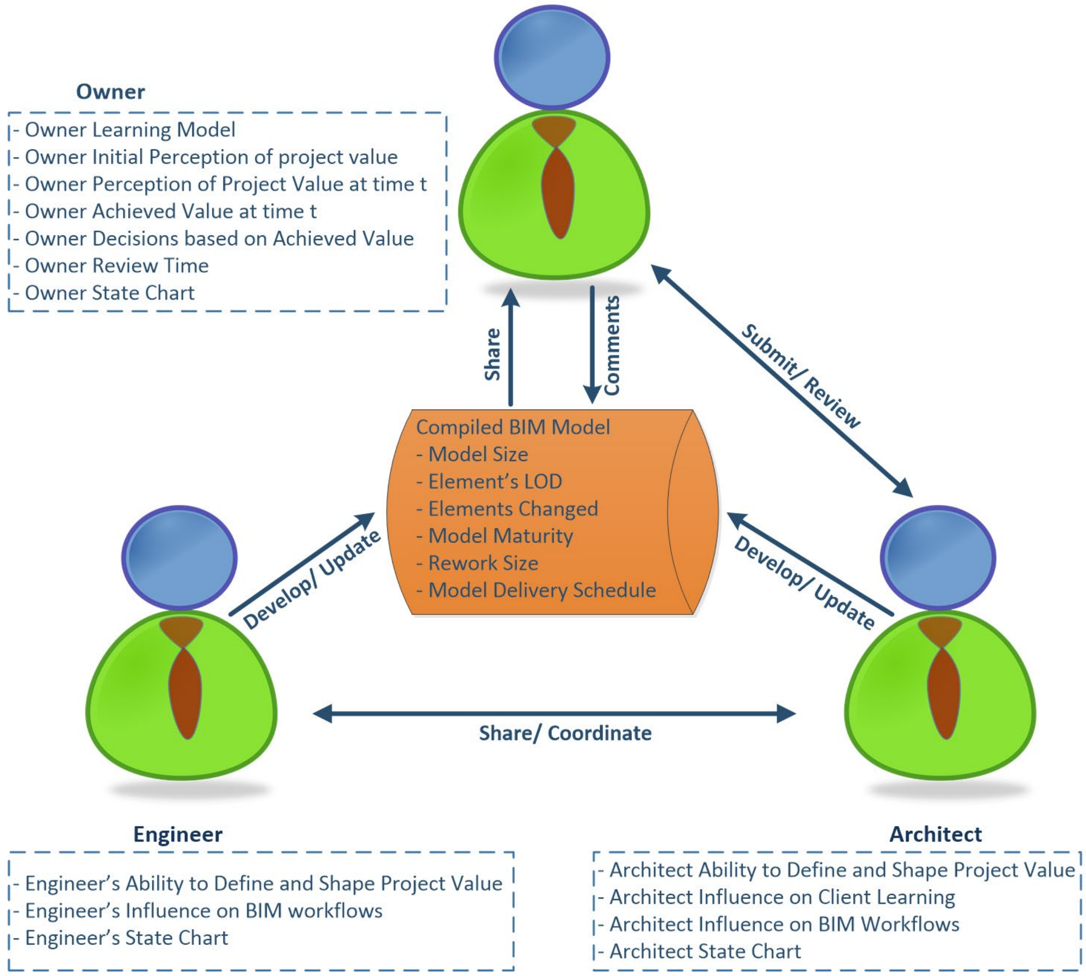

Figure 4-3: Simulation Conceptual Model

The third agent type defined in the ABM model is the engineer agent. This agent represents actual engineering consultants that have the role of providing adequate engineering solutions based on the developed architectural design and client value. The engineer agent can be a structural engineer, a mechanical engineer, an electrical engineer or any other specific engineering consultant. The role of the engineer agent is to develop and update the engineering BIM model based on the client needs and the performed coordination with the architect. The ability of the engineer to provide adequate engineering solutions differs from one engineer to another. While a high ability engineer can provide adequate engineering solutions that result in less rework and negative iterations, a low ability engineer may cause a greater amount of rework after each architect-engineer coordination. Therefore, the characteristics of the engineer agent does affect the corresponding design workflow among design participants. The characteristics of the engineer agent are further detailed in Chapter 5.

The fourth and fifth agent types defined in the ABM model are the architectural element (archElement) and the engineering element (engElement). These agent types represent the architectural and engineering BIM model elements that are created throughout the different stages of the design phase. Each individual archElement or engElement can witness several dynamics during the development of design. It can be created, deleted, changed, updated, or even developed. Specific metrics are defined to track these dynamics and the corresponding details are provided in Chapter 5.

Once the conceptual ABM model draft was ready, design professionals from an esteemed design firm were consulted for their feedback. The consulted designers have more than 20 years of experience in design management and have been engaged in different types of design projects. Nonetheless, the firm’s work scope covers a wide range of projects from residential, hotels, and towers to infrastructure projects and airports. Accordingly, the ABM concept model was refined and developed based on consultants’ comments. Nonetheless, the need for developing a process architecture to map the corresponding design workflows was highlighted by the design professionals. Therefore, a process architecture to represent BIM models’ exchanges and flows was developed as highlighted in Figure 4.5. The process shows BIM deliverables published and shared among different design parties, basically the architect, the client, and the engineer.

The resulting conceptual ABM model along with the process map are further developed into a computational ABM model using AnyLogic; a well-known simulation software used in Academia and practice. The details of the computational model are presented in Chapter 5. The developed model served as an artifact that represents the real BIM-based design process. In this regard, the model was used to further understand the different dynamics occurring during early design phases. Nonetheless, different project scenarios were tested under different project conditions. The scenarios represent combinations of different ranges of parameters that are created to describe different agents' characteristics.

In this regard, an actual case study project is used to calibrate the parameters' values used as inputs to the simulation experiment. Accordingly, the case study served as a starting point of the conducted simulation experiments and was used as a reference scenario. The simulation results of the case study scenario were compared to the actual performance of the case study project as a form of validation of the simulation model. Finally, different scenarios were tested, and results were plotted and analyzed to highlight the impact of stakeholders' characteristics on the dynamics of design process workflows.

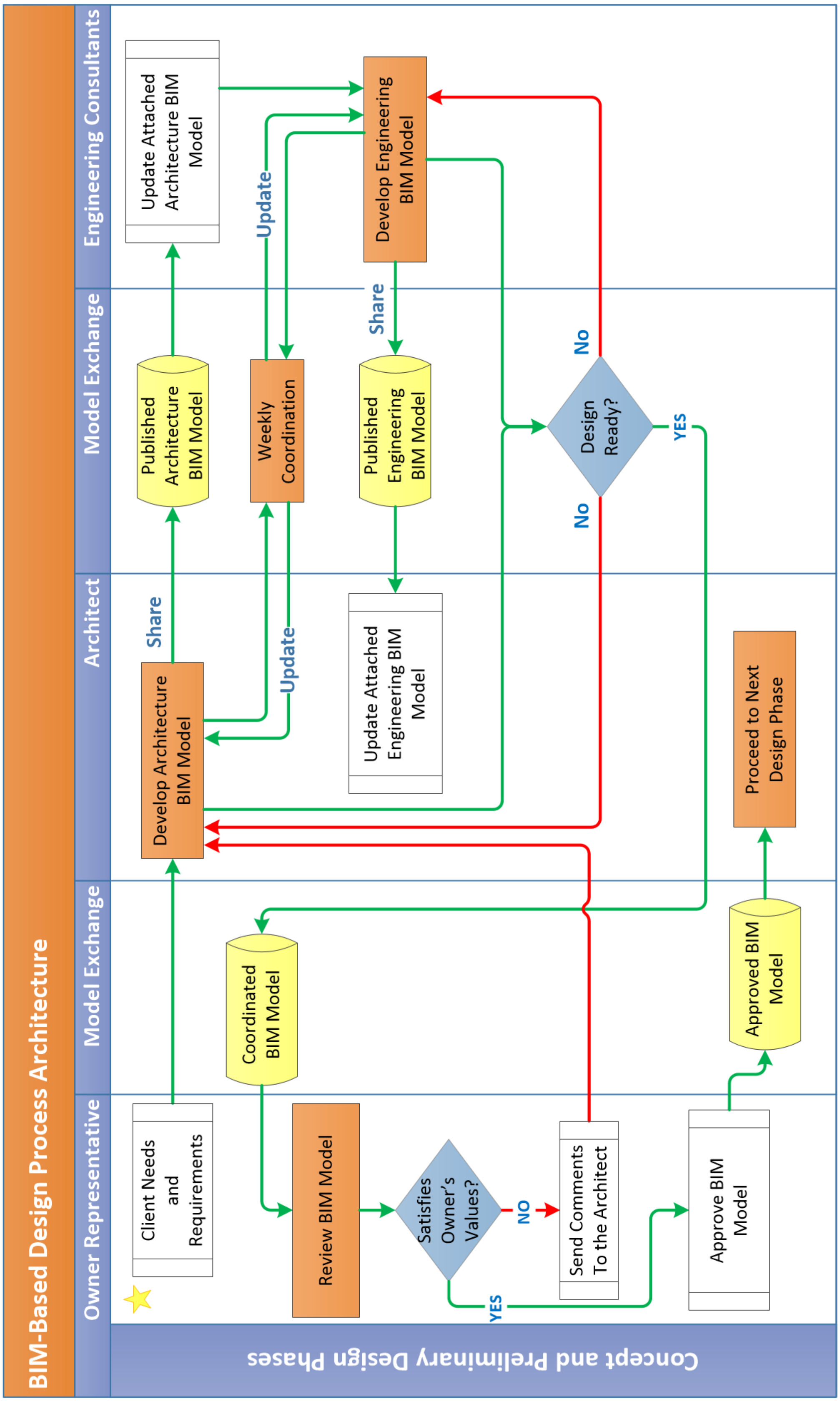

Figure 4-4: BIM-Based Design Process Architecture

4.2.2 Module 2: Monitoring and Controlling BIM-Based Design Projects

The study performed in module 1 resulted in several questions about the type of dynamics witnessed at the level of model elements during the development of the design solution. More precisely, how does the elements' geometry, information attached, Level of Development (LOD) and category types change over time. Based on that, module 2 of the study was developed to better understand these types of changes. For this purpose, a visual dashboard is designed to track changes related to BIM model content. While several changes can be extracted from a BIM model, only changes that can be used to infer about design development are monitored. Accordingly, several variables are developed to depict model changes in each consecutive version published on a BIM cloud as further elaborated in Chapter 6.

The designed dashboard is another artifact developed during this study to help the researcher better understand the nature of dynamics witnessed inside BIM models during design development. Nonetheless, the visual dashboard is further developed to serve as a useful tool that can be used by practitioners to better detect and control the development of BIM models' content. The design of the dashboard consisted of four major steps highlighted in Figure 4.5.

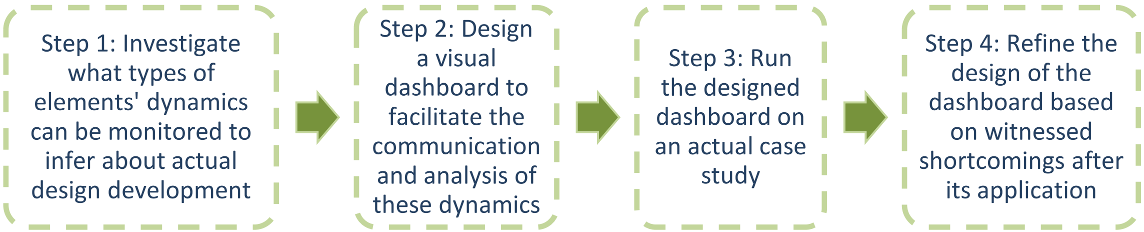

Figure 4-5: Dashboard Design Steps

In the first step, different types of elements' changes witnessed during the development of the design project were investigated. Changes related to elements' shape, location, data attached, LOD, as well as the number of elements' types were checked. Accordingly, different variables were created to represent each of these changes. Note that the selection of variables was also affected by which variables can be automatically detected using the current state-of-art of BIM technologies.

In the second step, a visual dashboard is designed to represent the defined variables from step 1. The decision to develop a visual dashboard is backed by the importance of visual management revealed in different studies in lean construction (Viana, et al. 2014, Koskela, Tezel and Tzortzopoulos 2018). In this regard, visual dashboards are among the important tools that can help construction managers track and control their project's performance throughout the project's duration. The development of the visual dashboard aims to facilitate the communication and analysis of defined variables' dynamics.

In the third step, the dashboard is implemented on an actual case study project to test its potentials and shortcomings. In this step, the design of the artifact witnessed several iterations, including one iteration after a peer review process, which led to the current design of the dashboard illustrated in Chapter 6. The design iterations aimed to enhance the visual representation of the artifact, to filter the corresponding model dynamics useful for design management purposes, and to enhance the artifact's readability and practicality.

At this stage, the dashboard was filled based on the actual project dynamics translated by the changes of defined variables from step 1. An analysis of the resulting dashboard is jointly performed by the author and the design team leader who managed and coordinated the authoring of the BIM model. The setup of the empirical study followed several steps as illustrated in Figure 4.7. The empirical project consists of six identical residential villas, each divided into two apartments. The project spans over four months covering the end of the schematic design phase and the design development phase. Data is gathered through direct access to project files using a cloud-based application which enabled the authors to export every published version to an excel file showing all data related to the model. Figure 4.6 shows the process followed to gather the required data. The BIM models are first authored locally on desktop computers, regularly shared on the cloud, extracted to an excel file, and compared to previously published versions using a “compare versions” tool. The resulting dashboard details and discussion are presented in Chapter 6.

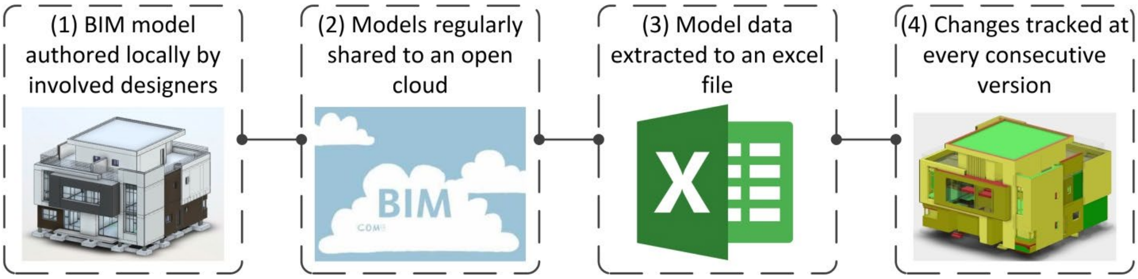

Figure 4-6: Data Gathering Procedure

4.2.3 Module 3: Standardizing the Development of BIM-Based Design Projects

Design is a multi-disciplinary process that involves many design experts from different domains. Accordingly, the development of corresponding BIM models comprises the gradual addition of design information from different disciplines to different model elements across the project’s timeline. For instance, while the architect can determine the planar shape and boundaries of an architectural floor, the structural engineer needs to determine the floor’s thickness, material properties, needed reinforcement and any other needed structural design information. Therefore, the same floor element in this case is receiving design information from two major inter-dependent design disciplines.

This scenario is so common in the design process where so many model elements require data to be determined from different design disciplines. In this context, the development of domain specific design information is dependent on the development of other domain specific information; which justifies the iterative nature of design projects. Accordingly, managing the generation of design information and attributing it to corresponding BIM model elements is a chaotic task in the absence of clear procedures or guidelines. Nonetheless, each discipline has different approaches to generate and add this data to the BIM model elements which can create confusion and misunderstanding among involved designers, especially because information generated is domain specific and requires expertise input.

Accordingly, this module proposes a systematic way to generate and store design information into the BIM model using an ontology-based framework. The developed ontology builds upon Basic Formal Ontology (BFO) developed by (Arp, Smith and Spear 2015) and aims to serve as a representation artefact of both the product and process aspects of BIM. The framework is expected to formalize the generation and sharing of design information among involved stakeholders, to increase the shared understanding among different design teams, to reduce rework resulting from mis-interpretation of design information, and to increase situational awareness by relating model elements to the ongoing design process activities.

In a multi-domain environment, the methods that can be used to build an ontology include: (1) developing a unified ontology that covers all AEC information used in the entire process, (2) developing domain-specific ontologies by corresponding domains' experts and aligning them for information exchange, or (3) developing a core (foundation) ontology that can be extended by all the involved domains (Niknam and Karshenas 2017).

Method (1) is difficult to implement where a globally shared ontology with unified semantics for all AEC information is needed. Even if developed, it would comprise a great number of semantics and rules that are hard to understand and maintain. Method (2) is more convenient than method (1); however, the lack of shared vocabulary among different domains makes it difficult to compare developed ontologies. Thus, mapping and alignment among developed ontologies would be needed to ensure integrity of shared information; a time consuming and error prone process. Method (3) requires creating a core ontology that includes the main concepts common to all involved domains. Therefore, domain experts must build their ontologies based on this core ontology (Niknam and Karshenas 2017). Method (3) addresses the shortcomings of methods (1) and (2) and best fits the objectives of this study; thus, it has been employed in this research.

The ontology developed in this study is based on Basic Formal Ontology (BFO) developed by Arp, Smith and Spear (2015). BFO is an upper level ontology created to support data integration in scientific research. BFO serves as a starting point for domain experts to build their domain specific ontologies by providing a common top-level ontology. Thus, BFO is designed to ensure that domain ontologies developed based on it represent universals in their respective domains in a consistent and coherent fashion (Arp, Smith and Spear 2015).

The development of the suggested ontology involves three main steps as highlighted in Figure 4.7. The first step targets the development of a BIM Product Ontology using BFO Continuants to represent BIM models and their constituents. The second step targets the development of a BIM Process Ontology based on BFO Occurrents to represent aspects of the BIM-based design process while step 3 presents logical relations used to relate involved ontology entities together. The developed framework is detailed in Chapter 7 of the study.

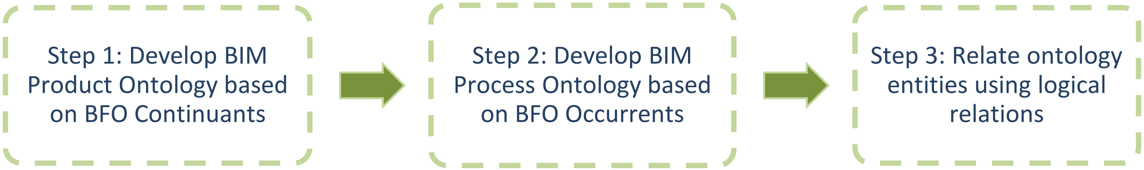

Figure 4-7: Ontology Development Steps

4.3 Research Methodology

4.3.1 Simulation Modelling

Simulation is a methodology used to represent a subset of a real-world phenomenon while focusing on important aspects and behaviors that are of interest to the researcher. In this regard, simulation can be used for different purposes depending on the target and scope of the research. It can be used to better understand the behavior of a complicated system, to solve problems, to optimize a process, to analyze agents' behaviors, or even to measure a system's performance (Abourizk 2010). In this context, simulation, if properly employed, can be a more reliable and comprehensive alternative than regular analytical or qualitative procedures. Simulation allows the researcher to perform different experiments under different scenarios and conditions. The flexibility offered by simulation may not be attained in real life where experimenting with real projects might be hard or just impossible. Even if possible, experimenting with real-life projects might harm the project's performance and affect its value.

While assessing the performance of design project within a network of interconnected workflows and stakeholders' dynamics is hard to capture using real life observations alone, simulation is employed in this study to provide the researcher more control over the process environment. Accordingly, agent-based simulation modeling is used in this study to mimic actual BIM-based design processes and to model the behavior of involved design stakeholders. In this regard, variables and parameters are developed to reflect agents' and process characteristics which can be controlled, measured, and manipulated across different simulation experiments. This approach allows to analyze, measure, and understand design workflow dynamics based on different project's conditions.

4.3.2 Case Study Application

Case studies are employed to provide more realistic and rigorous evidence to a conducted research study. They can be employed to help understand the behavior of complex systems that could not be comprehensively realized using experimental research alone (Zaidah 2007). In this regard, case studies can capture more realistic aspects about an actual phenomenon than other research methods. This is of high importance in the case of the studies that have some sort of social characteristics (Hodkinson and Hodkinson 2001) as in the case of the design process.

Two case studies are employed in this research both in modules 1 and 2. In module 1, an actual case study project is employed to serve as a data input for the developed simulation experiment. First, the case study is used to calibrate the simulation model as to reach comparable results when running the simulation experiment under conditions similar to those witnessed in the real project. In this context, the case study is used as a form of validation of the simulation model. Nonetheless, the case study served as a reference to analyze the results of the conducted simulation experiments that considered several project's scenarios.

Several measures were considered before selecting the corresponding case study; basically, the size and significance of the project, the accessibility to the project's data, the completeness of the project's archive where different BIM model deliveries were made across the project's timeline, and the adequacy of the project's phase as to suit the objectives of the research. Accordingly, the case study selected is an ongoing airport design project currently under the schematic design phase. The focus is on the arrival and departure building of the airport that witnessed interesting design dynamics across its early design development. Being an ongoing project, the researcher was able to understand the actual context of the project by consulting the main key designers currently working on it.

The second case study is employed in module 2 of the research to serve two main purposes: (1) data collection necessary to develop the BIM dashboard and (2) the application and testing of the designed dashboard. In addition to the measures considered in selecting the first case study, the use of advanced BIM applications was necessary to be able to collect the necessary project dynamics required in this module of the research. In this regard, the use of BIM360 as a platform to run and manage the design phase was a basic condition to select a suitable case study.

Accordingly, a residential development project consisting of six villas is selected to serve the research objectives of module 2 of the study. The project spans over a four-month period and it covers the end of the schematics and the entire design development phases. The research was able to get direct access to the project cloud where all necessary data was available. Being a live project, different kinds of model dynamics were detected on the spot; gives the researcher a greater understanding of the ongoing process which positively influenced the design of the desired dashboard.

4.4 Research Limitations

This section elaborates on the major limitations encountered across the development of the research. Since the study is divided into three major modules, the research limitations are classified accordingly as presented in the following sections.

4.4.1 Module 1 Limitations

Module 1 investigates the influence of the characteristics of design stakeholders' and their corresponding dynamics on the performance of design projects. In this regard, several limitations are acknowledged in this module. First, at the level of agents' definitions, not all involved design stakeholders are modelled. Only the architect, the owner, and the engineer agent that represents all engineering consultants are considered. This does not reflect the entire reality witnessed during design projects were a greater number of design professionals are involved. However, the defined agents are considered satisfactory for the scope and objectives of this module.

The second limitation is about the defined characteristics of selected agents. While any agent can have a wide range of characteristics that govern its behavior that affect design dynamics, only major and simplified characteristics are employed in this study to serve the research goals. Nonetheless, a simplified learning model is developed for the owner agent to model its learning behavior about the project value during design development. In this context, specific and targeted research can be conducted in future works around this topic.

4.4.2 Module 2 Limitations

Module 2 of this study targets the development of a visual dashboard to detect different BIM model dynamics during the design phase of construction projects. The dashboard is applied on a case study project as part of its development process, and therefore the dashboard design can be influenced by the setup of the corresponding case study project and involved practitioners. Therefore, the dashboard needs to be further tested on different projects and with other companies before it can be adopted as a visual tool that can be used to track model-based development. Moreover, the current case study project adopted to test the dashboard application covers only the architectural and structural BIM models; however, it is important in future studies to track the dynamics of MEP models also to have a comprehensive idea about the overall project' dynamics.

4.4.3 Module 3 Limitations

Module 3 targets the development of a top-level BIM ontology to represent BIM-based design projects at both the design product and process levels. In this module, only an illustrative example is used to showcase the developed ontology as a representational artifact. In this regard, the objective of this module is to develop a new approach to represent design information on BIM platforms and to link BIM model elements to corresponding design activities. Therefore, this module develops an ontology-based artifact to represent BIM projects and investigates the design management implications of such an approach. In this regard, the designed BIM ontology needs to be further developed and applied on actual case studies to test its practicality and robustness.

CHAPTER 5

EFFECTS OF STACKHOLDERS CHARACTERISTICS ON DESIGN WORKFLOW DYNAMICS

5.1 Preface

This chapter details the development of Module 1 of this study that aims to understand the effects of stakeholders' interactions on design workflow dynamics. The following sections elaborate on the experimental setup of the simulation modelling including the development of the ABM computational model, the setup of different stochastics experiments that target the development of the project under different conditions, and the analysis and discussion of the corresponding results.

5.2 Simulation Model Development

This section presents the development of the computational ABM model using AnyLogic Software. It includes several sub-sections that highlight the definition of model agents, their characteristics, and the corresponding experimental setup arranged to check different model development scenarios.

As presented in Chapter 4, different agent types are developed in this module to mimic the development of real BIM-Based design projects. The environment considered in this study is the design project, where designers from different disciplines work together to address client needs, while developing corresponding BIM models as highlighted in Figure 5.1. The project's client, the architect, the engineer, the architectural element and the engineering element are the five main agent types defined and used in this study. While the client, the architect and the engineer are defined as individual agents, the architectural elements and structural elements are defined as a population of agents that form the corresponding architectural and engineering BIM models consecutively. The following sections elaborate on each of the defined agents.

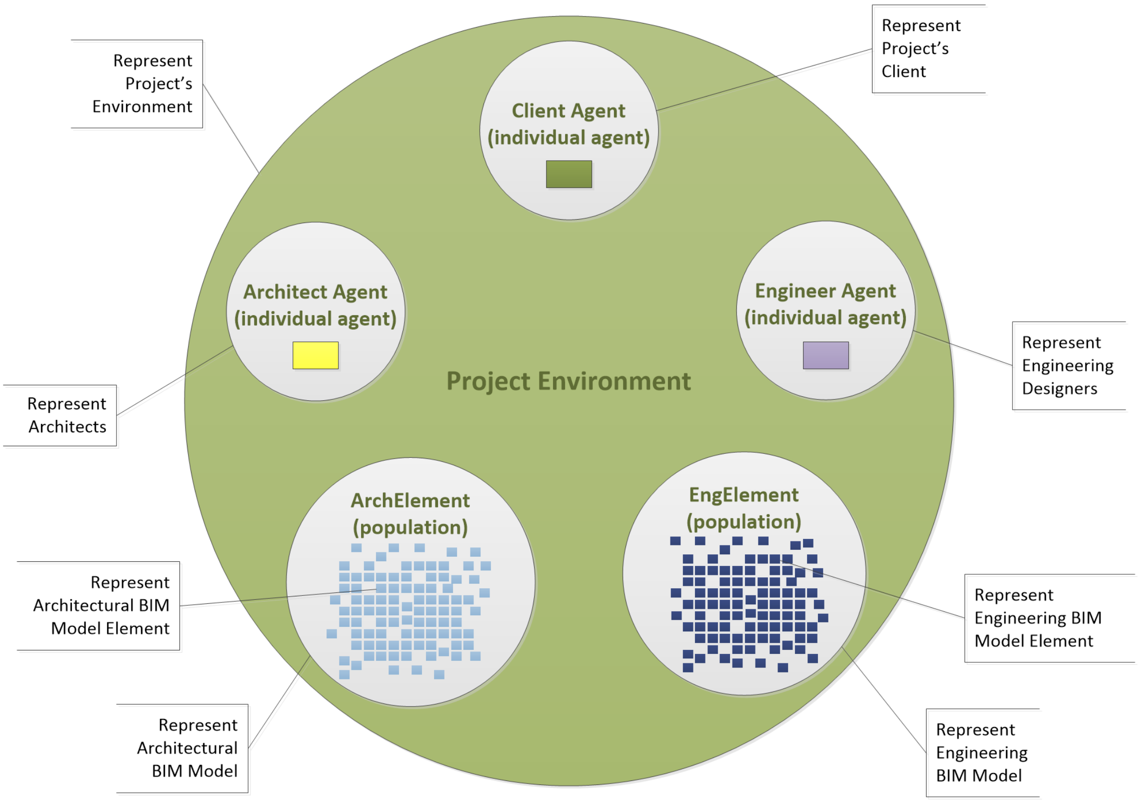

Figure 5-1: Simulation Model Environment

5.2.1 The Client Agent Type

5.2.1.1 Client Agent Characteristics

The client agent type represents the actual clients of real-life design projects. While the project's client can be an organization, a group of persons, or an individual, this study considers the case of an individual client responsible to define the project's value, to take decisions related to the development of the corresponding design solution, and to react to the architect's and engineer's deliverables across the project's phases. The following two sections elaborate on client agent's characteristics and state chart.

Different parameters and variables are defined to represent the characteristics of the client's agent. While a real client can have a wide range of characteristics that affect its behavior in a design project, only simplified characteristics related to the client's perception of project's value are developed in this study as highlighted in Tables 5.1 and 5.2.

$PPVc_0$, which stands for the Perception of Project's Value by the Client at time t_0, is a parameter defined to represent the perception of the client about the project's value at the start of the design phase. In the construction industry, value is often related to the understanding and achievement of client's needs and objectives (Bertelsen and Emmitt 2005). In this regard, the assessment of a project's value is affected by the customers' beliefs and morals that affect their attitudes and behaviors towards the delivered product and corresponding services (Thomson, et al. 2003). Thus, a project's value in the eyes of its client, is the result of an evaluative judgment based on the client's values and beliefs (Sánchez-Fernández and Iniesta-Bonillo 2007).

In this regard, the value of $PPVc_0$ depends on how much the client can initially perceive and outline the value of its project based on his/her needs and requirements. While this initial perception can be relatively accurate for clients who know what they want from a project, it can be vague for those who do not have a clear set of needs and requirements. Nonetheless, the ability of a client to accurately perceive a project's value decreases with the increase of project's complexity where different design stakeholders can alter and shape the project's value during the search for a design solution.

CKL, which stands for Client Knowledge Limit, represents the understanding limit of the client regarding the value of its project during each phase of the design process. In other words, CKL reflects how much can a client perceive the actual value of its project before being constructed and operated, based on produced design deliverables. Thus, the CKL value is affected by the ability of the client to understand design intent from one hand, and by the ability of the designers to properly communicate their corresponding design solution. Note that the CKL value is dependent also on the corresponding design phase where the client knowledge limit is expected to be higher in the preliminary design phase than in the concept phase because of the generation of more defined design deliverables which allow the client to extend its knowledge about the project’s value.

CRT, which stands for Client Review Time, represents the time needed by the client to review the deliverables submitted by the designers during the development of the project. CRT values are affected by the amount of design information that the client needs to digest while reviewing the design, and whether the client is engaged in the design process or not. An engaged client who is continuously updated on design progress is more likely to respond faster than a non-engaged client who would need more time to go over and understand the design deliverables. Nonetheless, the variability in CRT values is directly related to the client being committed to the project progress or not. A committed client is more likely to witness less variability in CRT values because he/she acknowledges the importance of his/her review decisions on the development of the design solution.

Table 5-1: Client Agent Parameters

Parameter	Description	Range
$PPVc_0$: Project Perceived Value at time t_0	The initial perception of the client about the actual value of its desired project.	0 – 1
CKL: Client Knowledge Limit	The ultimate knowledge limit of the client at each design phase	0 – 1
CRT: Client Review Time	The needed time by the client to respond back to designers' deliverables	NA

Table 5.2 presents the defined variables that also target client's characteristics. The difference between variables and parameters is that the variables are updated during the simulation run based on the dynamics witnessed in the simulation model that mimic the dynamics of real-life projects. Accordingly, these variables are defined to track the changes in client's status related to its perception of project's value.

PPVc represents the Perception of Project's Value by the Client at time t of the project's timeline. The PPVc variable is defined to track the changes in client's perception of project's value during the development of the design project. It is expected that the client would be progressively learning about the project's value as the design solution is uncovered at each design iteration. With the absence of specific models to represent client's learning process, an S-Curve generic model is employed. The S-Curve model can be employed to follow a learner's journey from un-familiarity to mastery and can be adopted at the levels of individuals or organizations (Dam 2008, Handy 1995). In this regard, Equation (1) is developed to model the learning behavior of the client during the design phase. Equation 1 updates the PPVc values based on an adjusted Sigmoid function. While every client can have a specific learning behavior, clients are expected to share the same learning trend that starts slowly at early project phases and then increases as the design got refined with every design iteration.

Nonetheless, PPVc values are affected by the initial PPVc$_0$ and the client knowledge limit (CKL) as shown in Equation (1) and abstracted in Figure 5.2. Although the client would be learning more about his/her project during the design phase, there is a limit to this knowledge at the end. Also, the rate at which the client is learning about his/her project is affected by two major parameters: parameter "k" that is related to the client being engaged or not in the design process, and parameter "l" that reflects the A/E team influence on client' learning rate. As for the extent of client knowledge (CKL), it is also affected by the A/E team's ability to shape and define the project's value, through the parameter "f". For instance, a high ability A/E team is more likely to be able to extend the client's knowledge limit on one hand by actively shaping project's value, and to accelerate the client's learning process.

$$PPV_C = PPV_{C0} + \frac{f.(CKL - PPV_{C0})}{1 + e^{-(x-5.k.l.)}} \qquad Eq(1)$$

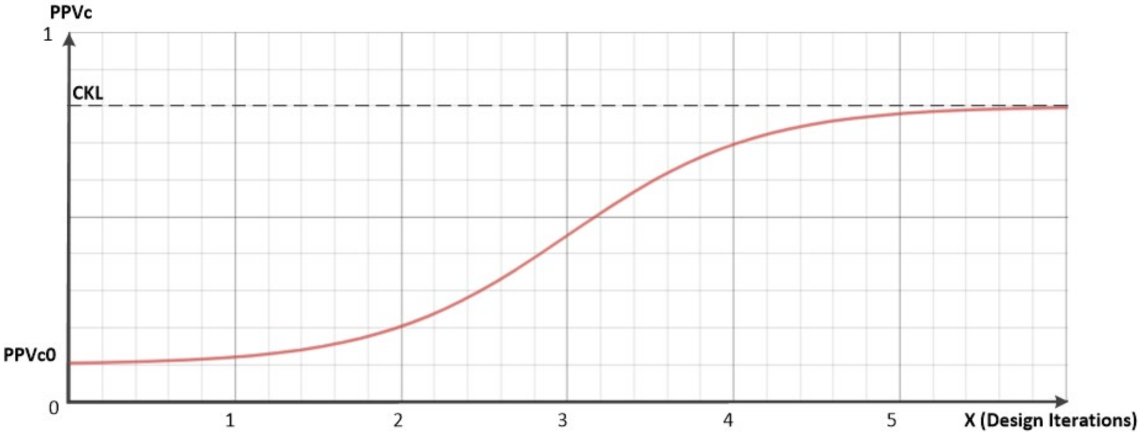

Figure 5-2: Client Learning Model Abstraction

In addition to the PPVc variable, three other main variables are defined. PAV, which stands for the Perceived Achieved Value, reflects the percentage of value achieved form the client's perspective. Thus, PAV is used to reflect on the satisfaction of the client in terms of achieved value. PAV is affected by the current PPVc of the client, his/ her ultimate CKL, and the architect's influence modeled through the parameter "f" as shown in Equation (2). For instance, if "f" is 1.2, CKL is 0.7, and PPVc is 0.35, the client would feel as achieving 40% of its project value.

$$PAV = \frac{PPVc}{f.CKL} \qquad Eq.(2)$$

Table 5-2: Client Agent Variables

Variable	Description	Range
PPVc: Project Perceived Value at time t	The actual perception of the client about the project's value at time t of the project	0 – 1
PAV: Perceived Achieved Value	The perceived achieved value at time t of the project.	0 – 1
HVG: Hidden Value Gap	The difference between the potentially achieved value of 1 and PPVc	0 – 1
CCI: Client Change Impact	The impact of client changes on the number of BIM model elements affected	0 – 1

HVG, which stands for Hidden Value Gap, reflects the gap between the potential value of 1.0 and client's current perception of project's value PPVc. In this regard, HVG is expected to decrease over time where PPVc values are increasing as the client is continuously learning about his/ her project's value. HVG is updated throughout the simulation experiments using Equation (3).

$$HVG = 1 - PPVc \qquad Eq.(3)$$

CCI, which stands for Client Change Impact, is defined to reflect the impact of client's changes on the developed BIM models. High CCI values are reflected in more elements witnessing changes in the reviewed BIM models, and therefore, more rework for the architect and engineer agents. In this context, CCI is affected by HVG, where higher HVG values are expected to initiate serious changes from the client side as soon as the corresponding gaps are discovered. The range and the maximum values of CCI are higher when HVG is big; however, the variability and values of the CCI variable decrease when HVG decreases. CCI is defined in this study to be randomly varying based on HVG values as presented in Table 5.3.

Table 5-3: Client Change Impact (CCI) Values

HVG range	**CCI range**
0.8 < HVG < 1.0	0.5 < CCI < 1.0
0.6 < HVG < 0.8	0.4 < CCI < 0.8
0.4 < HVG < 0.6	0.3 < CCI < 0.6
0.2 < HVG < 0.4	0.2 < CCI < 0.4
0.0 < HVG < 0.2	0.1 < CCI < 0.2

5.2.1.2 Client Agent State-Chart

Having defined the characteristics of the client agent type following a set of parameters and variables, this section presents the state-chart of the client agent during the development of the design project. Figure 5.3 shows the different states the client agent can pass through. Recall that only the conceptual and preliminary design phases are under the focus of this study and that only states related to these phases are considered.

The client can be at three main different state types: Idle, Reviewing, or Waiting between two consecutive design phases. After sharing his/ her needs and values with the Architect/ Engineer (AE) team before the start of the design process, the client agent enters the idle state that corresponds to the conceptual design phase, Idle_CD. When the AE team is ready to share the first issue of their conceptual design, the client agent moves to the Review_CD state which corresponds to the actual reviewing process performed by clients on real projects. In this state, the client agent reviews the conceptual design solution, weighs it against his/ her project values, and reacts accordingly.

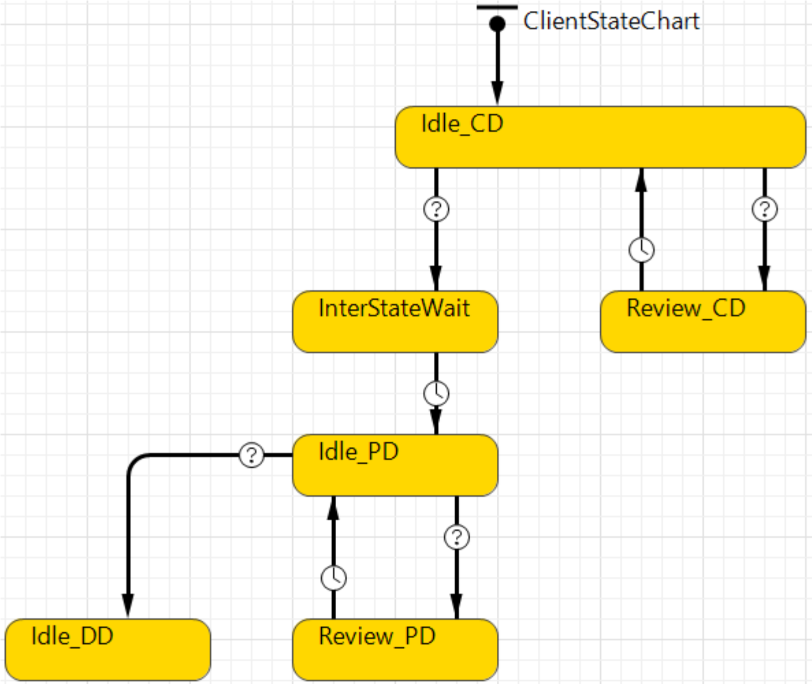

Figure 5-3: Client Agent State Chart

Two main decisions can be taken by the client agent after finishing the review process based on the degree to which its value is achieved by the proposed design. If the design product satisfies the client needs, the client would ask the AE team to proceed to the next phase. If not, he/ she would ask the AE team to engage in a new design iteration under the same phase to address corresponding comments. This process would repeat until the client feels that he/ she achieved the needed requirements at this stage of design.

In this context, the status of the client agent is updated through the update of corresponding variables. In this regard, PPVc, PAV, and HVG are updated based on equations 1, 2, and 3, while CCI is updated based on Table 5.3. Nonetheless, the variable “x” which reflects the number of design iteration in Equation (1) is updated incrementally at every review process that requests new changes in design. The update of these variables reflects the actual change in client’s status after reviewing the proposed design in real-life projects. In this regard, the satisfaction of the client agent is assessed by checking the value of the variable PAV which reflects the client’s satisfaction. In this study, it is assumed that the client agent is considered satisfied if PAV is at least 0.80. Once crossing this threshold, the client would demand the AE team to proceed to the next design phase.

Starting a new design phase, the client agent would witness an update for its corresponding parameters and variables. $PPVc_0$, corresponding to the preliminary design phase, would take the final value of the variable PPVc reached at the end of the conceptual design phase. It means that the client agent starts the preliminary design phase with more defined value. Nonetheless, CKL is also updated as to match the new knowledge limit the client would achieve by the end of the preliminary design phase. In this regard, the client knowledge limit in the preliminary design phase is expected to be higher than that of the concept phase since more design information is revealed. This allows the client to expend its knowledge limit, if compared to the concept phase.

Once updated, the client would engage in a new loop of reviewing design deliverables under the preliminary design phase. The same procedure followed in the concept phase is repeated in the preliminary design phase. Variables are assessed after every review process following Equations 1, 2, and 3 as well as Table 5.3. In this regard, the preliminary design phase would witness several iterations until the client’s value is achieved. Once the PAV variable reaches again a 0.80, the client would ask the

AE team to proceed to the next phase, the Design Development phase in this case. The client agent will then move the idle phase related to the design development phase, Idle_DD.

5.2.2 *The Architect/Engineer (AE) Team Characteristics*

The Architect/Engineer (AE) team represents the actual architectural and engineering teams involved in real life projects. The AE team is responsible for transforming the value of the client into an actual design product that can be constructed on site. Two main parameters, "f" and "l" are defined to represent the AE team characteristics as presented in Table 5.4. These two parameters are a forming part of Equation (1) that reflects the perceived project's value in the eyes of the client.

While parameter "f" is used to model the influence of the AE team on the client knowledge limit (CKL), "l" is used to model the competency of the AE team in realizing the defined client's value. In this regard, bigger "f" values are used to extend the CKL of the client, while bigger "l" values are used to shorten the time needed to reach a design solution that satisfies the client needs. For instance, a high ability AE team can extend the knowledge limit of the client by actively shaping and defining the project's value, while consuming a smaller number of iterations to converge to the required design solution. Within the AE team, two main agent types, the Architect and the Engineer agent types, are defined as shown in the following sections.

Table 5-4: AE Team Parameters

Parameter	Description	Type
f	AE team ability to shape and define project's value	Double
l	AE team ability to achieve defined project's value	Double

5.2.3 The Architect Agent Type

5.2.3.1 Architect Agent Characteristics

The Architect agent type represents the actual architects of real-life design projects. While the project's architect can be an organization, a group or an individual architect, this study considers an individual architect agent that represents the entire architecture team. The architect agent is responsible for the development of the architectural design solution, and to produce the corresponding architectural BIM models. The architect agent is also required to address client's comments in every design iteration.

In addition to the architect's influence on the project's value definition and realization, modelled as part of the AE team parameters, the architect agent has another parameter that affects the development of the architectural BIM model. In this regard, the Architect Production Rate (APR) parameter, presented in Table 5.5, is defined to reflect the production rate of the architect in terms of the number of architectural elements generated inside the BIM model at a certain LOD level. APR does not only reflect the time needed to model an element to a certain LOD level, but also it counts for the time needed to perform the architectural design task.

Table 5-5: Architect Agent Parameters

Parameter	Description	Type
APR	Architect's Production Rate	Double

5.2.3.2 Architect Agent State-Chart

The architect agent also has a set of states that he/she switches among them during the development of the design project as highlighted in Figure 5.4. While several states can exist in real situations, only the states corresponding to the development of the project are considered. Starting from an idle state before the start of the concept design, the architect moves into the DevelopDesign state which corresponds to the actual development of the architectural design solution. In this state, the architect tries to find an adequate design solution based on client's needs. Nonetheless, during this state, the architect would be creating architectural elements in the corresponding architectural BIM model.

During the development of design, the architect performs weekly coordination meetings with other engineering designers. During these meetings, the architect moves to the Coordinate state, where he/she checks for clashing issues against different involved disciplines. The architect repeatedly moves between these two states until reaching the desired conceptual design. Once reached, the architect agent moves to the ReadyToShare state, waiting for other disciplines to be ready to share the conceptual design with the client. Afterwards, the architect moves to the WaitClientReview state which corresponds to the actual period spent by the architect waiting for client review. Finally, the architect would either engage in a new design iteration under the conceptual design phase if the client is requesting changes in the proposed design or proceed to the preliminary design phase if the client's needs and value are satisfied. In the preliminary design phase, the architect would repeat the same procedure until reaching the desired preliminary design solution.

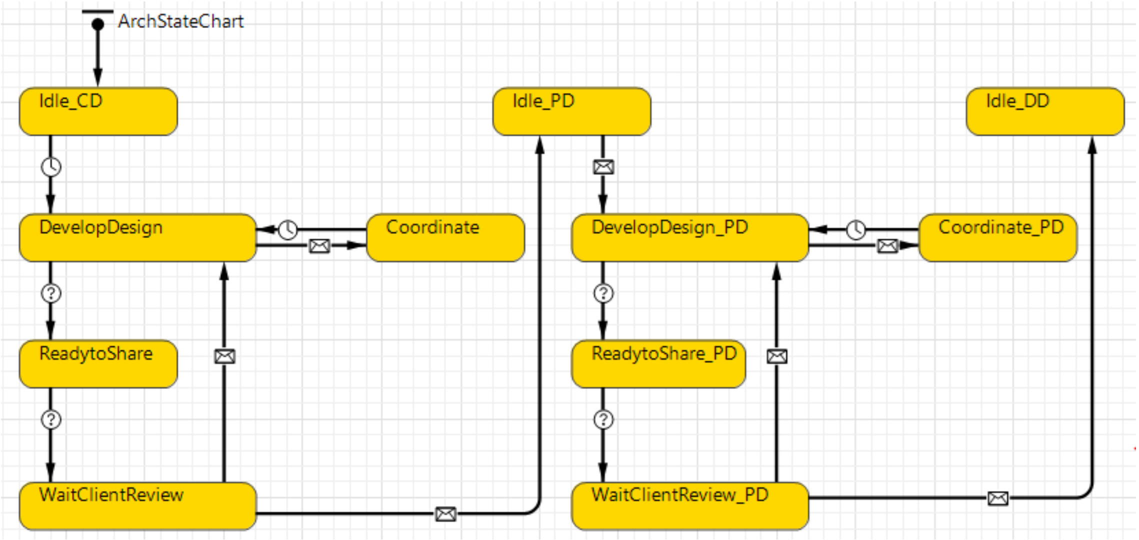

Figure 5-4: Architect Agent State Chart

5.2.4 The Engineer Agent Type

5.2.4.1 Engineer Agent Characteristics

The engineer agent type represents the actual engineering consultants of real-life design projects. While the project's engineer can be an organization, a group or an individual engineer, this study considers an individual engineer agent that represents all engineering consultants present in a project. The engineer agent is responsible for the development of the adequate engineering design solution based on the architectural design and client's needs. The engineer agent is responsible for the development of the engineering BIM model that represent the corresponding engineering design solution.

In addition to the engineer's influence on the project's value definition and realization, modelled as part of the AE team parameters, the engineer agent has another parameter that affects the development of the engineering BIM model. In this regard, the Engineer Production Rate (EPR), presented in Table 5.6, is developed to reflect the number of produced engineering elements in the engineering BIM model under a specific LOD level. EPR does not only reflect the time needed to model an element to a certain LOD level, but also it counts for the time needed to perform the engineering design task.

Table 5-6: Engineer Agent Parameter

Parameter	Description	Type
EPR	Engineer's Production Rate	Double

5.2.4.2 Engineer Agent State-Chart

The engineer agent also has a set of states that he/ she switches among them during the development of the design project as highlighted in Figure 5.5. While several states can exist in real situations, only the states corresponding to the development of the project are considered. Starting from an idle state before the start of the concept design, the architect moves into the DevelopDesign state which corresponds to the actual development of the engineering design solution. In this state, the engineer tries to find an adequate engineering design solution based on the developing architectural design and corresponding client needs. While in this state, the engineer would be creating engineering elements in the corresponding engineering BIM model.

During the development of the engineering design, the engineer performs several coordination meetings with the architect. During these meetings, the engineer agent moves to the coordination state, where he/she checks for clashing issues against the architectural BIM model. The engineer repeatedly moves between these two states until reaching the desired conceptual engineering design. Once reached, the engineer agent moves to the ReadyToShare state, waiting for the architect to be ready to share the conceptual design with the client. Afterwards, the engineer moves to the WaitClientReview state which corresponds to the actual period spent by the engineer waiting for client review. Finally, the engineer would either engage in a new design iteration under the conceptual design phase if the client is requesting changes in the proposed design or proceed to the preliminary design phase if the client's needs and values are satisfied. In the preliminary design phase, the engineer would repeat the same procedure until reaching the desired preliminary design solution.

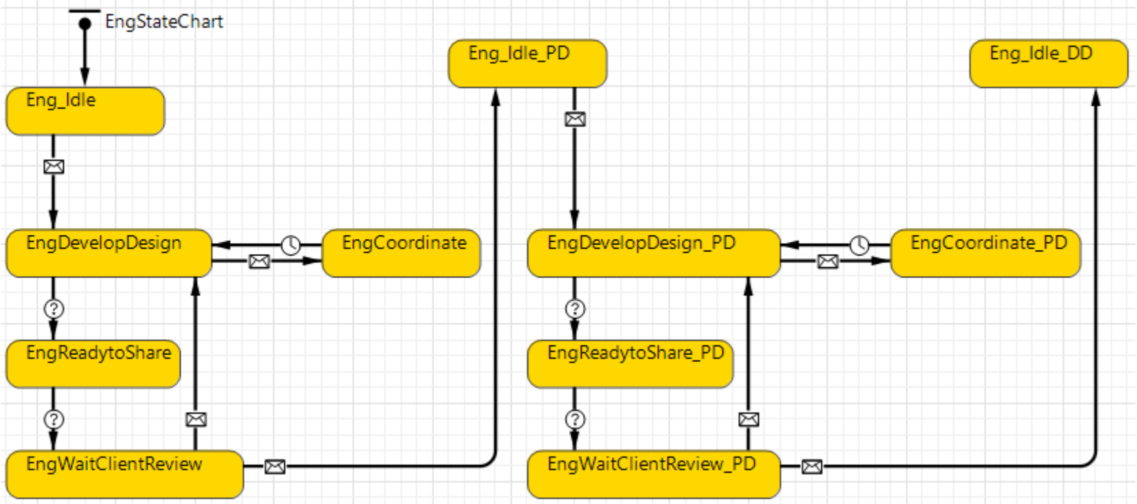

Figure 5-5: Engineer Agent State-Chart

5.2.5 The Architectural Element Agent Type

<u>5.2.5.1 ArchElement Characteristics</u>

The architectural element (ArchElement) agent type is defined to represent the architectural BIM model elements used by the architect to deliver the architectural design intent. For instance, an architectural element can be a partition wall, a furniture element, a window or any other element created in the architectural BIM model. While designing, the architect creates elements in the model, modify them, or even delete them according to the dynamics occurring across the design process.

In the simulation model, the architectural elements form a population of elements within the ArchElement agent type. This population of elements represents the actual architectural BIM model in real life projects. Two main variables are used to track the status of architectural elements during the development of the design process: C1, and C4 presented in Table 5.7. C1 is a Boolean variable that reflects the status of an element vis-à-vis the requested client changes. If C1 is true, then the element is not affected by the client changes, or in other words, the element is accepted by the client. If C1 is false, it shows that the element is affected by the client's changes and needs to be revised.

C4 is also a Boolean variable that tracks the status of an element related to the coordination occurring with other designers. If an architectural element is affected by the coordination, C4 turns false requiring the element to be redesigned. If the element is not affected, C4 would be true reflecting that the element is checked against other elements and it does not need to be changed.

Table 5-7: Architectural Element Variables

Variable	Description	Type
C1	Changes related to client review	Boolean
C4	Changes related to design coordination	Boolean

In addition to C1 and C4, two other variables are developed to reflect the status of the entire architectural elements' population, which represents the corresponding architectural BIM model. ArchModelSize and ArchBIMReady, presented in Table 5.8, are two variables used to track the size and status of the architectural BIM model respectively. The ArchModelSize changes during the design process where the architect is adding elements to the model, reflecting the increase in model size. The ArchBIMReady is used to detect if the model is ready to be shared with the client for review. ArchBIMReady is a Boolean variable that turns to be true if the population of elements reaches its final size and if all the elements are checked against other engineering elements (ie have C4 true), making the architectural model complete and clash free to be shared with client.

Table 5-8: Architectural BIM model Variables

Variable	Description	Type
ArchModelSize	The size of the architectural BIM model in terms of created elements	Boolean
ArchBIMReady	Readiness of the architectural BIM model to be shared with client for review.	Boolean

5.2.5.2 ArchElement State-Chart

In this context, an architectural element passes through different states during the design process as reflected in Figure 5.6. First, the element is created in the simulation environment and joins the "CD_WIP" state that reflects the work in progress state of the conceptual design phase. The element then moves to the "Coordination" state whenever a coordination meeting is scheduled. After the coordination meeting, the element would either witness changes and joins the "ArchRework" state for adjustments or remains intact and joins the "CD-WIP" state for further design development. Any architectural element would continue to shuffle among these states until the architectural model becomes ready.

Once the architectural model is ready, every architectural element would move to the "ReadyToShare" state. The elements would wait in this state until the other engineering model is also ready for sharing. Whenever the architectural and engineering BIM model are ready, they would be shared with the client for review. After client review, the architectural model can either engage in a new design iteration under the concept phase if the client's value is not satisfied yet or becomes ready if the value is satisfied.

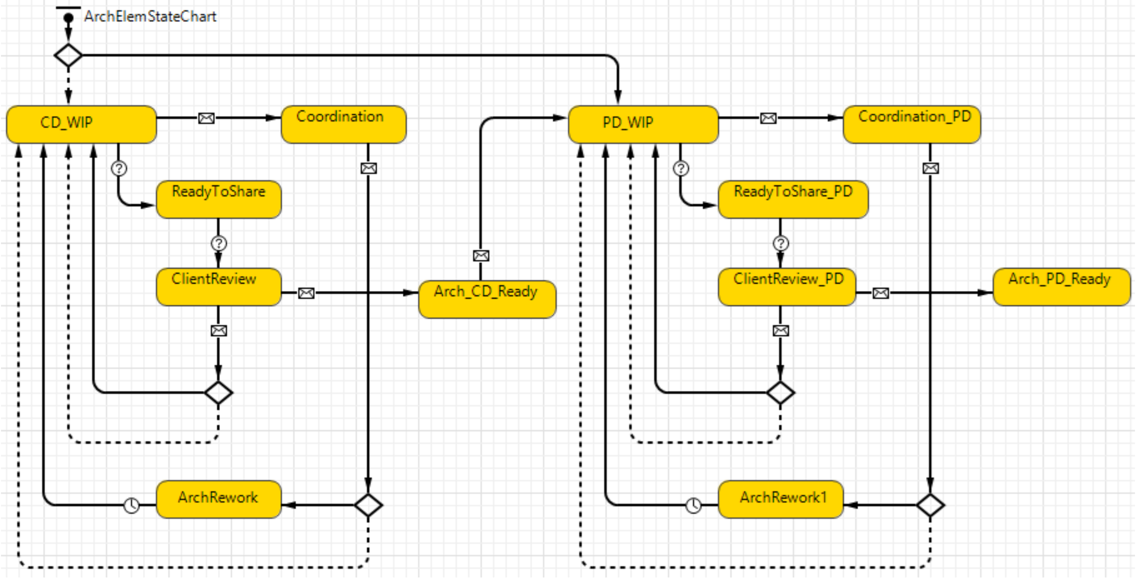

Figure 5-6: Architectural Element State Chart

5.2.6 The Engineering Element Agent Type

5.2.6.1 EngElement Characteristics

The engineering element (EngElement) agent type is defined to represent the engineering BIM model elements used by involved engineers to deliver their engineering design intent. For instance, an engineering element can be a structural beam, a mechanical pipe, an electric cable tray or any other element created in the engineering BIM model. While designing, the engineer agent creates elements in the model, modify them, or even delete them according to the dynamics occurring across the design process.

In the simulation model, the engineering elements form a population of elements within the EngElement agent type. This population of elements represents the actual engineering BIM model in real life projects. Similar to architectural elements, C1, and C4 variables are used to track the status of engineering elements during the development of the design process as presented in Table 5.7.

In addition to C1 and C4, two other variables are developed to reflect the status of the entire engineering elements' population, which represents the corresponding engineering BIM model. EngModelSize and EngBIMReady, presented in Table 5.9, are two variables used to track the size and status of the engineering BIM model respectively. The EngModelSize changes during the design process where the engineer agent is adding elements to the model, reflecting the increase in model size. The EngBIMReady is used to detect if the engineering model is ready to be shared with the client for review. EngBIMReady is a Boolean variable that turns true if the population of elements reaches its final size and if all the elements are checked against other modeled elements (i.e. have C4 true), making the engineering model complete and clash free to be shared with the client.

Table 5-9: Engineering BIM model Variables

Variable	Description	Type
EngModelSize	The size of the engineering BIM model in terms of created elements	Boolean
EngBIMReady	Readiness of the engineering BIM model to be shared with client for review.	Boolean

5.2.6.2 EngElement State-Chart

The engineering element also passes through different states during the design process as shown in Figure 5.7, similar to the states that the architecture element passes through. Thus, for states description and element's flow among them refer to section 5.1.5.2.

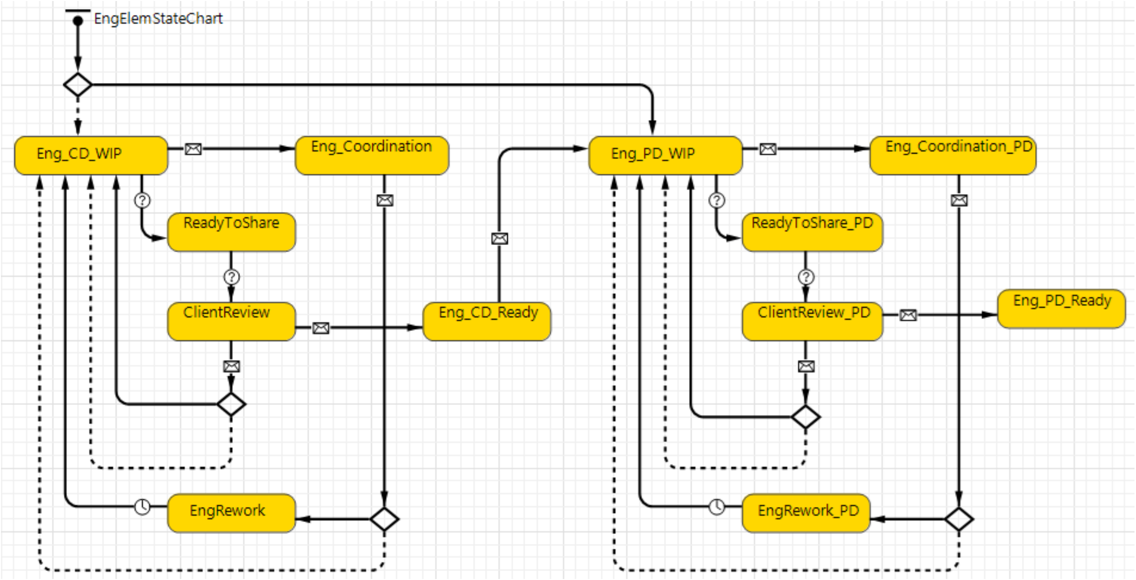

Figure 5-7: Engineering Element State Chart

5.3 Experimentation Setup

This section elaborates on the setup of the simulation experiments run to explore different model development scenarios. Two main steps were performed during experimentation: (1) the calibration of the simulation model parameters based on the case study project data, and (2) the definition of different projects scenarios created to test different project development conditions.

5.3.1 Model Verification, Validation, and Calibration

5.3.1.1 Model Verification

Model verification aims to ensure that the developed simulation model correctly delivers the intended concept. For this purpose, several steps were followed as per the guidelines of Bennett, et al. (2013): (a) evaluating the alignment of the model's aims and objectives against the study scope, (b) checking the validity of the input data and the consistensy of the output results, (c) visually tracking the performance of defined agents through the model's interface where different agents' states and transitions are monitored throughout the model run while cross checking the dynamics of defined variables against the input data used, (d) monitoring model logical performance by detecting the sensitivty of variables' values against changing specific model parameters, and (e) performing necessary adjustments whenever needed for a correct simulation modeling.

5.3.1.2 Model Validation

Model verification aims to ensure that the developed simulation model is a representative and credible artefact of the actual system under study. For this purpose, some techniques outlined by Sargent (2011) are used in this study to validate the model, mainly: (a) face validation, where experts in BIM-based design project (BIM manager, BIM coordinator, and architect Design Team Leader) were consulted to give their feedback about the credibility of the developed model which was adjusted based on their comments to better reflect actual real-life projects. In this regard, the experts provided feedback regarding the characteristic of defined agents, the corresponding state-charts and the overall of the developed agent-based simulation model, (b) output validation, where output from the model such as project's duration and BIM models' sharing dates were checked against actual project's duration and related data-logs.

5.3.1.3 Model Calibration

The calibration of the model targets the calibration of agents' parameters based on the actual case-study agents' characteristics and the corresponding actual project's performance. The corresponding values that calibrate the simulation parameters (agents and project's parameters) to the simulation output results (project duration and model sharing dates) are presented in Table 5.10.

The actual BIM models' development and sharing dates with the client where tracked using the logs of the company. In this regard, four major submissions were performed in the concept design phase and three in the preliminary design phase. The average interval between consecutive model submittals is three months in the concept design phase and six months in the preliminary design phase. Also, around 2 months of idle time was witnessed between the concept and preliminary design phase. These intervals are considered as major milestones in the airport design development process and were also used as reference milestones to compare different project development scenarios.

Table 5-10: Parameter Values to Calibrate the Simulation Model

Client Agent					**AE Team**	
PPVc$_0$	CKL		CRT	k	f	l
0.05	CD phase: 0.35	PD phase: 0.65	15–30 days	0.60	1.20	0.60

Running the simulation model based on the parameter values of Table 5.10 and the stochastic values of APR and EPR presented in Table 5.11, leads to the generation of 4 conceptual and 3 preliminary design iterations as shown in Figure 5.7. Nonetheless, the duration of the simulated project coincides with the actual project duration. Note that the differences between simulated dates (dashed lines) and the model sharing milestones (solid lines) is due to the stochastic variability of APR, EPR, and CRT parameters.

The actual project's client was technically highly knowledgeable; however, the complexity of the project reduced its initial perception of project's value, which led to many design iterations in the concept and preliminary design phase. Thus, a low PPVc0 value for the client agent is used in the simulation model. As for the client CKL values at the end of the concept and schematic design phases, they were estimated with the help of the AE team based on actual project's performance. Nonetheless, the actual client was engaged in the design process where a specific team from the design firm was continuously updating the client about the actual progress of the project.

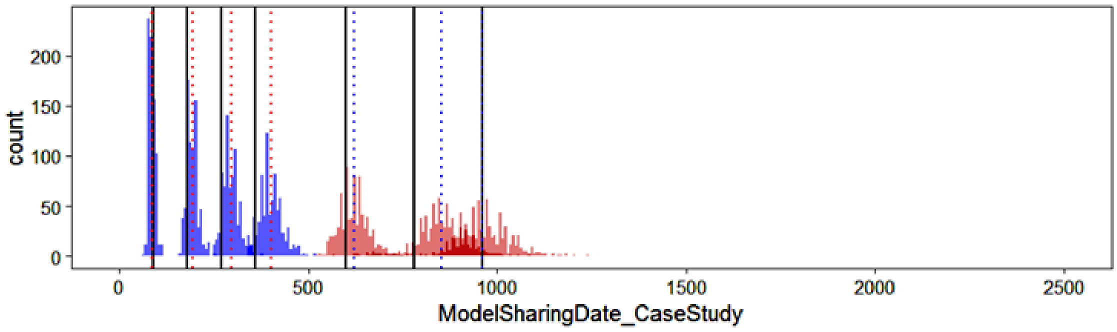

Figure 5-8: Simulation Output based on Table 5.8 parameters values

As for the AE team, and the corresponding firm, they are specialized in large scale infrastructure projects like this airport project. Accordingly, the firm portfolio and the engaged personnel are considered to be actively shaping the project's value based on their wide experience in this kind of projects. Therefore, the values of the AE team parameters, "f" and "l" are specified accordingly. Concerning the productivity of the architecture and engineering teams, APR and EPR parameters were estimated based on the size of architectural and engineering BIM models and the time that was required to develop them during each design iteration as shown in Table 5.11. The average values are then calculated, and the normal distribution is used to estimate APR and EPR values.

Table 5-11: APR and EPR Average Values

Design Phase	**Model Issue #**	**Development Duration** (days)	**Arch. Model Size**	**Eng. Model Size**	**APR** Min-max	**EPR** Min-Max
Concept	0	60 – 75	27200	32801	360 – 450	435 – 545
	1	60 – 75	26900	30321	350 – 450	400 – 505
	2	60 – 75	22644	34415	300 – 380	460 – 575
	3	60 – 75	25392	33608	340 – 425	450 – 560
					Normal (380, 25)	Normal (490, 24)
Preliminary	0	150 – 165	66730	31021	400 – 445	190 – 205
	1	150 – 165	71760	28286	430 – 480	170 – 190
	2	150 – 165	71200	28700	430 – 475	175 – 190
					Normal (443, 14)	Normal (186, 8)

5.3.2 Scenarios Definition

Different scenarios are developed to test different project development conditions as presented in Table 5.12. In this context, several types of clients, AE teams, and project setups are investigated.

Two types of clients are differentiated in this study, knowledgeable versus non-knowledgeable clients as presented in Table 5.13. Knowledgeable clients have higher initial perception of project's values at the beginning of the design process manifested in higher PPVc0 values. Nonetheless, knowledgeable client can reach higher knowledge limits at the end of each design stage manifested by bigger CKL values.

Also, two types of AE teams are investigated: high ability versus low ability teams as highlighted in Table 5.14. High ability teams have higher "f" values showing their ability to extend the knowledge limit of the client while actively defining and shaping the project value. Nonetheless, high ability teams have lower "l" values that reflect their high ability in achieving the project's value by quickly meeting client's needs.

Table 5-12: Project Scenarios

Scenario	Client Type	Client Engaged	AE Team's Ability	Design Planning Level
1	Knowledgeable	Engaged	High	Properly Planned
2	Knowledgeable	Engaged	High	Poorly Planned
3	Knowledgeable	Engaged	Low	Properly Planned
4	Knowledgeable	Engaged	Low	Poorly Planned
5	Knowledgeable	Not Engaged	High	Properly Planned
6	Knowledgeable	Not Engaged	High	Poorly Planned
7	Knowledgeable	Not Engaged	Low	Properly Planned
8	Knowledgeable	Not Engaged	Low	Poorly Planned
9	Non- Knowledgeable	Engaged	High	Properly Planned
10	Non- Knowledgeable	Engaged	High	Poorly Planned
11	Non- Knowledgeable	Engaged	Low	Properly Planned
12	Non- Knowledgeable	Engaged	Low	Poorly Planned
13	Non- Knowledgeable	Not Engaged	High	Properly Planned
14	Non- Knowledgeable	Not Engaged	High	Poorly Planned
15	Non- Knowledgeable	Not Engaged	Low	Properly Planned
16	Non- Knowledgeable	Not Engaged	Low	Poorly Planned

Table 5-13: Client Types

Client Type	**PPV$_{c0}$**	**CKL**	
		Concept Phase	Preliminary Phase
Knowledgeable	Uni. (0.10, 0.20)	Uni. (0.30, 0.40)	Uni. (0.60, 0.70)
Non_ Knowledgeable	Uni. (0.00, 0.10)	Uni. (0.20, 0.30)	Uni. (0.50, 0.60)

Table 5-14: AE Team Types

AE Team Ability	**f**	**l**
High	Uni. (1.05, 1.20)	Uni. (0.5, 0.6)
Low	Uni. (0.80, 0.95)	Uni. (1.0, 1.10)

The study also differentiates among different project's conditions concerning the collaboration protocols with the client and the planning quality of the design process as illustrated in Tables 5.15 and 5.16 consecutively. In this regard, one type of projects considers the client being engaged in the design process, while the other does not. This engagement affects the "k" and CRT values where engaged clients have lower CRT and "k" values, reflecting a less review time and faster learning rate.

As for the planning quality, the design process can either be properly or poorly planned. While a properly planned design process leads to a less percentage of rework, a poorly planned process is more likely to witness more rework due to poor sequence of design activities among involved disciplines. Nonetheless, the type of rework generated in a poorly planned process can take more time to resolve where the effects of the resulting design alteration can be high. In this study, the triangular distribution is used to estimate the time needed to finish the corresponding rework. The percentages and durations are estimated after consulting the experts involved in the case study project.

Table 5-15: Project Setup

Client Engaged	CRT (days)	k
Yes	Uni. (15, 30)	Uni. (0.5, 0.6)
No	Uni. (15, 45)	Uni. (1.0, 1.10)

Table 5-16: Design Planning Levels

Design Planning	Rework Percentage	Rework Resolving Duration (days)
Proper	0 – 5 %	Triangular (1, 5, 10)
Poor	5 – 15%	Triangular (1, 5, 20)

5.4 Results Analysis and Discussion

This section presents and discusses the results of the conducted simulation experiments. The discussion would focus on the effects of stakeholders' characteristics and project's conditions on the performance of the project during the conceptual and preliminary design phases. The discussion also would consider the case study as a reference project to interpret the results of the conducted experiments. The following sections elaborate on the effects of different agents' characteristics and project's setups on design workflow dynamics.

The graphs used to communicate the simulation results show the distributions resulting from running the model for 750 simulation iterations. The y-axis shows the count reflecting the number of iterations having the corresponding x-values that represent the values of the variables under the focus of the study. The graphs used to communicate the simulation results read as follows:

- Blue distribution is related to the concept design phase
- Red distribution is related to the preliminary design phase
- Orange distribution is related to the overall project duration
- Dashed lines represent the average values of each distribution
- Solid lines represent the project's milestones of the case study project.

5.4.1 Effects of Client characteristics

The characteristics of the client play a major role in shaping the dynamics of a design project. Holding a specific project's value, the client is an essential player in the design process and a key decision maker that highly affects its performance. This study differentiates between two types of clients based on their understanding of the project's value. While a knowledgeable client is expected to have a higher initial perception of project's value reflecting its mature understanding of his/ her needs and requirements, an un-knowledgeable client is more likely to have less initial perception of project's value reflecting a vague understanding of project's objectives.

The effects of client's characteristics are studied against the time performance of the project, the rework caused during the design phase, the achieved value by the end of early design stages, and the hidden risks that can affect project's performance in downstream phases. To test the effects of client characteristics, all other project's parameters are fixed. For instance, scenarios 1 and 9 that only differ in client's type are compared against each other to detect the influence of client's characteristics on project's performance.

5.4.1.1 Project Duration

The simulation results show that the client type affects the duration of the project as shown in Figure 5.90. For instance, in the case of an engaged client, high ability AE teams, and properly planned design processes (ie scenarios 1 and 9), projects having knowledgeable clients are more likely to finish before the projects having un-knowledgeable clients as shown in Figure 5.9.

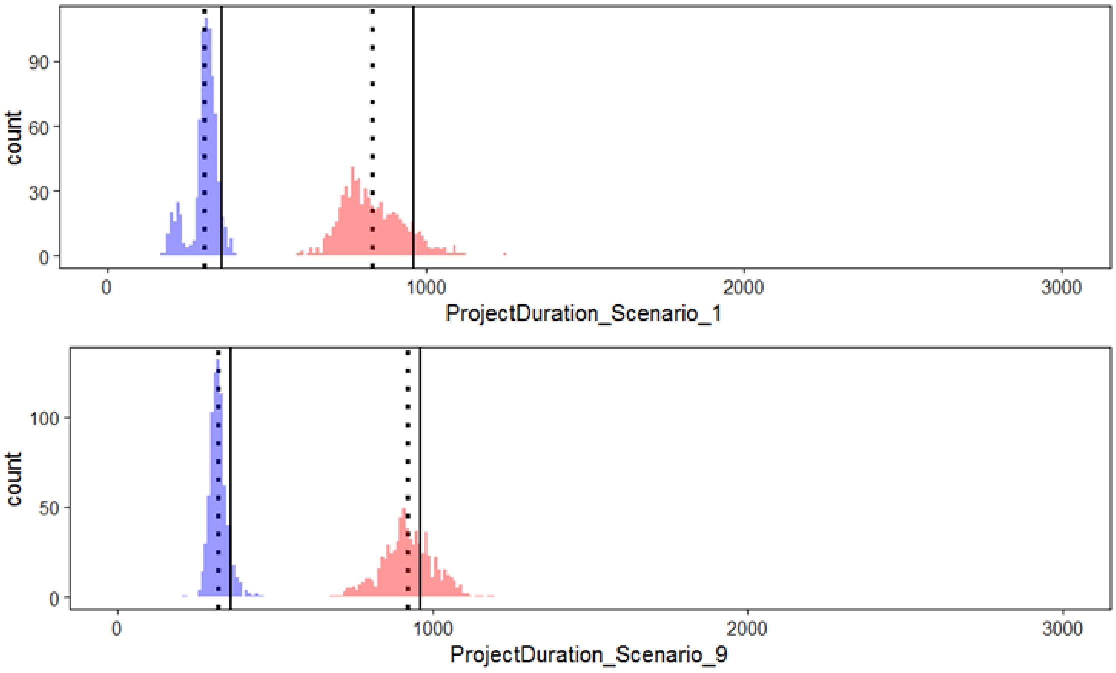

Figure 5-9: Project Duration (Knowledgeable [Sc-1] vs. Non-Knowledgeable [Sc- 9] Clients)

Nonetheless, if we compare other scenarios that differ only in client type (ex: scenario 2 vs 10, scenario 3 vs 11, etc.), projects having knowledgeable clients are always more likely to require less time duration as shown in Appendix A. In this context, the simulation output results show that the client's initial perception of project's value ($PPVc_0$) and the extent to which the client can perceive and define the project's value during the design phase (CKL), have a direct impact on project's final duration.

Acknowledging this impact, the planning of the design process should consider the type of the project's client and the degree to which his/ her requirements and needs are defined at the beginning of the design process to enhance the reliability of the design process plan. Assuming that the client knows what he/ she wants from a project can cannibalize the project's performance if the client turns to be an un-knowledgeable client. In this regard, more time should be invested in the pre-design phase to enhance the definition of the project's value and to increase the client's understanding of his/her needs and requirements. For instance, pre-design workshops that bring together the AE teams and the client can help better explore the client's perception of the project's value, better refine project's constraints and needs, and increase the shared understanding among involved stakeholders about the objectives of the project.

5.4.1.2 Rework

The simulation results also show that the client type affects the amount of rework witnessed in the design process as shown in Figure 5.10. Nonetheless, the amount of rework witnessed during the preliminary design phase (red distribution) is much higher in scenario 9 where the client was initially un-knowledgeable.

Therefore, un-knowledgeable clients are more likely to cause more rework during the design process since they are more likely to request changes while progressively uncovering the value of their project after each design iteration. For instance, the client may discover new criteria in the preliminary design phase that can cause serious changes in the desired design product. In this context, the impact of the generated rework is higher in the preliminary design phase than in the concept design phase where the generated BIM models have already consumed more design effort to reach the schematic design requirements (LOD levels for example).

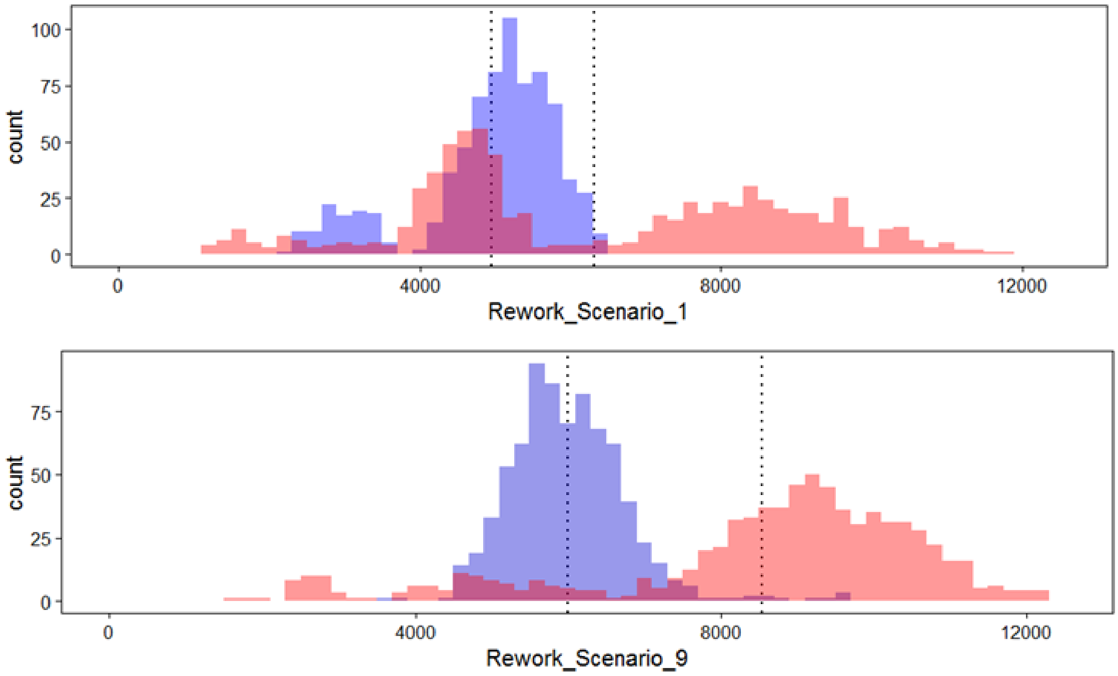

Figure 5-10: Rework (knowledgeable [Sc-1] Vs. Un-Knowledgeable [Sc-9] Client)

Accordingly, design managers should consider the impact of the client type on the expected rework while planning for the development of the design project. Ignoring this impact might lead to an unreliable estimation of needed man-hours to perform the corresponding design task which may urge the AE team to perform overtime or even increase its size to avoid missing design submission deadlines. Moreover, the unreliable planning of needed man-hours can lead to an un-reliable cost estimation of the design project, which may affect the profitability of the project and the AE – Client relationship.

5.4.1.3 Value Achieved and Hidden Project's Risk

In addition to the effects of client's characteristics on project's duration and generated rework, the client type also has an influence on the project's value achieved during the design process and the project's embedded risks. While the Hidden Value Gap (HVG) variable is tracked to detect the achieved project's value and the corresponding hidden gap between current achieved value and the ideal value of 1.0, the Client Change Impact (CCI) variable is tracked to detect the hidden risks related to possible future design changes requested by the owner. Note that the higher the HVG is, the bigger the hidden value gap, and the higher the CCI could be.

Figures 5.11 and 5.12 compare the HVG and the CCI of scenarios 1 and 9. The results show that knowledgeable clients are more likely to achieve a bigger percentage of the ideal project's value reflected in smaller HVG results. In other words, clients who have well defined their project's value, by actively developing project's needs and requirements, are more likely to reduce the gap between the actual value of the produced design product and the ideal design product value achievable within the context of the corresponding project.

Nonetheless, the CCI results of knowledgeable clients at the end of early design stages are smaller than those of un-knowledgeable clients as shown in Figure 5.11. These results show that knowledgeable clients, who finished early design stages with less hidden value gap, are less likely to cause serious design changes in downstream phases. However, un-knowledgeable clients who finished early project design phases with higher HVG values, are more likely to request changes that can highly impact the produced design product on one hand and the performance of the project on the other.

Note that the impact of design changes increases as the project progresses along different downstream phases. Nonetheless, the cost of changes in downstream stages, especially during the construction phase, are much higher than the cost of these changes in early design phases. Therefore, investing more time to educate the client about the project's value in early design phases and comprehensively define project's value can help reduce the risks of changes in downstream project stages.

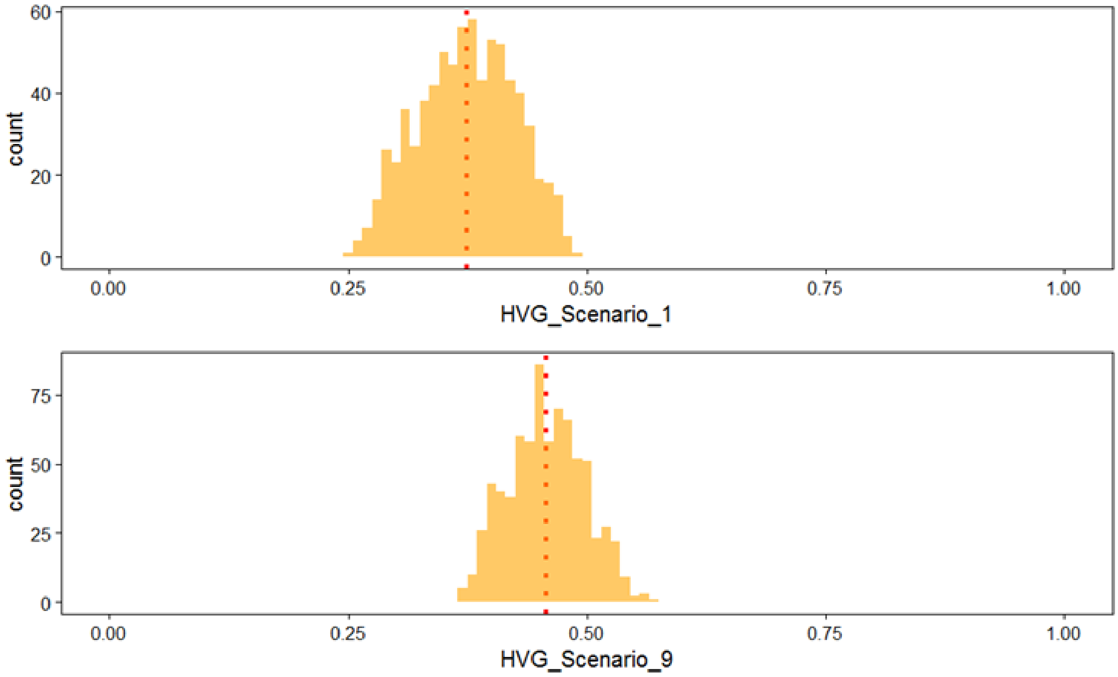

Figure 5-11: HVG Distribution and Mean Values (Knowledgeable [Sc-1] Vs. Un-Knowledgeable [Sc-9] Clients)

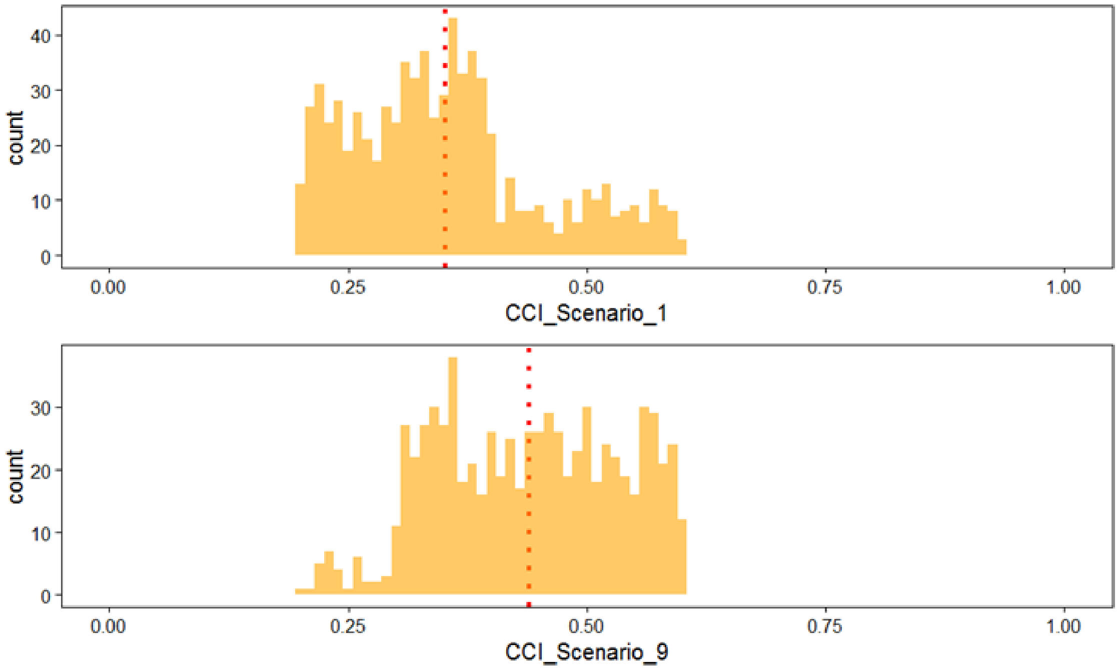

Figure 5-12: CCI Distribution and Mean Values (Knowledgeable [Sc-1] Vs. Un-Knowledgeable [Sc-9] Clients)

5.4.2 Effects of AE Team Ability

This section explores the effects of the AE team's characteristics on design project's dynamics. The study differentiates between two types of AE teams: high and low ability AE teams. High ability AE teams have higher ability to actively shape and define project's value and to expand client's knowledge limit about its project value. Nonetheless, high ability AE teams can converge faster to the desired design solution while adequately addressing client's needs and requirements. In this study, the effects of the AE team characteristics are studied against the time performance of the project, generated rework, value achieved and hidden embedded risks that can affect downstream project phases.

5.4.2.1 Project Duration

The simulation results show that high ability AE teams are more likely to require less design iterations to converge to the required design solution as shown in Appendix B. For instance, the high ability AE team of scenario 1 required on average 2.86 iterations in the concept design phase, and 2.51 in the preliminary design phase to develop the required design model. However, the AE team of scenario 3 having less ability required 3.72 iterations in the concept phase and 3.96 in the preliminary design phase. Therefore, high ability AE teams are expected to reach desired design faster than low ability AE teams regardless of another project’s condition as shown in Appendix A. For instance, Figure 5.13 shows the difference in project’s duration between scenarios 1 and 3 that only differ in the AE team characteristics.

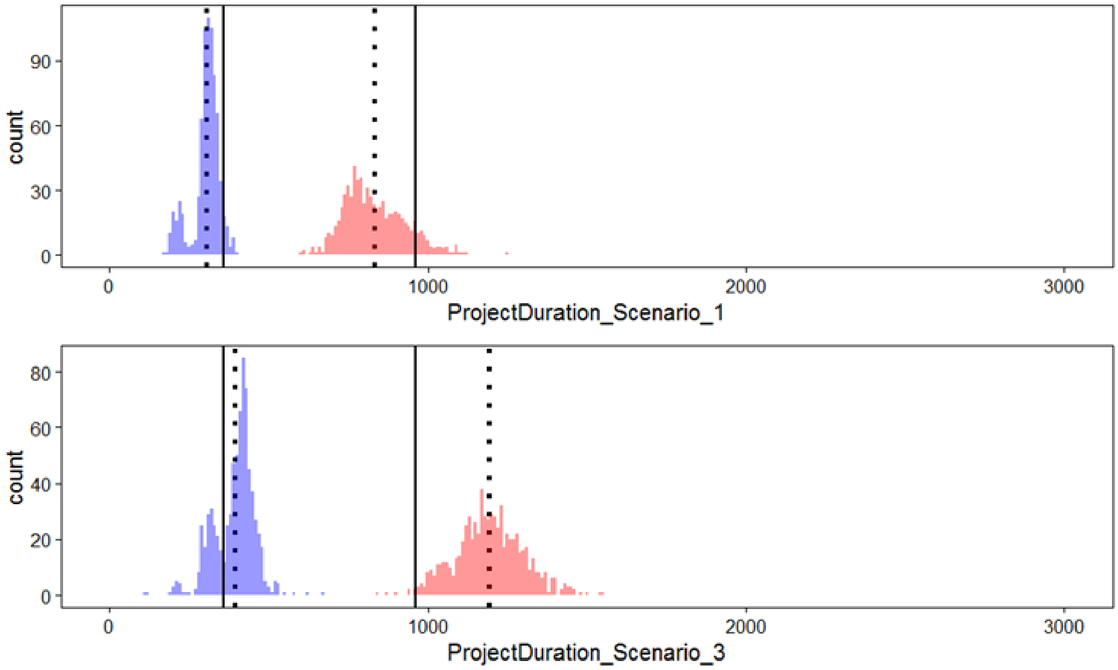

Figure 5-13: Project Duration (High vs Low Ability AE Teams)

5.4.2.2 Rework

The simulation results also show that the AE team ability affects the amount of rework witnessed in the design process as shown in Figure 5.14. The failure to address client's needs result in requesting more design changes from the client, leading to more rework and negative design iterations. This fact may affect the value of the design project, where the AE team working under the burden of heavy rework might lose interest in the design project which may lead to the generation of sub-optimal design solutions. Nonetheless, substantial design rework might lead to the generation of design errors that can also affects the value of the final design product.

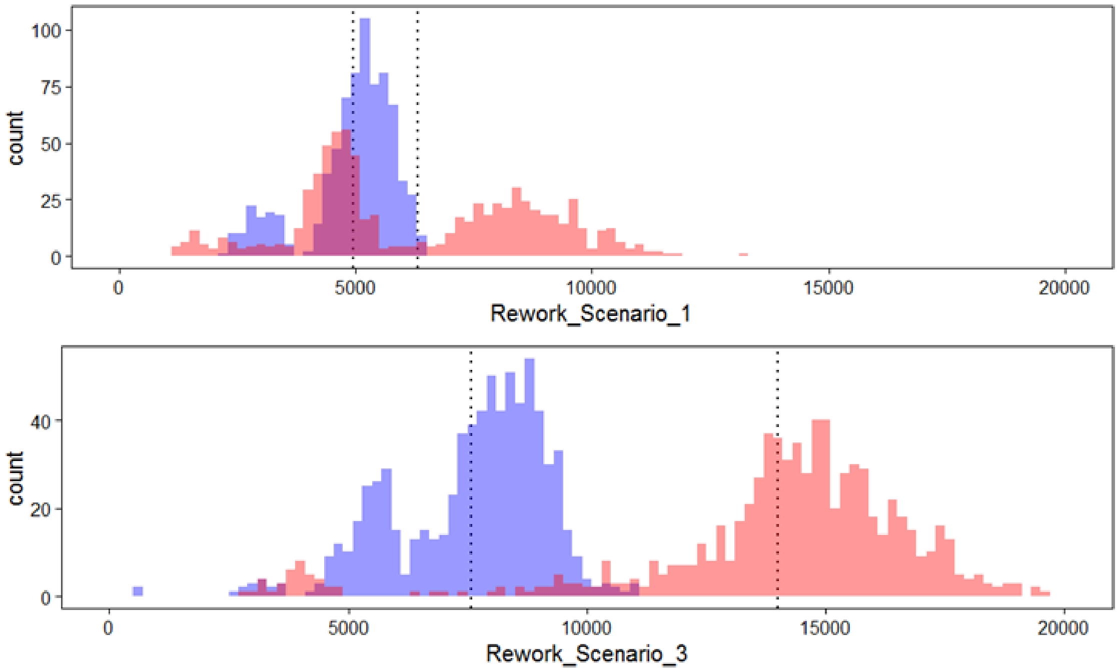

Figure 5-14: Rework (High [Sc-1] vs Low Ability [Sc-3] AE Teams)

5.4.2.3 Value Achieved and Hidden Project's Risk

The simulation results also show that the characteristics of the AE team affect the value achieved during the design phase as highlighted in Figure 5.15. Scenario 1 having a high ability AE team on board is more likely to finish the preliminary design phase with less hidden value gap. In this context, the client of scenario 3 would proceed to downstream phases with higher HVG values, the fact that can increase the probability of initiating design changes whenever hidden value criteria are surfaced anywhere in downstream stages. In this context, the impact of these changes is also higher in the case of low ability AE teams as highlighted in Figure 5.16.

In this regard, the achieved project's value and the performance of the design process seems to be dependent on the characteristics of the designers participating in the project. In other words, different design teams would provide different design solution for a same client giving the same project's needs and requirements. Nonetheless, the value of the generated design and the resulting client satisfaction is therefore dependent on the AE team characteristics.

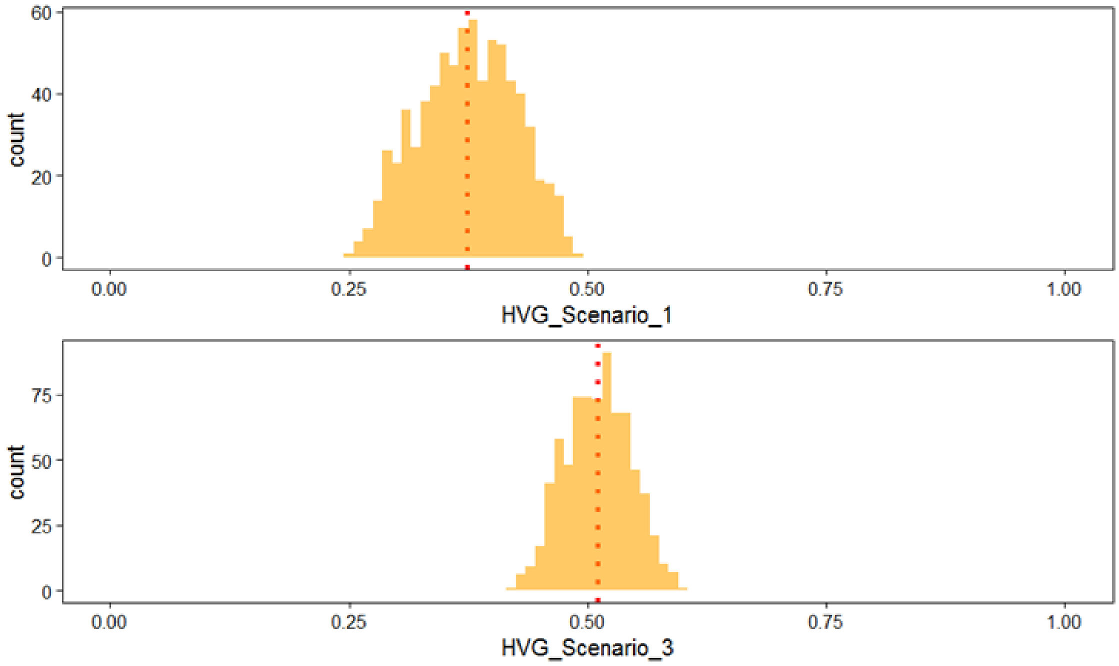

Figure 5-15: HVG Distribution and Mean Values (High [Sc-1] vs Low Ability [Sc-3] AE Teams)

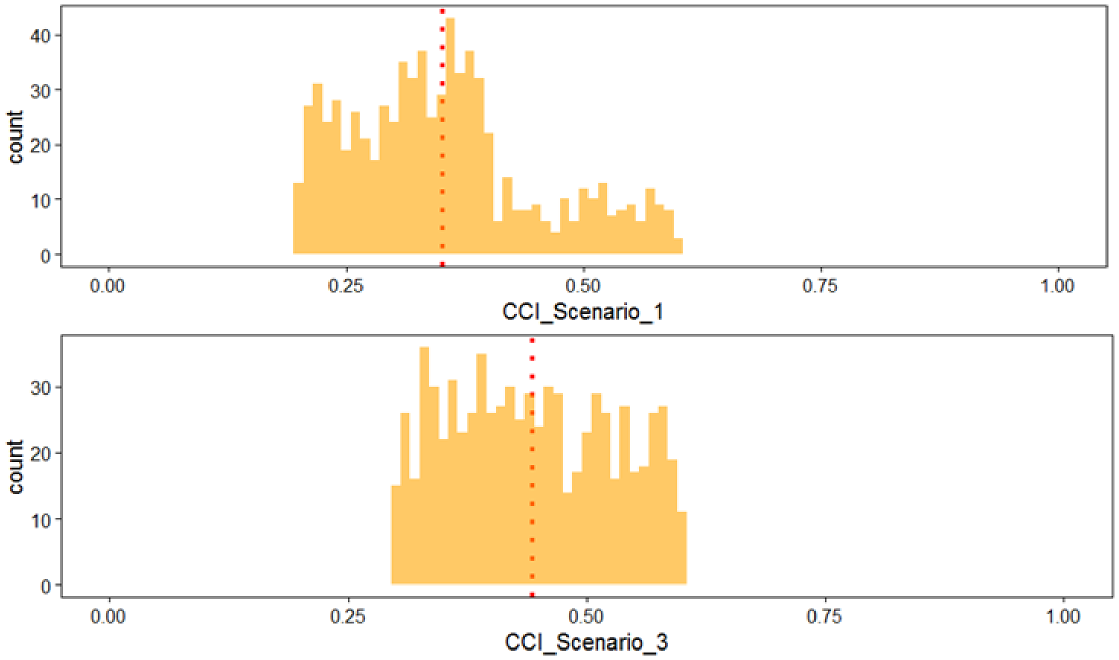

Figure 5-16: CCI Distribution and Mean Values (High [Sc-1] vs Low Ability [Sc-3] AE Teams)

In this regard, the design process needs to be less dependent on designers' characteristics to ensure the optimum achievement of client's value and a smooth performance of the project. Among the possible improvements in this regard is the employment of generative design that is less dependent on the designers' ability in shaping and generating the design solution.

5.4.3 Effects of Project Setup

This study also addresses the setup of the design process regarding the collaboration with the client. More specifically, the study differentiates between two types of project's setups: those having the client engaged in the design process and those who do not. Engaged clients are more likely to learn faster about their project's value while continuously being updated about the design progress throughout the design process. However, un-engaged clients are only able to detect the progress of the design on specific milestones related to specific design delivery schedules. For instance, these milestones are traditionally related to project phases; basically, concept, schematic, design development, and construction documentation phases. In the latter approach, clients need to wait until the corresponding design deliverables are ready at each milestone before they can react to the suggested design product.

5.4.3.1 Project's Duration

The simulation results show that the engagement of the client in the design process have positive impact on the project's time performance manifested in less project's duration as shown in Figure 5.17. In this context, an engaged client who can learn faster about his project's value and take less time to perform design reviews can help reduce the duration of the design process and therefore the overall project's duration. In this regard, engaging the client in the design process can lead to substantial cut-offs in the design process duration, which is much needed in projects tight on time such in the case of fast-track projects.

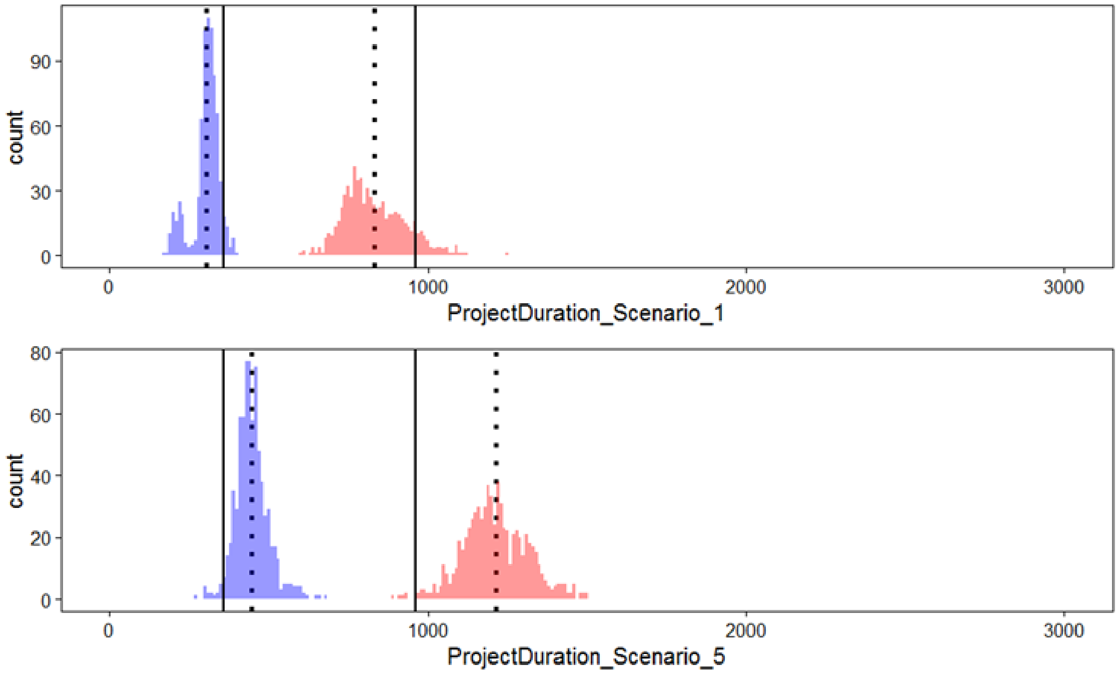

Figure 5-17: Project Duration (Engaged [Sc-1] Vs. Non-Engaged [Sc-5] Client)

5.4.3.2 Value Achieved and Hidden Project's Risk

In this study, the parameter (k) used to reflect whether a client is engaged in a design process or not is defined such as to affect the learning rate of the client only, not its final knowledge limit CKL as modelled in Equation 1. In this regard, the final HVG and CCI values witnessed by the end of the projects that only differ in project's setup, are similar as shown in Figures 5.18 and 5.20.

However, HVG and CCI follow different patterns across the project's duration depending on the project setup as shown in Figures 5.19 and 5.21 that show the averaged HVG and CCI results after 750 different simulation runs. For instance, a client engaged in the design process, as in the case of scenario 1, would witness a faster decrease in HVG values during the timeline of the project as shown in Figure 5.19. Accordingly, engaging the client in the design process would accelerate his/her learning about its project's value, which by its turn would decrease the effects of possible client's changes. In this regard, a faster decrease in CCI values is also witnessed in the case of engaged clients as shown in Figure 5.21. Nonetheless, in the case of a short project's duration, engaged clients would achieve more of their project's value during the allocated design time than un-engaged clients as highlighted in Figure 5.19.

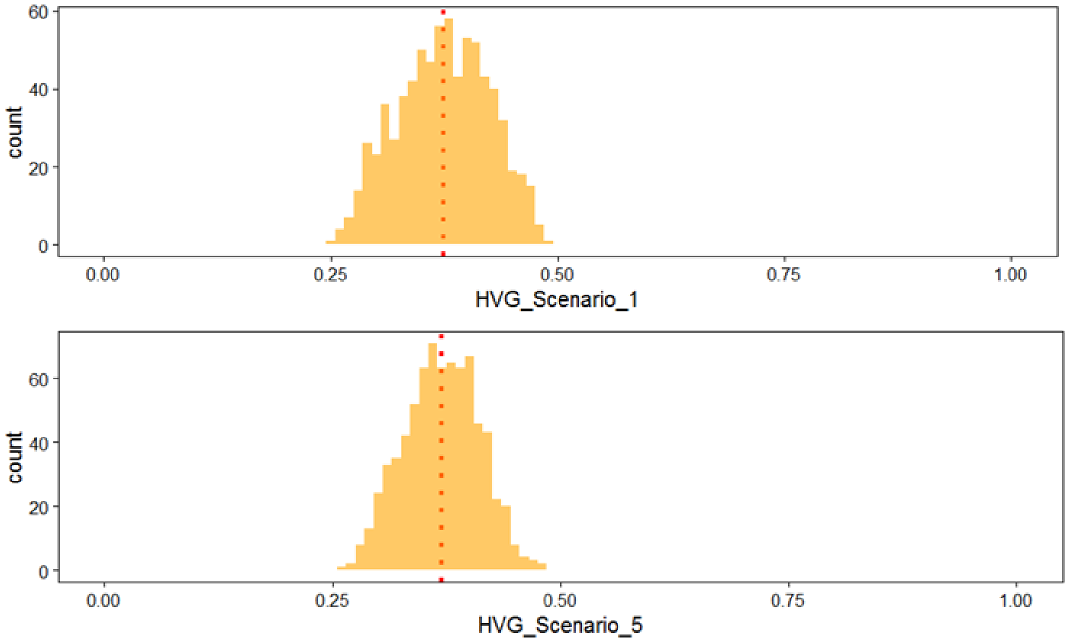

Figure 5-18:HVG (Engaged [Sc-1] Vs. Non-Engaged [Sc-5] Client)

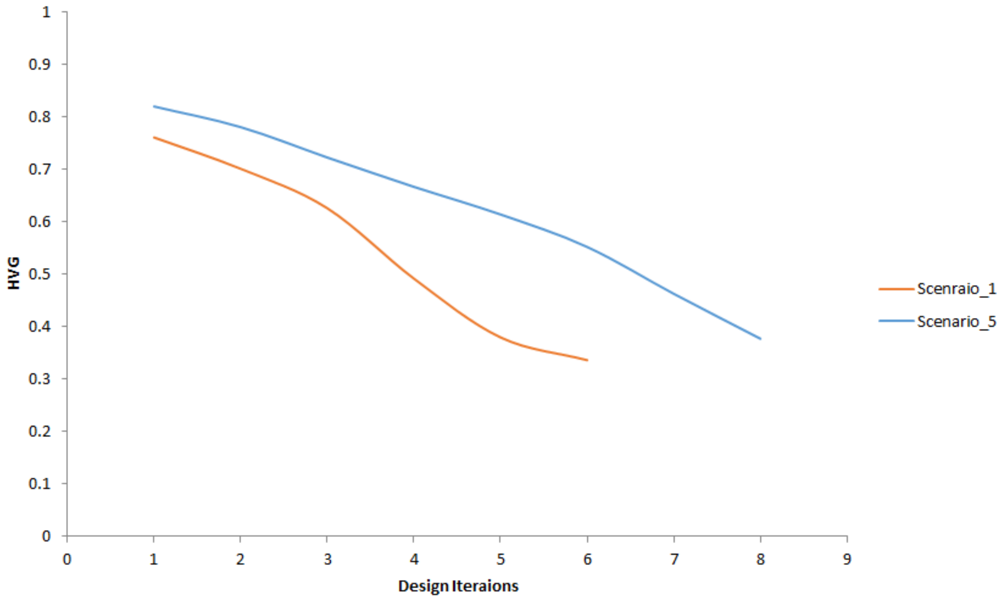

Figure 5-19: HVG Trend during Design (Engaged [Sc-1] Vs. Un-Engaged [Sc-5] Client)

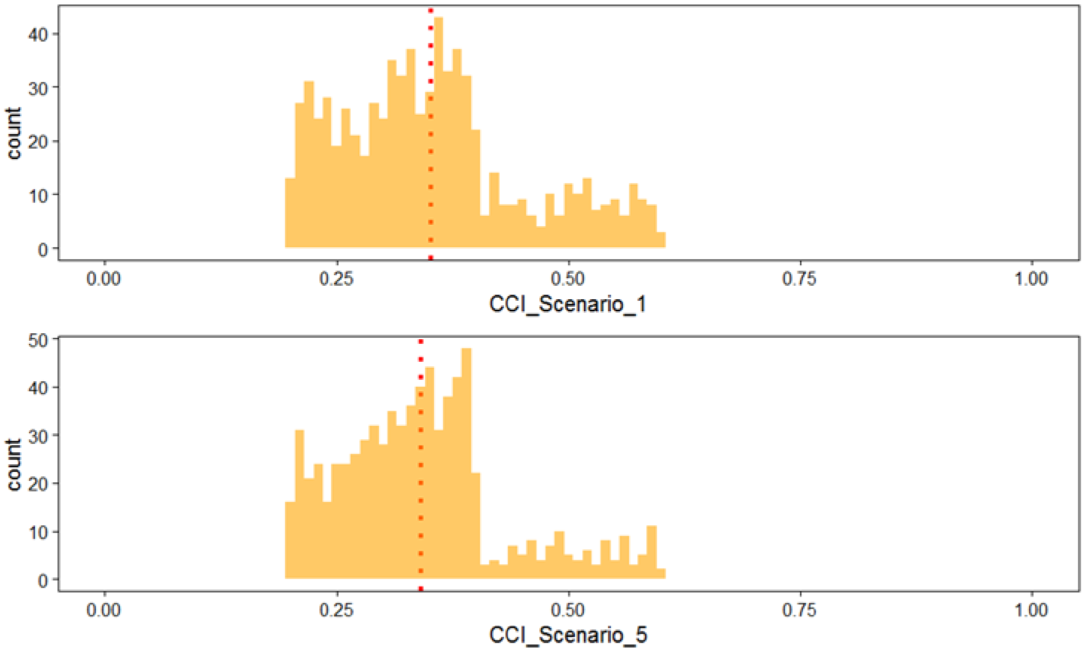

Figure 5-20: CCI (Engaged [Sc-1] Vs. Non-Engaged [Sc-5] Client)

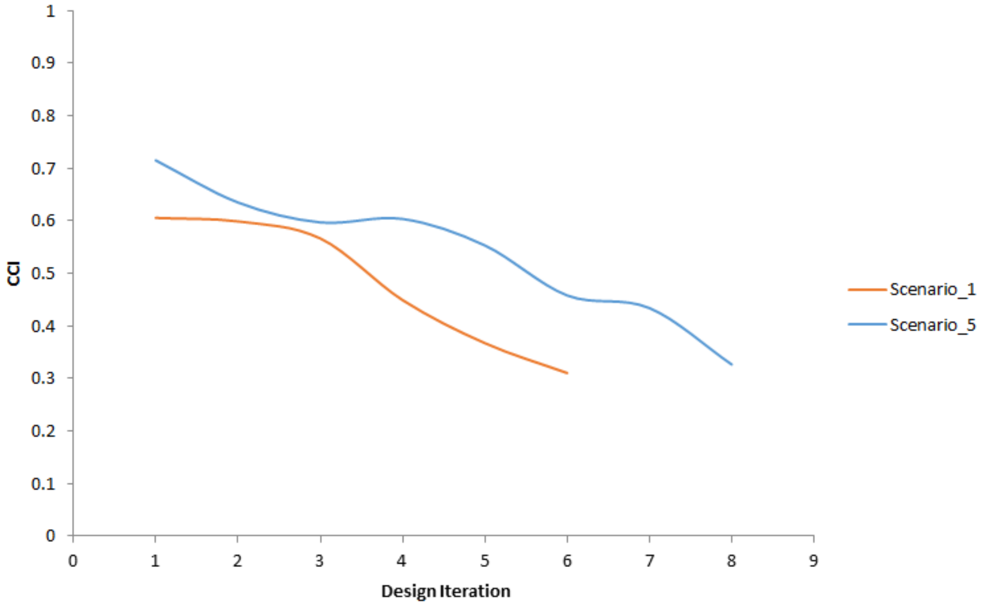

Figure 5-21: CCI Trend during Design (Engaged [Sc-1] Vs. Un-Engaged [Sc-5] Client)

5.4.3.3 Rework

Engaging the client in the design process has also effects on the total amount of rework witnessed during the design phase as shown in Figure 5.22. In this context, engaged clients are expected to learn faster about their project's value as shown in section 5.3.3.2 which would result in fewer design changes and less rework.

In this context, engaging the client seems to be beneficial for the AE teams if they want to avoid extensive rework and wasteful man-hours. Nonetheless, reducing rework can reduce the risk of generating errors during the design phase, which would help increase the value of the final design product as well.

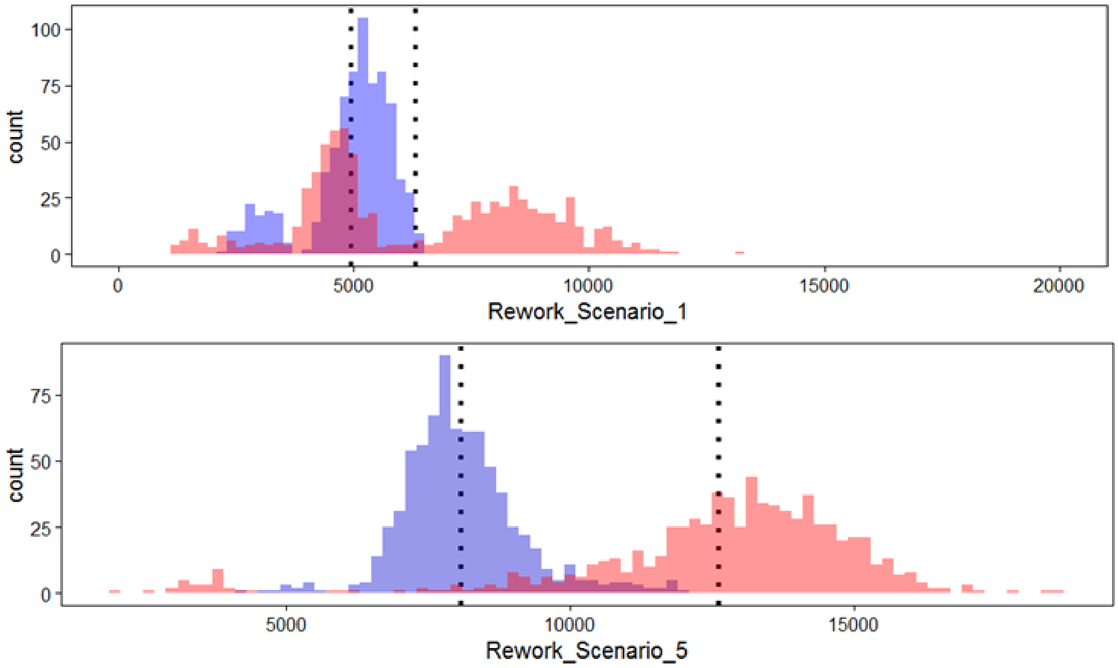

Figure 5-22: Rework (Engaged [Sc-1] Vs. Non-Engaged [Sc-5] Client)

5.4.4 Effects of Design Process Planning

This study also investigates the effects of design planning on the overall performance of the design process. In this context, this research differentiates between proper and poor planning of a design process at two different levels: (1) the level of design tasks and (2) the level of BIM model progression. At the level of design tasks, properly planned design projects have their design tasks ordered in an optimum sequence as to reduce negative iterations throughout the process. At the level of BIM model progression, properly planned design projects consider the right selection of model elements and their LOD levels based on information dependency among different involved disciplines at each phase of the design process. In this research, the level of design planning is considered to affect the dynamics of BIM model elements during the design process. For instance, model elements in a poorly design process have more chance to witness more rework than the elements in a properly planned design process, because of higher probability of witnessing negative iterations.

5.4.4.1 Project Duration and rework

Figure 5.23 shows that the planning level of the design process can affect the duration of the project; however, the biggest impact of the planning level is on the amount of generated rework as presented in Figure 5.24. In this context, poorly planned design projects can witness more rework throughout the process. Nonetheless, the number of elements that can be affected by rework can witness substantial increase in the preliminary design phase where a bigger number of elements is modeled under each discipline. Therefore, a change in one model element can lead to cascading changes in other connected elements.

In this regard, the AE team members need to properly plan the development of their BIM models as to avoid rework during the development of design. Otherwise, a big percentage of the planned man-hours would be spent on none value adding tasks dealing with rework activities. Nonetheless, engaging in continuous rework can push the AE team members to ignore the preset plan and act reactively to ongoing design dynamics which by its turn would aggravate the effect of generated rework.

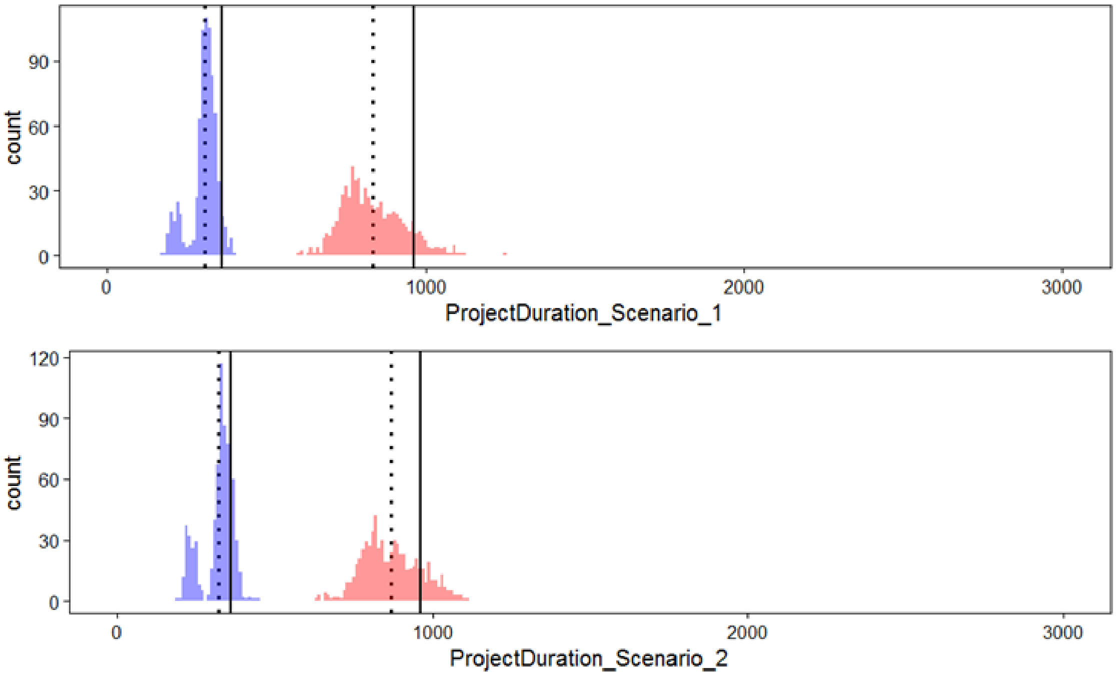

Figure 5-23: Project Duration (Proper [Sc-1] Vs. Poor [Sc-2] Planning)

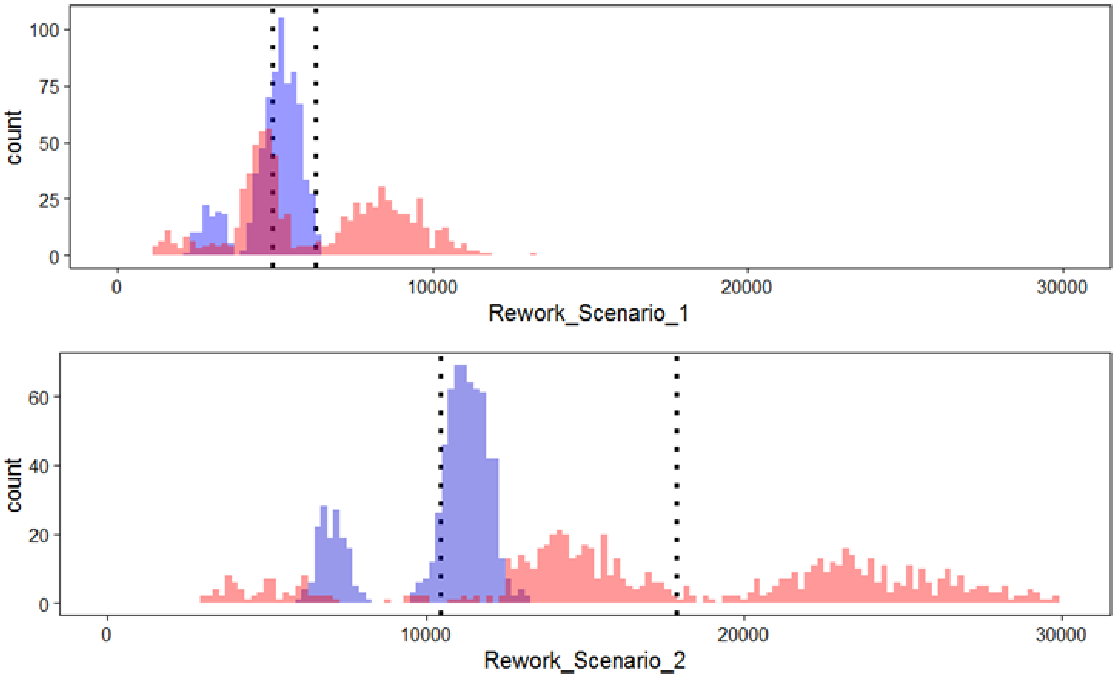

Figure 5-24: Rework (Proper [Sc-1] Vs. Poor [Sc-2] Planning)

CHAPTER 6

MONITORING AND CONTROLLING BIM-BASED DESIGN PROJECTS

6.1 Introduction

The Architecture, Engineering and Construction (AEC) industry is witnessing a technological shift towards the implementation of Building Information Modeling (BIM) as a data repository of lifecycle building information (Fadeyi 2017). The use of BIM aims to enhance information workflow among practitioners by facilitating the share and use of generated data. Accordingly, understanding the dynamics of BIM models across the project's timeline is crucial to reaping the full benefits of BIM. In this regard, this chapter introduces five variables to track model dynamics at the level of model elements where design information is delivered. Nonetheless, a dashboard is designed to represent these dynamics visually to facilitate their interpretation and use by involved stakeholders.

Generating and sharing design information using BIM differs from conventional 2D CAD processes (Al Hattab and Hamzeh 2013). The major difference resides in the use of parametric model elements not drawings. Therefore, the generated design intent is being shared using data-rich models which are supposed to carry necessary design information. This difference brought by technology advancement is reshaping the work processes in the AEC industry especially that geometry and data are combined in a unified BIM model repository (Fadeyi 2017). For example, a Door element modeled in BIM holds not only the dimensions of the door, but also its material properties, manufacturer, cost, installation manual, etc. Therefore, a thorough understanding of the characteristics of the new process is needed to enhance the management of BIM-based design projects while increasing the value of generated models.

In BIM, the development of design is manifested by the creation of new elements, deletion of others and the variation of previously created elements. Nonetheless, the generation of design information is translated into the addition and modification of elements' properties across the project's timeline (Poirier, Staub-French and Forgues 2015). Therefore, the development of design leaves imprints in the BIM model that can be used to infer about the progress of the design process as well as the maturity of the generated design. Several studies have investigated the evolution of BIM models during project's development (Leite, et al. 2011, Poirier, Staub-French and Forgues 2015, Tribelsky and Sacks 2010, Berard 2012, Al Hattab and Hamzeh 2018, Pilehchian, Staub-French and Nepal 2015, Pilehchian 2012). While some of these studies have targeted aspects related to the BIM model development, other studies have focused on aspects related to process characteristics; however, little research have investigated the dynamics occurring at the level of model elements or correlated between these dynamics and the development of design where the problem-solution space is evolving.

Enhancing the management of design using Building Information Modeling (BIM) can increase the value of design solutions as well as the quality of the final design deliverables (Eastman, et al. 2008). While design is an iterative and a multi-disciplinary process that occurs in a social context among different stakeholders (Cross and Cross 1995), BIM can be approached as a process that aims to formalize the generation and sharing of information related to the construction project across the project's timeline (Azhar 2011).

In this context, different designers are engaged in domain specific design processes which entail several loops and iterations across the project's timeline as abstracted in Figure 6.1. Moreover, these discipline-specific design processes cross each other during a project's development due to information dependencies among them. For instance, the structural design process crosses and intermingles with the architectural design process at different project's stages as abstracted in Figure 6.1. The complexity of the resulting design process, which comprises a big list of sub-design processes, renders design a chaotic and complex process to manage.

In this regard, transforming design from a chaotic iterative process occurring across multidisciplinary domains, to a streamlined information generation process linked to actual BIM model development as abstracted in Figure 6.1, promises to enhance the quality of design management, which in turn can increase the overall project's value to clients. Although individual designers follow specific thinking patterns that could not be quantitatively tracked, their design solutions, their decisions, and actions are translated into BIM models that continuously develop and change throughout the design phase. Accordingly, the abstract thinking of designers in different involved disciplines is translated into tangible BIM models that can be quantitatively monitored.

In this regard, this chapter aims to present a new construct to monitor BIM development by tracking changes occurring at the level of model elements. The study designs a visual dashboard that tracks several defined variables related to model dynamics. The dashboard is expected to provide new knowledge about the development of BIM models, to reveal important process characteristics, and to help design managers enhance the overall project's management.

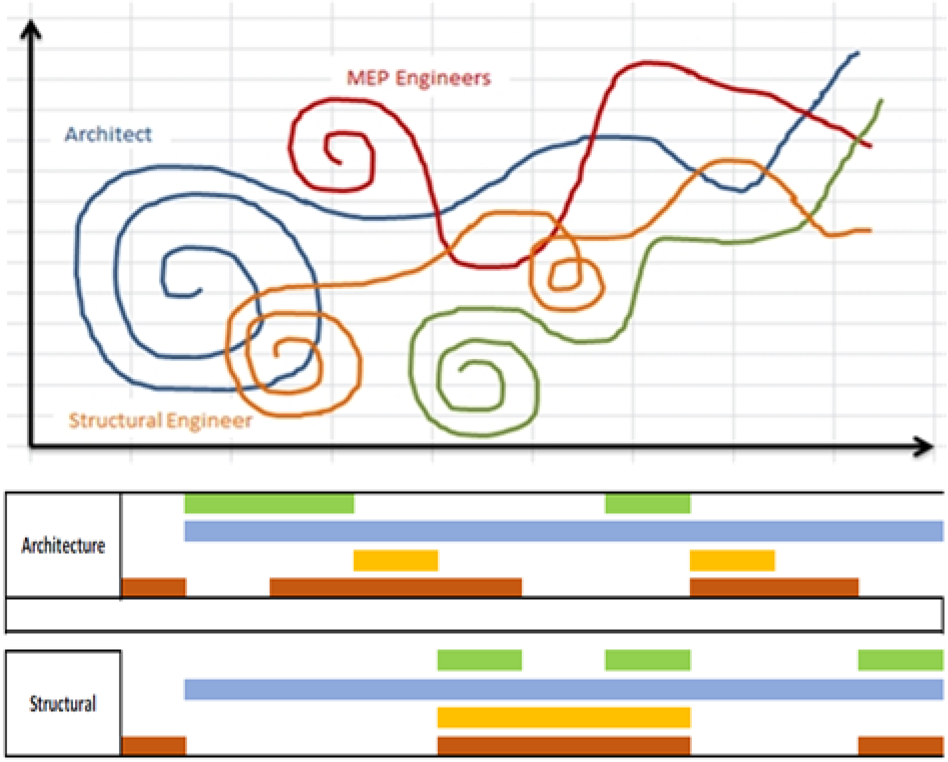

Figure 6-1: Abstract representation of transforming design from a chaotic thinking process to a streamlined information generation process.

6.2 Dashboard Design

6.2.1 Selection of Model Variables

The dashboard is designed to track changes related to model elements. While several changes can be extracted from a BIM model, only changes that can be used to infer about design development are monitored. Accordingly, five variables are defined in this study to depict model changes in each consecutive version published on the BIM cloud, as illustrated in Table 6.1.

Table 6-1: Dashboard defined variables

Variable ID	Description
N	Changes in the number of elements between two consecutive versions
G	Geometry related changes between two consecutive versions
D	Data related changes between two consecutive versions
T	Number of used Types in each model version
LOD	LOD level of corresponding elements

The first variable (N) targets the changes related to the number of modeled elements in the BIM model. It depicts the changes in modeled elements between two consecutive versions reflecting a change in the model size or category of model elements. The second variable (G) tracks the elements witnessing geometry related changes in each consecutive model version. Geometry changes include changes in element's size, shape, and location. The third variable (D) tracks the number of elements witnessing data related changes in each consecutive model version. Data changes include changes in any type of element's attached data including its identification, material properties, or any other non-geometrical data. The fourth variable (T) highlights the number of Types used in the model at each published version. A Type is a parent class comprising elements having similar geometry and data properties. The fifth variable monitors the LOD level of modeled elements. The LOD level reflects the Level of Development of the corresponding model elements as per the guidelines of BIM Forum (2018).

6.2.2 Dashboard Visualization

Once the variables are defined, the design of the dashboard focused on selecting suitable visual tools to represent the changes at each published model version. First, histogram charts were employed to show the changes witnessed in the defined variables. While the histograms are good to represent the changes in the variable's values for each consecutive model version, they do not convey relationships among tracked variables especially that it is hard to superimpose several histograms in a single dashboard. Therefore, the histogram-based dashboard led to the generation of several dashboards; each targeting one or two variables at maximum. Thus, the defined variables were not initially combined into a single dashboard and the need to design a visual representation that is able to comprehensively show the dynamics of these variables on one sheet was acknowledged.

Therefore, a new visual design was sought to enhance the representation of the variables' changes witnessed during the development of design. In this regard, the dashboard design employed a Gantt chart representation to communicate the dynamics of defined variables. The Gantt chart enabled researchers to illustrate the changes of the variables in each category of elements, at each published model version, while combining all model categories into a single dashboard per discipline. Thus, the Gantt-based dashboard was able to summarize all variables' dynamics on a single sheet; rendering it more convenient to practitioners. The resulting generic dashboard is shown in Figures 6.2. Note that the current developed dashboard presents only a generic user interface layer. Future additions and interconnected dashboard entities are planned to be added to convey additional BIM model dynamics and to provide more flexibility to users. Nonetheless, the dashboard can be further developed to enable its use as an add-in application to available BIM software.

The dashboard classifies the model elements according to their categories shown on the left of the dashboard as shown in Figure 6.2. In every category, the dashboard tracks the start of the modelling task presented by a red diamond, and the changes in variables' values in a color-coded fashion. Changes in the variable N that represents the changes in the number of elements modelled under a certain category are highlighted in green. Changes in the variable G representing the number of elements that witnessed geometry related changes are highlighted in blue, while changes in the variable D representing the number of elements that witnessed property changes are highlighted in orange.

The dashboard also tracks the number of element types employed in each category and highlights the changes in their number in dark brown. The dashboard also tracks the LOD of model elements under each category reflecting its corresponding level of development. As for the base of comparison, the dashboard can compare any two published model versions across the timeline of the project which enables the design managers to track the progress of their project between any two points in time.

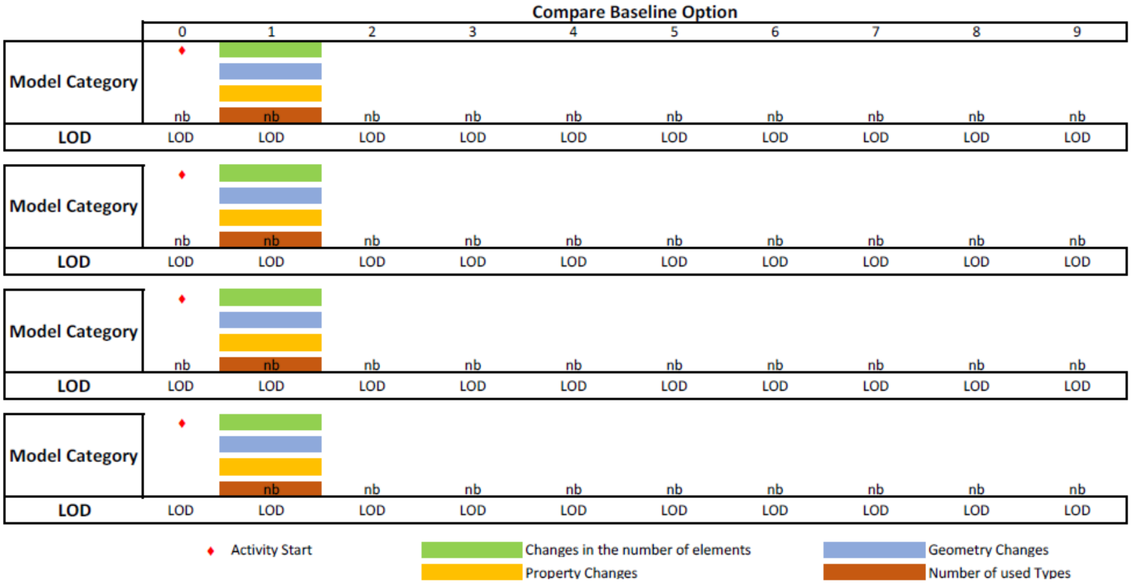

Figure 6-2: Generic BIM Dashboard

6.3 Case Study Application

The dashboard is implemented on an actual case study project to test its potentials and shortcomings. In this step, the design of the artifact witnessed several iterations, including one iteration after a peer review process, which led to the current design of the dashboard presented in Figure 6.2. The design of the dashboard aimed to enhance the visual representation of the artifact, to filter the corresponding model dynamics useful for design management purposes, and to enhance the artifact's readability and practicality.

The setup of the empirical study followed several steps as illustrated in Figure 4.6. in the methods section of this study. The empirical project consists of six identical residential villas, each divided into two apartments. The project spans over four months covering the end of the schematic design phase and the design development phase. Data is gathered through direct access to project files using a cloud-based application which enabled the authors to export every published version to an excel file showing all data related to the model. Figure 4.6 shows the process followed to gather the required data. The BIM models are first authored locally on desktop computers, regularly shared on the cloud, extracted to an excel file, and compared to previously published versions using a "compare versions" tool.

Figures 6.3 and 6.4 highlight the resulting dashboards after tracking the variables' changes at each published model version for the architectural and structural BIM models consecutively. Note that only significant changes higher than 5% are shown in the dashboard. For each category of elements (ex: partitions, doors, columns, etc.), the dashboard shows the start date of each activity and the changes in the monitored variables in a color-coded fashion. For instance, the "Partitions" category showed in the Architectural BIM Dashboard (Figure 6.3), witnessed significant changes in the “N” variable for versions 1, 2, and 6 while witnessing continuous changes in the “G” variable for all versions. Therefore, although the number of modeled partitions did not fluctuate in all published versions, the modeled partitions were witnessing continuous geometry changes due to design development and coordination.

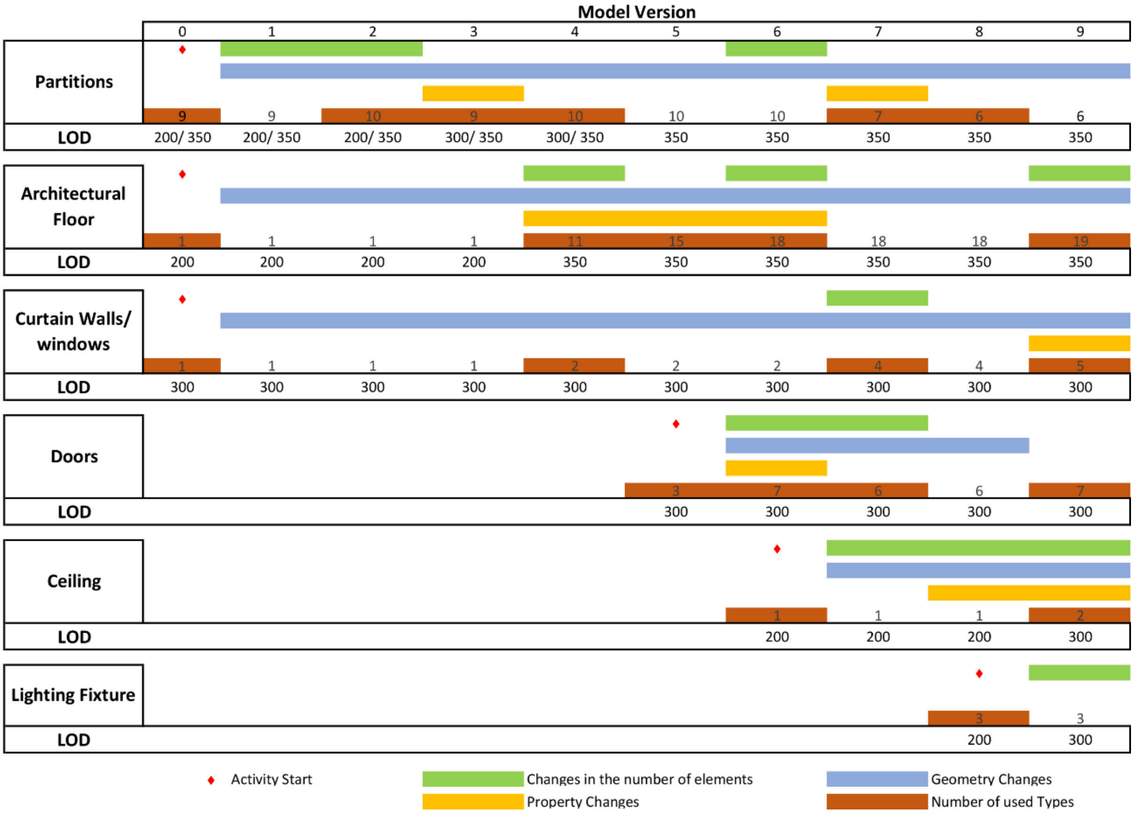

Figure 6-3: BIM Dashboard: Architectural Model Dynamics

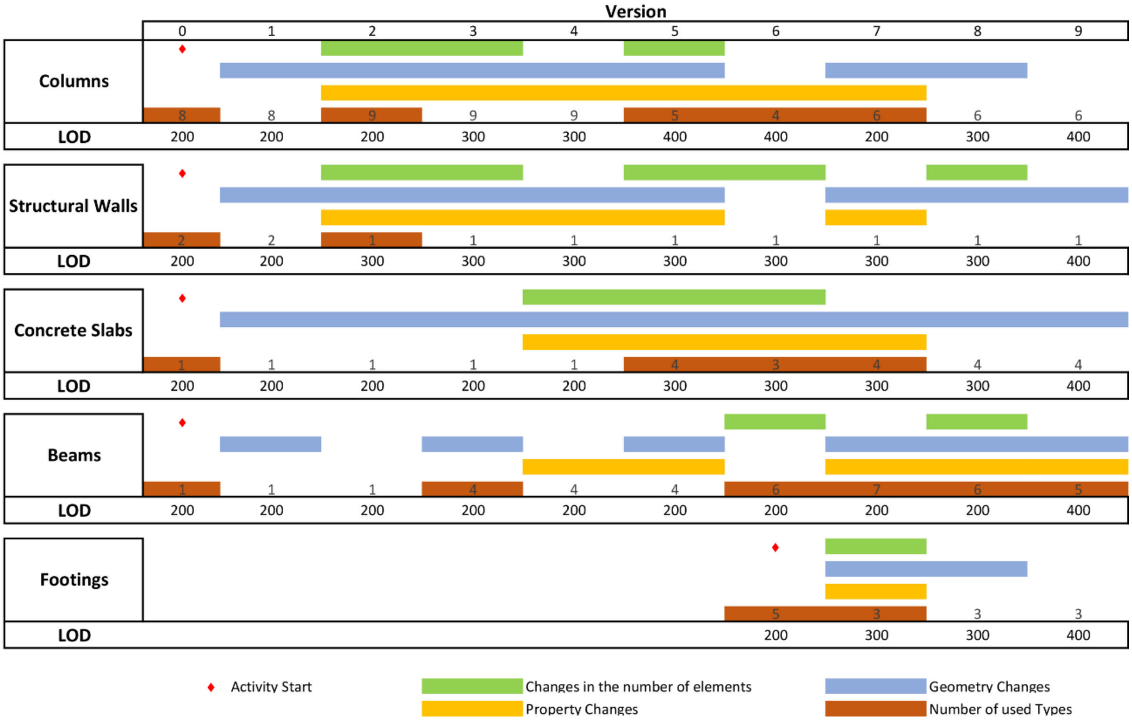

Figure 6-4: BIM Dashboard: Architectural Model Dynamics

6.3.1 Dashboard Analysis

This section investigates the types of design management aspects that can be inferred through the dashboard. In this context, the authors along with the design team leader explored what type of design related characteristics can be understood by tracking the dynamic changes of defined variables. Several aspects are identified and highlighted as follows:

- **Model categories under development**: the dashboard shows which categories of the model are being under development. For example, only “Partitions”, “Curtain Walls”, Windows”, and “Architectural Floors” categories are being under development for the first four versions of the architectural BIM model shown in Figure 6.3. In this context, each category witnessing changes in one or all its variables signals the involvement of the corresponding discipline in that specific version. In this regard, the dashboard can be employed to specify model progression across the timeline of the project. While the current use of table representation to specify model progression specification MPS (including model element author and LOD) is useful to plan the progression of elements that need to be modeled, the dashboard can add the time dimension to current MPS approach which is crucial for project maneuvering across different development phases. In this regard, the planned MPS can be used as a baseline in the dashboard.

- **Performance against schedule**: while the dashboard shows the start date of each design activity, the corresponding duration can be inferred by monitoring all versions having changes in the defined variables. In this regard, a certain category is said to reach its final design status if all variables witness no more changes. Nonetheless, comparing the actual start/end dates related to a certain model category against a pre-set model progression plan can show discrepancies between planned and actual design progress. In this regard, a dashboard showing the model progression plan can be superimposed to the dashboard showing actual progress to infer about the project's performance at any given time. Thus, design managers can keep track of the actual model progress, assess conformance to plan, and act accordingly especially if a critical category of elements is witnessing serious delays that can cause cascading delays in downstream design activities, which can affect the overall project's duration. Moreover, keeping track of actual LOD levels is important for the design manager to inquire about the actual level of development of a corresponding category. In this regard, the failure to reach a planned LOD level can threaten the development of other related categories and therefore disrupt the corresponding workflow.

- **Types of tasks performed**: the dashboard differentiates between three types of tasks accomplished by the designers across the project's timeline. The first task is the authoring of elements manifested by the creation and deletion of elements while developing the design solution. This task is manifested by the variable “N” showing the changes in categories’ overall size, and therefore model’s size. The second type of tasks is the development and coordination of created elements manifested by the changes of variables “G” and “D” showing geometry and data related changes respectively. The third type of tasks is the assignment of LOD values for modeled elements to reflect design reliability in each stage. Changes in LOD values from one version to another can either reflect an increase of element’s reliability if LOD increases its value or a loss of reliability due to design changes if LOD values decrease.

- **Design dependency and work sequence**: another important aspect shown by the dashboard is the work sequence followed to develop the corresponding design. The dashboard shows which categories are involved in each version and tracks the start date of other categories showing the followed sequence to develop the design solution. Note that this sequence can be due to either design dependency (ex: Columns category before Footing category), or to planning decisions focusing on certain categories of the model while postponing others (ex: Doors category postponed to version 5 although it can start earlier).

- **Indications of Design Progress**: the progress of design can be inferred from the dashboard at several fronts depending on which variable is witnessing changes as follows:

    - “N” variable: changes in the “N” variable signal the occurrence of changes related to the authoring activity manifested by the creation and deletion of elements. If “N” is witnessing changes in each new version, the BIM model is therefore still witnessing changes in its size in terms of the number of modeled elements. Note than if “N” witnesses no further changes, the model can be said to reach its final size, without negating the fact that elements can still witness geometry and data related changes.

- “T” variable: changes in the “T” variable reflect changes in the number of used Types (classes) in the model. On one hand, if “T” is increasing from one version to another for a certain category, it means that additional classes are being used to model more types of needed elements. In other words, an increase of the “T” value can signal the transformation of design from ‘generic’ to ‘defined’ as more accurate information is being generated. For instance, the number of used Types to model the architectural floors increased from 1 (generic Type to model all floor’s layers) in version 3 to 11 in version 4 to model the different forming layers of the floors including different types of tiles and toppings in each room. On the other hand, if “T” is decreasing from one version to another, it can reflect a designer’s decision to use standardized classes as in the case of “Columns” where “T” dropped from 9 at version 4 to 6 in the final versions. This means that the designer wanted to decrease the number of used column types to standardize and facilitate construction works.
- “G” variable: changes in the “G” variable reflect design changes related to the geometry characteristics of model elements. These changes can be related to element’s shape, size, or location. While continuous changes in the “G” variable can signal the occurrence of consecutive design iterations where elements are coordinated and developed, zero changes can reflect the

convergence of elements to their desired sizes and final locations in the model.

- "D" variable: changes in the "D" variable highlight the number of elements witnessing changes in their non-geometrical properties. Several types of properties are covered by the "D" variable including elements' identity, material, cost, specification or any other design related information. Changes in the "D" variable highlight the development of model elements in terms of added data, while zero "D" values can reflect the convergence of elements to their desired design information.
- LOD variable: the LOD variable reflects the design reliability of modeled elements as per the guidelines of BIMForum (2018). Nonetheless, assigned LOD values reflect the conformance of elements to the required geometrical representation and data richness required at each LOD level. In this context, an increase in LOD values for a certain category of modeled elements signal the progress of the design of this category as more accurate design data is generated, coordinated, and communicated to other users.

- **Rework**: rework can be inferred from the dashboard by monitoring the sudden decrease in LOD values across project's development. For instance, "Columns" in Figure 4 witnessed an increase in their LOD value to LOD 400 at version 5 which reflects the "Columns" reaching a shop-drawings level of detail where reinforcement details and concrete specification were added to the model. However, a sudden drop of the LOD value to LOD 200 occurred at version 7 along with changes in the "G" and "D" variables. These changes signal the occurrence of a major design change related to columns' geometry and specification which led to this decrease in the LOD value to 200.

6.4 Discussion of Results

The dashboard reveals several dynamics occurring at the level of BIM model elements. In addition to design development aspects inferred from the dashboard as shown in Section 6, other factors related to the overall process characteristics are brought to surface. First, the dashboard shows which variables are witnessing more changes than the others. In this case study, the variable "G" is witnessing the most changes among almost all published versions and categories. Accordingly, elements seem to continuously witness geometry related changes whether due to coordination among disciplines or due to intra-disciplinary development. In both situations, continuous geometry changes especially for an essential category like the "Partitions" category increases the chance of design changes in other model categories (like columns, slabs, and structural walls) because of design dependencies. Accordingly, design managers who can detect the continuous occurrence of these changes by referring to the dashboard, can investigate the root causes of these changes and act upon them, thus providing more stability to the work of other downstream designers and reducing possible rework.

Second, the dashboard reveals the modelling decisions adopted by the designers in terms of LOD requirements. For example, the designers in the case study have directly adopted the planned LOD 350 requirements to model exterior walls without following a gradual development across lower LOD levels. This decision led to modeling each wall's layer separately, thus significantly increasing the number of modelled elements under this category very early in the process. Consequently, designers needed to individually update these modelled layers every time design coordination affected exterior walls, which took extra time and effort. In this regard, designers should have avoided the adoption of high LOD level at the beginning of design to avoid major rework as noted by (Said and Reginato 2018). Moreover, designed beams in the structural BIM model jumped from LOD 200 to LOD 400 between versions 8 and 9 without passing through the intermediate LOD 300 level. One reason behind this jump is pushing the delivery of the model at version 9 with elements modeled as per the required LODs. These kinds of jumps reveal inappropriate planning of categories' development and may cause design errors and loss of value during the design process.

Third, designers in the case-study have assigned LOD values by assessing the development of elements at each model version. This procedure is error prone and can under or over estimates the actual LOD of modeled elements. Sometimes, designers kept the LOD at a lower level although the actual LOD is higher thus reducing reliability. This hinders downstream users from starting their design tasks where they needed to await upstream designers to assign higher LOD values to their elements. Therefore, the assignment of LOD values impacts the flow of information which sometimes lead to un-necessary interruption of workflow. In this context, the concept of LOD should be addressed from a new perspective that allows automatic calculation based on model circumstances and facts as suggested by (Abou-Ibrahim and Hamzeh 2016) not just the subjective decision of involved designers.

Fourth, the dashboard can be used for planning and scheduling purposes if employed prior to the start of design. For instance, the planning of the design development stage can include: the selection of model categories to be designed at each stage, the logical dependencies among these categories, the resulting start dates and durations, and the LOD levels needed to satisfy necessary information flow among involved stakeholders. Nonetheless, design managers can allocate major decision gates throughout the process to control model dynamics without affecting the value of the generated design. For instance, decision gates can be allocated to cease changes in the "N", "G", and "D" variables for a certain category to allow other dependent categories to safely proceed with their design while minimizing the possibility of rework.

Fifth, the developed dashboard can promote lean design management at several fronts. As a visual tool, the dashboard increases transparency among involved designers where work performed by each discipline is tracked in a transparent manner without uncovering specific firm expertise. Thus, the dashboard helps design managers to detect who does what, and to monitor how discipline models are evolving without uncovering confidential firm knowledge. In this context, unusual model dynamics can be visually detected triggering the need to perform root cause analysis to avoid future occurrence. In this regard, design managers can promote decisions that lead to the overall enhancement of design workflow while avoiding decisions that lead to working in silos. Nonetheless, flow discontinuity can be detected by the dashboard if a category of elements is witnessing clear cells for several versions; thus, witnessing no changes in variables' values although it is not finished yet. Workflow discontinuity leads to idle resources and can cause substantial delays in overall project's duration. Another important lean aspect uncovered by the dashboard is the occurrence of negative iterations that are a form of waste in the process that need to be minimized.

Sixth, the state-of-art of the used BIM technology can affect the quality of detected model changes as several shortcomings might be encountered as also noted by

(Pilehchian, Staub-French and Nepal 2015). For instance, the application used in the case study to compare model versions does not differentiate between negligible and serious modifications of elements' geometry. Nonetheless, it does not diagnose logical dependencies among elements and cannot recognize the deletion and addition of the same element during the modeling process where nothing has changed. Moreover, modeling issues like splitting and joining elements further complicates the tracking of changes where the same wall is counted changed if divided into several walls although its position and properties are the same. These software issues need to be addressed in future BIM applications to enhance the tracking of model changes across different versions.

Seventh, although tracking Size, Geometry, Property, Type and LOD changes gives design managers an idea about the actual design progress, a more detailed tracking of elements' changes is needed. At the level of geometry changes, it is beneficial to differentiate among size changes, shape changes and location changes. In this context, size changes can reflect development in a specific discipline, shape changes can reflect changes of element's Level of Detail (LOD), and location changes can reflect coordination with other elements. For property changes, classifying them into sub-categories can be of great benefit to design managers in monitoring the progress of design as data is added to model elements. For instance, changing the material of an element differs from adding constructability details. Moreover, it should be noted that the tracked model dynamics are not self-explanatory, but they require the intervention of experienced designers to correlate the dashboard results to actual design changes. This fact is considered a shortcoming of the current dashboard design and requires future enhancements. For instance, adding design activities to the dashboard and correlating them to model categories under development can be a possible solution.

Taking the above points into consideration, the dashboard can be employed in real life projects as a planning, monitoring and control tool to enhance the management of BIM-based design projects. At the planning level, the model progression plan comprising the set of categories that need to be modeled at each project phase, in each discipline, the required LOD levels, as well as the start/end dates of corresponding design activities can all be represented using the dashboard. Nonetheless, the logical sequence that needs to be followed while developing model categories can be mapped to the dashboard as to reduce the amount of rework. Once the design development plan is modeled using the dashboard, the design manager can continuously check actual model development against the plan and control the model progress accordingly. In this regard, discrepancies between actual and planned model progressions, whether related to time performance or generated LOD levels, can be visually detected allowing the design manager to take adequate decisions accordingly. For instance, a manager can ask to increase the design team size to accelerate the development of a corresponding critical category to avoid delaying subsequent categories. Moreover, the ability of the dashboard to pop-up changes generated at the level of elements' geometry and information levels can be of great value for design managers. For instance, a sudden geometry change in the structural beams' category can alert the design manager about possible clashes with other model elements such as mechanical pipes, or false ceiling; thus, pushing him/her to follow up the change with other involved disciplines. With the absence of such a dashboard, changes of this kind can go un-noticed by the design manager and persist as hidden clashes that may cause problems in downstream phases whenever discovered.

CHAPTER 7

AN ONTOLOGY-BASED REPRESENTATION OF BIM MODELS AND PROCESSES

7.1 Introduction

Building Information Modelling (BIM) is the zeitgeist of today's modern construction industry. Whether used in design, construction, operation, or maintenance phases, BIM is a game changer in the way construction information is being generated, developed, communicated, and used by involved stakeholders. In such a long chain of information generation and handoff among several practitioners, keeping track of the produced data while keeping an eye on client's value is a big challenge.

BIM can be approached as an n-dimensional compilation of parametric data into central or combined local models. The proper adoption of BIM helps streamline design workflows and facilitate coordination among involved domains in a 3D environment (Barlish and Sullivan 2012, Eastman, Lee, et al. 2009, Hartmann 2010). Despite these benefits, project participants face challenges and bottlenecks when interacting using BIM and sometimes prefer to revert to conventional 2D drawings instead; hence under-utilizing the potential of the 3D platform (Leicht, Messner and Poerschke 2014).

Furthermore, although BIM coordination tools are already available, there is a lack of efficient coordination strategies to bring together the fragmented work processes (Dossick and Neff 2010, Lee and Kim 2014). In this context, using BIM in isolation with little or no integration among different domains is nothing but working in silos; albeit on BIM platforms. So, if each practitioner is generating specific in-house BIM models with specific representation of the design and corresponding components, the process would not be far from traditional 2D processes (Dossick and Neff 2010).

On a different level, researchers note that most construction knowledge is tacit where knowledge acquired throughout the process is kept in the minds of design experts (Khalfan, et al. 2002). A great part of this knowledge is not captured and lost although it can be of benefit if systematically documented (Wang and Leite 2012). This fact is partially due to the lack of organized processes and the reliance on informal ways of collaboration while running the design and construction processes (Khalfan, et al. 2002, Kamara, et al. 2002).

To support collaboration among involved parties at different project stages, BIM needs to overcome several compatibility issues at the product and the process levels. At the product level, the lack of software interoperability and functionality is seen as a major barrier facing BIM adoption (Eastman, Teicholz, et al. 2008). In this context, the Industry Foundation Classes (IFC) is developed to enable different BIM software to talk to each other (buildingSMART n.d.).

IFC allows design teams to share data in a neutral format. It provides a comprehensive structure of information to suit the needs of all involved stakeholders in the AEC industry at all project phases. However, IFC schemas do not take into account how information is created and shared by practitioners in practice. Nonetheless, several concerns are raised about the current structure and use of IFC. Current IFC schemas are ambiguous, redundant, and lack semantics clarity needed to map entities and corresponding relationships. This fact leads sometimes to the generation of multiple data structures serving to represent the same information (Venugopal, Eastman and Teizer 2015); thus, threatening the integrity and quality of shared information.

Several attempts have been made to enhance the use of IFC. Among them is the Model View Definition (MVD) approach. MVD is a subset of the model extracted to provide a complete representation of the information concepts needed for a particular BIM use throughout the construction process (Aram, et al. 2010, Venugopa, et al. 2012). However, domain-specific information embedded in MVDs is generated separately by domain experts with a vague scope. In this context, MVD targets software developers for software certification purposes, but not the way practitioners use the software (buildingSMART 2010). Nonetheless, the required level of detail needed for the majority of model exchanges is not specified (Venugopal, Eastman and Teizer 2015) despite its importance for integrating work processes (Abou-Ibrahim and Hamzeh 2016). Accordingly, the consistency of information embedded in MVDs is questionable (Lee, Eastman and Solihin 2016).

In this context, several researchers suggest the formalizing of the IFC structure by employing ontological principles and semantics (Lee, Eastman and Solihin 2016, Venugopal, Eastman and Teizer 2015). Ontology is a representational artefact intended to represent some combination of universals, defined classes, and certain relations between them by employing a defined taxonomy (Arp, Smith and Spear 2015). It is developed based on fundamental propositions of domain experts following clear knowledge classes and hierarchy using semantic relationships (Gruber et al. 1993).

Ontology is used in several engineering and design domains. For instance, ontology is used to represent and capture dynamic design intent in the mechanical field

(Khan, Demoly and Kim 2016), to manage product design and encountered changes (Gruhier, Demoly and Gomes 2017), enhance CAD to CAD solid modelling interoperability and incorporate design knowledge into CAD systems (Khan, Demoly and Kim 2017), to describe products' relationships over space and time in integrated design (E. Gruhier, F. Demoly, et al. 2016), and to collaboratively develop Product Service Systems (Correia, et al. 2017). However, the use of ontology in the AEC industry is still sparse compared to other fields. For instance, ontology is used to enhance information management and sharing (El-Diraby 2013, Ruikar, et al. 2007), to model construction processes for simulation purposes (Benevolenskiy, et al. 2012), to create a bill of quantity for cost generation purposes (Xu, et al. 2016), to combine BIM and GIS data (Le and Jeong 2016), and to enable automated compliance regulation checking (Liebich, et al. 2002).

In BIM, ontologies are used at the software level to systematically structure the IFC schemas. This implementation led to the development of the ifcOWL Ontology. IfcOWL employs a Web Ontology Language (OWL) to represent IFC data (buildingSMART n.d.). It aims at avoiding inconsistencies while mapping information generated by domain experts. The ifcOWL ontology presents a semantic web representation of IFC that can be used in creating a web of building data linking many construction domains together (OpenBIMStandards n.d.).

While the use of ontology to systematically structure IFC schemas can help reduce compatibility problems at the product level, BIM still needs to overcome compatibility issues at the process level. Although enhancing software interoperability removes software barriers, it does not intuitively lead to changing the architecture of the BIM process. In this regard, this research addresses the compatibility issues at the BIM process level taking into account practitioners' needs where information is gradually generated, coordinated, updated, and added into the BIM model throughout the course of several design processes. Nonetheless, the majority of BIM users (architects, designers, contractors, etc.) are not aware of software sophistications; thus, a simple and clear BIM structure is needed at the user interface.

This chapter proposes a systematic way to generate and store construction information into the BIM model using an ontology-based framework. The developed ontology builds upon Basic Formal Ontology (BFO) developed by (Arp, Smith and Spear 2015) and aims to serve as a representation artefact of both the product and process aspects of BIM. In this regard, the suggested framework contributes to the use of ontologies in the AEC industry and it is expected to formalize the generation and sharing of construction information among involved stakeholders. To achieve those objectives, the Continuant and Occurrent aspects of BFO are employed along with the Ontology of Relations to logically represent the relations among involved product and process entities. Continuants are used to represent entities that continue to exist through time (BIM model entities, properties, etc), occurrent are used to represent entities that occur or happen and are used to represent processes (BIM related activities), and the relations are used to define logical relationships among different modelled ontology entities to represent required information about these entities.

7.2 BIM Product Ontology

This section describes the ontology developed to represent BIM models and their constituents being the product aspect of BIM. In this regard, BIM models are information databases that store data related to building elements during the project's lifecycle. They consist of elements representing actual building components like walls, windows, pipes, etc.

In this context, the BFO Continuant category is employed to represent these model elements as well as their related properties. The BFO Continuant category is designed to represent entities that continue to exist through time although they may lose or gain parts during their existence (ex: organisms gain and loses cells) (Arp, Smith and Spear 2015). Therefore, BIM models, corresponding elements, and their properties which continue to exist during the lifetime of the project and which can gain and lose parts during their development are best represented by using the BFO Continuant category of the BFO ontology.

Figure 7.1 presents the developed BIM Product Ontology which is considered in this study as a top-level ontology for BIM models. New general Classes are introduced to represent three major aspects of BIM models: (1) Building Elements, (2) Model Spaces, (3) Elements' Properties, and (4) Elements' Functions. These new Classes are defined based on BFO Continuant classes as illustrated in Figure 7.1.

7.2.1 BIM Model Elements

Four Classes are introduced to differentiate among elements in a BIM model. While BIM elements reflect actual building components, the four suggested Classes aim to cover all forms of building elements under the suggested BIM Product Ontology. These Classes are designed to be generic as to enable them to represent the widest possible range of building elements in all involved disciplines. The following sub-sections elaborate on each of these Classes.

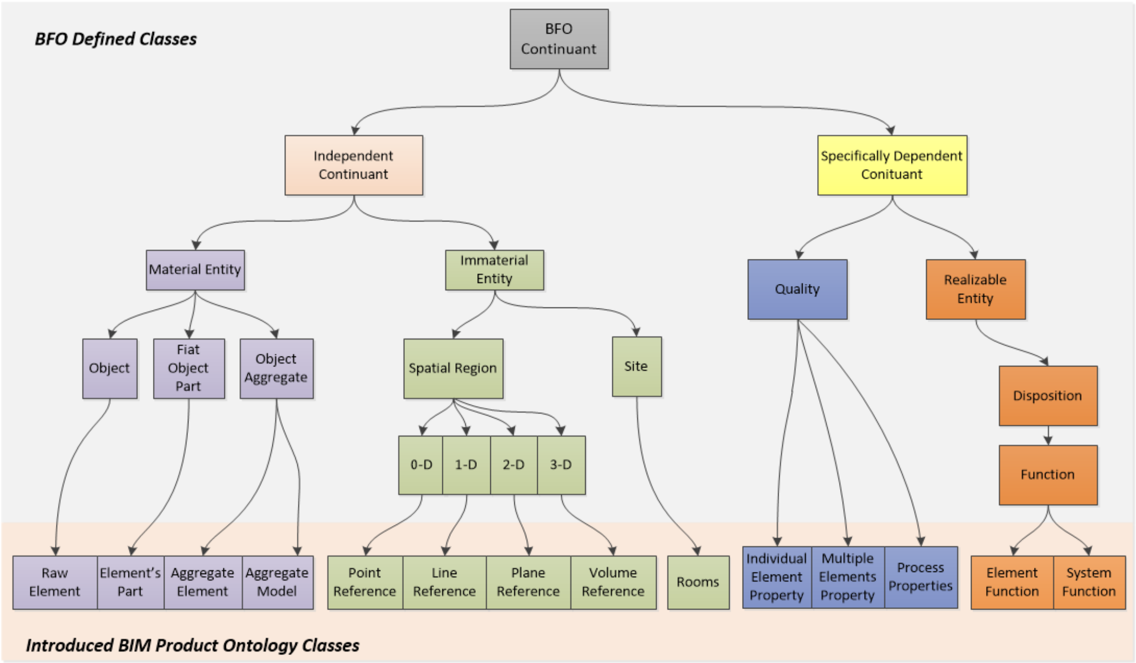

Figure 7-1: BIM Product Ontology (adjusted from (Arp, Smith and Spear 2015))

7.2.1.1 Raw Element

Raw building elements like steel columns, steel bars, mechanical pipes, etc. refer to elements that are not further divided in the scope of the construction process. In other words, these elements are dealt with at this granular level in the scope of construction related activities whether in design, construction, operation or maintenance phases. These elements are represented in this study using BFO: Object category as presented in Figure 7.1 because: (1) they are spatially extended in three dimensions; and (2) they are causally unified ("meaning its parts are tied together by relations of connection in such a way that if one part of the object is moved in space then its other parts will likely be moved also") (Arp, Smith and Spear 2015).

7.2.1.2 Element's Part

The elements in BIM models include parts that do not independently form objects by their own. Examples of these parts could be the top of a concrete slab which is part of the concrete slab, the upper one third of a column, or any other part selected by the designer without being able to form an independent object by its own. Those parts are represented in this study using BFO: Fiat Object Part as highlighted in Figure 7.1 because they are material entities that form part of a bigger object with no physical discontinuity. Note that fiat parts are not themselves independent objects delineated by clear boundaries; however, the term fiat is used to point out to some decisions that could be made by the designer to define the boundaries of that specific part (Arp, Smith and Spear 2015). For instance, a structural designer can define the spacing of steel stirrups in the case of a concrete column by referring to the column's fiat parts (ex: 10 cm spacing in the top and bottom 1/3 of column's height, and 20 cm in the middle fiat column's part).

7.2.1.3 Aggregate Element

Some elements in BIM models are formed by the connection of distinct independent objects together reflecting the actual structure of their corresponding building components (ex: a window is formed of aluminum frame, glass panels, rollers, etc). Note that these forming objects are independent and they exist regardless of the existence of the aggregate object. Examples of aggregate elements in BIM models include windows, doors, concrete slabs, etc. Aggregate elements in BIM models are represented using BFO: Object Aggregate Class. As defined by Arp, Smith and Spear (2015), an object aggregate is a material entity that is made up of a collection of objects that are separate from each other and share no parts in common.

7.2.1.4 Aggregate Model

In addition to defining individual model elements, Aggregate Models are introduced in this study to refer to a set of BIM model elements. An aggregate model can represent the entire BIM model, for example the architectural BIM model, or a system such as drainage system, or a defined set of elements selected by the designer like the columns present in the second floor of the building. Therefore, aggregate models can include True Elements (ex: steel columns, steel beams, bolts, tiles, cladding tiles, bathroom accessories, etc), Elements Parts (ex: top surface of a slab) and Aggregate Elements (ex: double partition walls, windows, doors, etc).

7.2.2 Elements' Properties

Having defined four Classes of model elements in section 7.2 based on BFO Independent Continuants, this section defines elements' properties based on BFO Dependent Continuants. A dependent continuant depends on one or more specific independent continuants for it to exist. For example, the color of a tomato could not exist without the tomato itself being its bearer (Arp, Smith and Spear 2015). In this regard, two sub-classes of Dependent Continuants are employed in this study, BFO: Quality and BFO: Realizable entities as described in the following sections.

7.2.2.1 Element's Quality

Qualities depend on other entities, mainly independent continuants, to exist. Mass, height, color, and shape are examples of qualities that require independent continuants as their bearers to exist. In addition to relying on dependent continuants to exist, qualities can depend on entities of other types, like processes, to exist. For example, the beating quality of one's heart depends not only on the heart but also on the beating process the heart participates in (Arp, Smith and Spear 2015). Therefore, three main sub-classes are defined in this study under the BFO: Quality class to: (1) describe the properties of individual model elements (shape of a column, linear mass of a partition wall, size of a couch, thickness of a slab), (2) to describe the properties of multiple model elements or even the entire model (ex: material cost of the entire building), and (3) to describe the properties of involved processes (ex: cost of the design process, duration of construction process).

7.2.2.2 Elements' Functions

Realizable entities like qualities also depend on Independent Continuants to exist; however, they are only exhibited through certain characteristic processes of realization. Therefore, a Realizable entity is defined as a Dependent Continuant that has at least one Independent Continuant entity as its bearer, and where the corresponding realizable instances can only be manifested in associated processes the bearer instance participates in (Arp, Smith and Spear 2015). In the developed BIM Product Ontology, two sub-classes are defined under the BFO: Function class to define element's and system's functions. For example, the function of a pump element to pump water in a drainage system can be defined using a specific function (ex: PumpWater) that depends on the independent continuant instance "pump" and the process instance "pumping water". Also, the function of a heating system modelled in BIM to heat the building to a certain degree can be represented using a specific function (ex: HeatBbuilding) that relies on all the elements that form the heating system (boilers, pipes, pumps, fittings, etc) and that is manifested through the process instance of "heating this specific building".

7.2.3 Model Spaces

The model spaces are represented in this study using two categories of BFO Immaterial Entities, the BFO: Spatial Region and the BFO: Site. Spatial regions exist independently of material entities and therefore do not change; however, sites are demarcated by material entities and therefore do change as their bounding material changes shape or location. Four different spatial dimensions are defined in BFO including 0D, 1D, 2D, and 3D spatial regions. The BIM Product Ontology uses these dimensions to identify independent spaces in the model like reference points (0D, ex: GIS reference point corresponding to the project site), reference line (1D, ex: a grid axis), levels, plans, sections (2D, ex: plan view of floor 1, section view of building, etc.) and volumetric spaces (3D, ex: the 3D model space). Nonetheless, the BIM Product Ontology employs the BFO: Site to identify dependent locations in the model like rooms and specific model zones that are demarcated by the elements in the model (ex: the walls demarcating a room).

7.3 BIM Process Ontology

While section 7.2 presents BIM Product Ontology to define BIM models and their constituting elements, this section introduces BIM Process Ontology to define the different processes witnessed by these model elements during project's lifecycle. Examples of these processes include the design process of an element, its actual construction process on site, its operation process as well as its maintenance process.

The BFO: Process is employed in this study to define the different processes witnessed during the lifetime of a project. As defined by Arp, Smith and Spear (2015), "a BFO: process is an occurrent entity that exists in time by occurring or happening, has temporal parts, and always depends on some (at least one) material entity". For instance, the architectural design process of a building is an occurrent entity that exists in time, has temporal parts (ex: concept design, schematics design) and depends on material entities (ex: BIM models, BIM elements, Elements' properties, etc.).

Figure 7.2 presents the BIM Process Ontology which is developed based on BFO: Process Ontology. The following Classes are defined to capture process aspects in the BIM process.

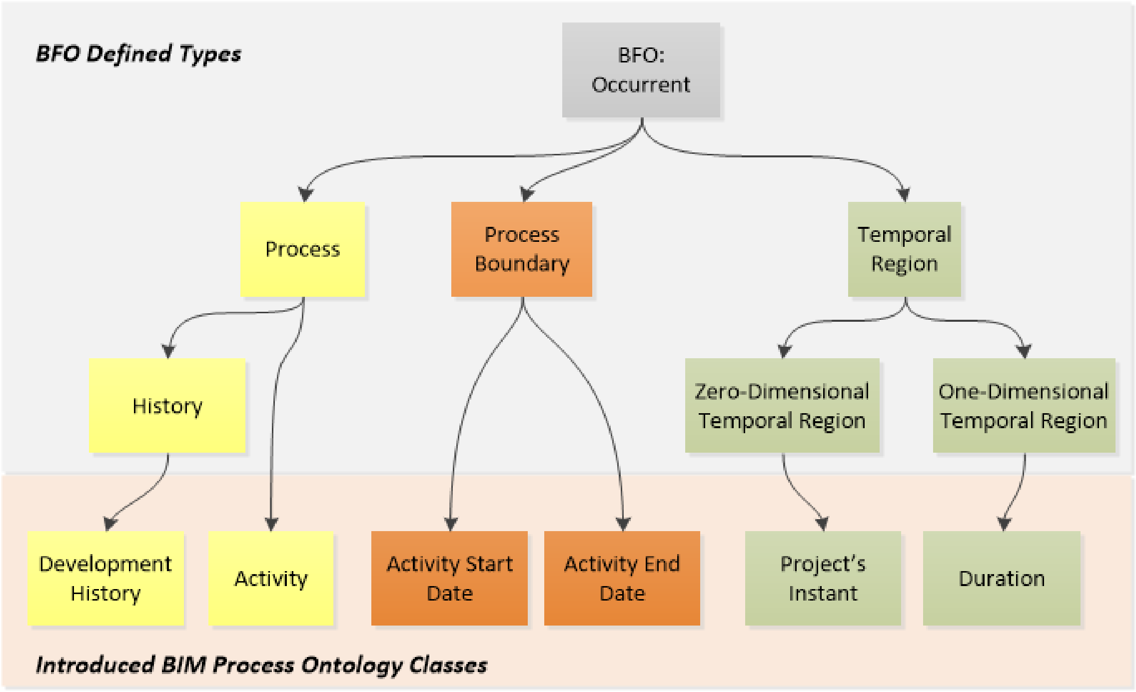

Figure 7-2: BIM Process Ontology (adjusted from (Arp, Smith and Spear 2015))

7.3.1 Activity

All activities witnessed during the BIM process (ex: Structural Design, Sizing of Columns, material selection, schematic architectural design, etc) are defined as processes in the BIM Process Ontology. These activities satisfy the requirements of a BFO: Process where they occur in time, have temporal parts (as multiple sub-activities), and always depend on at least one material entity to exist (BIM models, designers, owners, etc).

7.3.2 Activity Start and End Dates

Two process boundaries are defined in BIM Process Ontology: Activity Start Date and Activity End Date. These two process boundaries are defined as BFO: Process

Boundary which is an occurrent entity that is the instantaneous temporal boundary of a process (Arp, Smith and Spear 2015), in this case the corresponding activity.

7.3.3 Project's Instant

A Project Instant is defined as a Zero-Dimensional Temporal region which is a sub-category of BFO: Temporal Region. The BFO: Zero-Dimensional Temporal region defines the smallest instant of time that is not extended (Arp, Smith and Spear 2015) such as this moment or the moment a model element (column) is added to the structural BIM model for example. A project Instant is used to delineate important moments in project's development time (ex: creation instant of an element, the instant an element changes location, shape, properties, etc.).

7.3.4 Duration

Duration is defined in the BIM Process Ontology as a One-Dimensional Temporal region which is a temporal region that extends in time as defined by Arp, Smith and Spear (2015). Therefore, durations have further temporal regions as parts including the project's instants that occur during the corresponding duration. Durations are used in the BIM Process Ontology to denote the time intervals taken to finish a certain activity.

7.3.5 Development History

The Development History is defined in the BIM Process Ontology as a BFO: History which is defined as the sum of all processes happening in the spatiotemporal region occupied by the corresponding material entity or site under focus (Arp, Smith and Spear 2015). Therefore, the Development History is used in the BIM Process Ontology to archive the comprehensive development of BIM models, the individual development of model elements as well as the development of defined model sites (ex: different levels, landscapes, etc).

7.4 Logical Relations

While sections 7.2 and 7.3 introduced BIM Product Ontology (Figure 7.1) and BIM Process Ontology (Figure 7.2), this section aims to define the main logical relations needed to capture important information about modeled elements and occurring processes throughout a BIM-based design projects. In this context, the developed relations in this study are based on three major types of relations developed by Arp, Smith, and Spear (2015) in the BFO ontology:

- Relations holding between one universal and another which reflect the relations among the different categories of a defined ontology (ex.: a column “is a” structural element, a structural design process “is a” design process).
- Relations holding between a particular and a universal needed whenever an ontology is applied to a portion of reality such as when applying the developed BIM ontology to a specific BIM-based project (ex: the relation of instantiation: column c in this BIM model “instance of” Column).
- Relations holding between one particular and another (ex: relations among BIM model elements: steel rebar T14 “continuant part of” column c, relations among design activities: activity a “occurrent part of” activity b).

Table 7.1 presents a set of logical relations used to correlate between the different categories of the developed BIM-based ontology based on the three defined types of relations.

Table 7-1: Ontology Logical Relations (adjusted from (Arp, Smith and Spear 2015))

Relation Type	**Relation**
universal-universal	1. *"is_a" (is a subtype of)* a. Continuants example: a Column *is_a* Structural Element a Structural Element *is_a* Model Element b. Occurrents example: Column's Design *is_a* Structural Design Process Structural Design Process *is_a* Design Process
particular-universal	1. *"***instance_of***"* a. Continuants example: column c in this BIM model **instance_of** Column_Class level-1 **instance_of** Level_Class b. Occurrents example: column c design **instance_of** Column_Design_Process
particular-particular	1. **located in** used to relate a continuant instance and a spatial region it occupies ex: column c located in floor 1 - also, a time dimension can be added here: ex: column c located in floor 1 **at** t 2. **continuant_part_of** presents the parthood relation between two continuant instances at a specific time when one instance is a part of the other. ex: column c **continuant_part_of** structural system s **at** t room 103 **continuant_part_of** level-1 3. **occurrent_part_of** presents the parthood relation between two occurrent instances independently of time when one process is a subprocess of the other. ex: column sizing **occurrent_part_of** column design architectural design **occurrent_part_of** building design 4. **inheres_in** presents the relation between a specifically dependent continuant (quality, function, etc.) and an independent continuant at time t. ex: weight **inheres_in** wall-a **at** time t concrete f'c **inheres_in** concrete-M30 **at** time t production rate r **inheres_in** team-1 **at** time t

5. **has_participant** presents the relation between a process and a continuant
ex: column design **has_participant** column c **at** time t

6. **starts_at** presents the relation between a process instance and its corresponding start date
ex: column design **starts_at** time t

7. **finishes_at** presents the relation between a process instance and its corresponding finish date
ex: column design **finishes_at** time t'

8. **has_duration** presents the relation between a process instance and its corresponding duration
ex: column design **has_duration** T

9. **preceded by** presents the relation between two occurrent instances
ex: structural design **preceded by** architectural design
column grid development **preceded by** space design

The developed relations allow the designers to (1) relate BIM model entities (both continuants and occurrents) to their universals based on logically clear semantic hierarchies; (2) to locate model elements in defined spaces in the model; (3) to define elements properties and functions; (4) to define the parthood relations among model entities, (5) to semantically define design activities, and (6) to correlate between defined model elements and corresponding design activities in different project phases.

7.5 Illustrative Example

This section presents an illustrative example to showcase the use of the developed ontology and corresponding relations to represent BIM model elements and related design processes. The example shows the definition of a concrete column "col.c" modelled in a specific BIM model at a given instant of time, as illustrated in Figure 7.3. In this context, different information related to col.c and the BIM model can be inferred as follows:

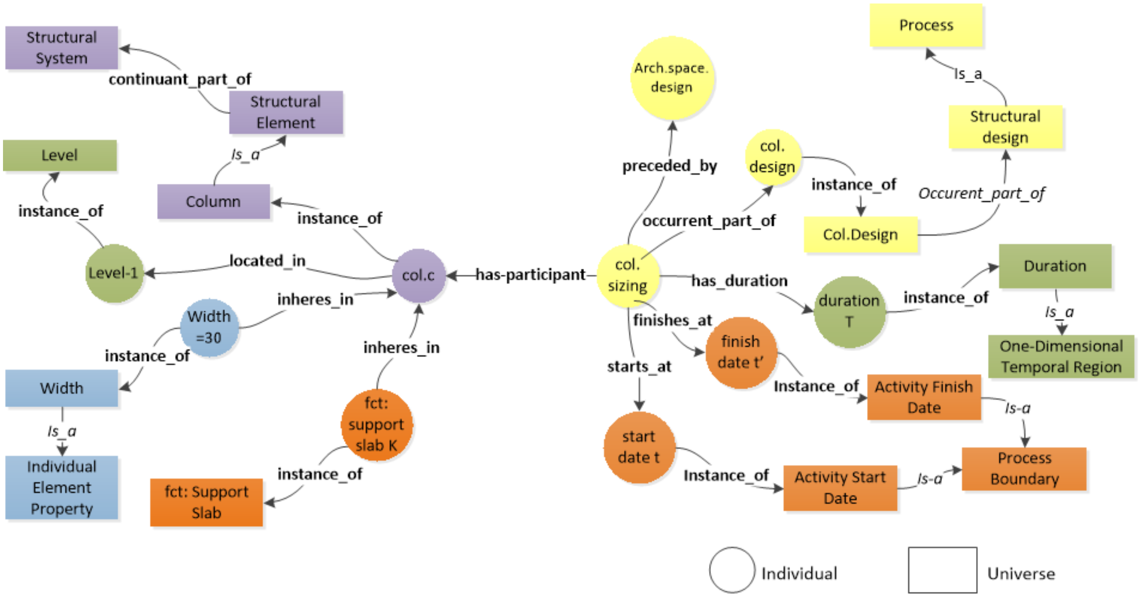

Figure 7-3: Illustrative Example for BIM Ontology Use

- col.c **instance_of** Column
- Column *is_a* (is a subtype of) Structural Element
- Structural Element **continuant_part_of** Structural System
- col.c **located_in** level-1 **at** time t
- level-1 **instance_of** Level
- width=30 **inheres_in** col.c **at** time t
- width=30 **instance_of** Width
- Width *is-a* Individual Element Property
- fct:support slab k **inheres_in** col.c **at** time t
- fct:support slab k **instance_of** fct:Support Slab
- col.c **participates_in** col sizing **at** time t
- col. sizing **occurrent_part_of** col. design
- col. design **instance_of** Col. Design
- Col. design **occurrent_part_of** Structural Design

- Structural Design *is-a* process
- col. sizing **preceded_by** arch.space.design
- col. sizing **starts_at** time t
- col. sizing **finishes_at** time t’
- col. sizing **has_duration** duration-T
- duration-T instance_of Duration
- Duration *is_a* one-dimensional temporal region

7.6 Discussion

The developed BIM Product Ontology and BIM Process Ontology serve as representation artefacts of both the BIM models and involved BIM processes. These ontologies are developed based on Basic Formal Ontology (BFO) by Arp, Smith and Spear (2015) and they are designed to be as top-level ontologies for BIM. Thus, they employ the division of BFO that separates the world into continuant entities and occurrent entities related through logical relationships.

BIM Product Ontology presents a clear division of BIM models based on the continuant category of BFO. Model elements, their properties and functions, and model spaces are clearly defined following a systematic hierarchy that relates BIM Product Ontology entities to the BFO ontology. At the level of model elements, BIM Product Ontology presents a general classification of elements based on their actual structure regardless of their specific disciplines. Elements therefore are divided into “Raw Elements” that represent undividable elements in the scope of construction related activities (ex: steel rebar, water pump, tile, pipe, etc), “Element’s Part” that represents fiat parts of modelled elements based on identification decisions taken by the designers (ex: surface of a floor, specific area of a slab, etc), and “Aggregate Elements” that represent elements formed of distinct objects that can exist outside of the aggregate object (ex: window formed of frame, glass panels, accessories). Moreover, an “Aggregate Model” class is added to represent groups of elements like systems or entire BIM models (ex: structural system is an Aggregate Model comprising all structural elements in the model).

This classification of model elements enables designers to logically relate model elements together as well as to relate model elements to their domain systems, using defined BFO relationships. For instance, the parthood relation can be used to relate a fiat Element Part to its element (ex: surface of a slab **continuant_part_of** slab), an Aggregate Element to its forming objects (ex: glass panel **continuant_part_of** window), and an element to its corresponding system at a specific time (ex: steel beam **continuant_part_of** structural farming system **at** time t, a window **continuant_part_of** architectural system **at** time t).

The differentiation among elements’ types enables the systematic addition of their properties and functions. Consider adding the properties of a window, some properties are related to the entire window as an Aggregate Element (height, width, cost, etc.) while other properties are related to its constituting parts (ex: thermal coefficient of glass, material of the frame, etc). Nonetheless, BIM Product Ontology allows the addition of properties and functions related to a group of elements using Multiple Elements Property defined under BFO: Quality (ex: construction cost of structural frame, heating function of the HVAC system, etc.).

In addition to classifying model elements based on their constituting parts, the classes of the developed BIM Product Ontology can be linked to already existing standard classification systems. For instance, the "*is_a*" relationship can be employed to relate a defined class in the BIM ontology to a corresponding class in Uniformat II or IFC. For example, a window element in a model can be classified as an instance of Uniformat II B2020-Exterior Windows Class. This flexibility enables designers to author their BIM models following a systematic ontological structure that logically relates model entities together, while keeping the possibility of linking different model elements to available standard classification systems.

While the developed BIM Product Ontology can be employed as a representational artefact for BIM models and their content, BIM Process Ontology is developed to represent the corresponding design activities. The BIM Process Ontology defines Activities as BFO: Processes having Activity Start Date and Activity End Dates as BFO: Process Boundaries. Activity Duration is defined as BFO: One-Dimensional Temporal Region formed of all Instants (Zero-Dimensional Temporal Region) occurring between activity's start and end dates. Moreover, BIM Process Ontology defines Development History as a category of BFO: History comprising all processes the element participates in; therefore, chronologically capturing the development history of elements as well as of models.

BIM Process Ontology expands the representation of BIM in the fourth dimension being the time dimension. Accordingly, model elements and their development status can be linked to actual events or instants occurring throughout the life cycle of the project. For example, an element having two different LOD (Level of Development) levels in two distinct moments during project's development can be represented as follows: LOD200 **inheres_in** element "a" **at** August 15, 2018, and

LOD300 **inheres_in** element “a” **at** September 4, 2018; thus, chronologically tracing the development status of the corresponding element.

Accordingly, BIM Product Ontology and BIM Process Ontology can be employed to represent different aspects of BIM whether at the product level or occurring design processes. Nonetheless, relating each model element to corresponding activities through the relation “**has_participant**” can be used to recognize all involved elements and properties participating in specific activities which can increase contextual awareness of multidisciplinary designers, and enhance collaboration among them.

Moreover, representing BIM models using solid logical relationships can be used to enhance parametric modelling across the design phase. If achieved, designers would be able to capture more aspects of the actual building characteristics with all the constraints and relations that exist; thus, making BIM models more realistic and useful. Also enhancing parametric modelling in BIM can be employed to track the effects of changes on modelled elements as well as on their functions and properties.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Preface

Managing the design phase of construction projects is a challenging form of management in the Architecture, Engineering and Construction (AEC) industry. While the management of construction can be approached from a linear production perspective, the management of design deals with managing iterative and creative ideas in a social and multidisciplinary environment. Because the difference between the two processes is structural, the use of construction-based measures has failed to properly address the design phase characteristics.

Many aspects complicate the management of design projects. Some of these aspects are related to the nature of design being an ill-structured and creative process that is basically based upon iterative loops of analysis, synthesis and evaluation. Other aspects are caused by the involvement of several stakeholders from different backgrounds and mentalities with relative attitudes towards a project’s value. Therefore, a proper approach towards managing a design process should consider the chaotic nature of the design activity on one hand and understand its social context on the other.

Several researchers have addressed the management of design projects acknowledging their iterative nature and social characteristics. While some studies have focused on enhancing the sequencing of design activities as to reduce rework generated by negative iterations, other studies have addressed the social context of the design process by analyzing the underlying social network structure. In this context, different frameworks were developed to enhance the setup of the design process and to efficiently manage the corresponding design workflow.

While previous studies tried to tackle the problems that hinder the management of design projects from different angles, the actual understanding of stakeholders' dynamics, their perception of project's value, the decisions they take, and the resulting effects on design project's development are still under-studied. Assuming a generic representation of stakeholder's characteristics does not give a realistic picture about actual design projects. In this regard, each design project is unique not just because of the corresponding design problem, but also due to the types and characteristics of individuals involved in the process. Ignoring these aspects might affect the quality of a design project's plan which by its turn can affect the overall project's performance.

Meanwhile, the industry is witnessing a technological shift towards the implementation of Building Information Modeling (BIM) as a collaboration platform among different involved stakeholders. Although the ultimate benefits of BIM as a work process are yet to be realized, BIM has proven to be a game changer in the way design intent is being generated and communicated among involved players. The major driver behind this change is the object-oriented nature of BIM software that allows designers to work with virtual model elements to represent their design. While several studies have investigated the use of BIM in the design process, the correlations between design process dynamics and BIM model progression are not efficiently developed.

In this regard, this study explores design management from a new perspective. First, it aims to understand the actual effects of stakeholders' characteristics on design development and corresponding BIM model dynamics. Second, it investigates different project's setups and studies the corresponding effects on project's overall performance. Third, it employs the new findings to enhance the quality of design project planning acknowledging the effects of stakeholders' characteristics and process setup. Fourth, the study contributes to the practical aspects of design management by developing a visual dashboard that aims to enhance the scheduling, monitoring, and control of BIM-based design projects, and fifth, the study develops a BIM ontology as a step towards standardizing the representation of BIM-based design projects to increase their semantic richness and readability by computers.

This chapter summarizes the research study and highlights its key findings. Also, recommendations and practical suggestions based on the research outcomes are presented. Research contributions are also highlighted. Finally, future research plans and ideas that need to be explored are suggested for future research.

8.2 Research Summary

8.2.1 Summary of Research Methods

The research method employed in this study is Design Science Research (DSR). DSR is known as a form of constructive research that aims to design useful artefacts to serve human purposes. DSR is suitable to conduct research in the construction management field where innovative concepts and tools can be developed to address practical field problems and to add value to involved stakeholders.

The research is divided into three modules, each comprising the development of a model artefact that serves the corresponding research objectives. Module 1 aims to understand the dynamics of design workflows resulting from the interactions among different involved design stakeholders. In specific, this module investigates the effects of interactions among the project’s client, the architect and the engineer on BIM models’ dynamics in the concept and preliminary design stages. For that purpose, an agent-based simulation model is developed to mimic the dynamics of real-life design projects. Different project’s scenarios were developed and tested accordingly.

The second module of the study aims to better understand the types of dynamics witnessed at the level of BIM model elements during the development of design. While several changes can be extracted from a BIM model, only changes that can be used to infer about design development are monitored. Accordingly, a visual dashboard is designed to track changes related to BIM model content by defining a set of variables that track changes related to element’s type, geometry, attached information, and LOD levels. The dashboard is then applied on an actual case study project during its schematic and design development phases. The application of the dashboard showed that it can be used as a practical tool to enhance the scheduling, monitoring, and control of BIM-based design projects.

The third module proposes a systematic way to generate and store design information into the BIM model by developing an ontology-based framework. The developed ontology builds upon Basic Formal Ontology (BFO) and aims to serve as a representation artefact of both the product and process aspects of BIM. The framework is designed to formalize the generation and sharing of design information among involved stakeholders, aiming to increase the shared understanding among different involved stakeholders.

8.2.2 Summary of Results

8.2.2.1 Module 1

The results of the study were categorized according to corresponding modules. For module 1, the results of the simulation experiments are detailed in Chapter 5. The results show that the characteristics of involved stakeholders and the setup of the design process can affect the performance of design projects in terms of project's duration, value achieved, rework generated and project's risks.

First, the client's initial perception of project's value and the extent to which he/she can perceive the project's needs and requirements during the design phase are major factors that affect the project's performance. At the level of project's duration, projects having knowledgeable clients on board are more likely to finish earlier if compared to projects having unknowledgeable clients regardless of other project's conditions. At the level of achieved value, knowledgeable clients have more chance to reach a higher percentage of the possibly achievable project's value during early project's phases. This fact leads to reducing the project's risks related to work changes in downstream phases resulting in less overall rework.

Second, the ability of the Architect/Engineer (AE) team to actively shape and define the project's value plays a major role in shaping the performance of a design project. In this regard, high ability AE teams are more likely to require less time before converging to a final design solution that satisfies the client's value; thus, reducing the overall project's duration by substantially reducing the number of needed design iterations related to client reviews. Moreover, a high ability AE team can help the client achieve a higher percentage of the possible achievable project's value by expanding its knowledge about the project's needs and requirements at early project's phases.

Accordingly, high ability AE teams can help reduce the project's risk related to possible design changes generated by client's requests; because clients are exploring much of their project's value early on in the process.

Third, the design process setup affects the overall performance of a design project. The results show that engaging the client in design can positively impact the design process. For instance, engaged clients are more likely to learn faster about their project's value which enabled them to achieve project's needs in a relatively shorter period if compared to non-engaged clients. In this regard, the fast convergence to the desired design solution early in the process decreased the risk of generating changes in downstream phases, which can help reduce the number of man-hours wasted on rework.

Fourth, planning the development of design projects among engaged AE teams has a direct impact on the amount of rework generated during the design process. Nonetheless, a higher rework size can affect the time performance of a project where more of the time dedicated to design development is wasted on negative iterations. In this regard, design managers can feel the urge to increase the teams' capacity or even push their team members to perform overtime to avoid missing delivery deadlines. This approach increases the load on involved AE teams and may affect the overall quality of the design product where errors and omissions are more likely to occur.

8.2.2.2 Module 2

The results of Module 2 of this study, presented in Chapter 6, show that the developed dashboard can help design managers better monitor and control the performance of BIM-based design projects. The dashboard is designed to track several dynamics occurring at the level of BIM model elements, including changes related to the number of elements existing in the model, changes in element's geometry, changes in information attached, changes in the number of elements' types used, as well as changes in elements' LOD.

The dashboard can be used to compare design progress between any two model versions. For instance, design managers can use the dashboard to track weekly model dynamics in one hand, and to check design progress on the other. In this regard, the dashboard can be used to infer about several project's dynamics including: (1) the categories of elements that are currently under development; (2) the types of tasks performed (ex: geometry, data, or LOD related); (3) design dependency and work sequence that can be shown by highlighting when did the work on each category of elements started relatively to other categories; (4) design progress that can be inferred by analyzing the changes in each of the defined variables, and (5) major rework manifested by the sudden drop of elements' LOD values.

8.2.2.3 Module 3

Module 3 of this study, detailed in Chapter 7, presents the development of a top-level ontology for BIM-based design projects using Basic Formal Ontology (BFO). While the developed BIM Product Ontology targets the formal representation of BIM model's content using the BFO: Continuant category, the BIM Process Ontology tries to formalize the definition of design activities using the BFO: Occurrent category. Nonetheless, logical Relations were developed to connect the entities of the developed ontology together.

The developed BIM Product Ontology defines new classes under the BFO: Continuant category to enable a clear division of BIM model's content. In this regard, the developed ontology devises new classes to represent BIM model elements and differentiates among them based on their structure. In this regard, the ontology presents four new classes to categorize model elements accordingly; basically “Raw Elements”, “Element’s Part”, “Aggregate Elements”, and “Aggregate Models”.

Nonetheless, the BIM Product ontology presents a definition of element’s properties and differentiates between element’s qualities and functions. While a quality represents a property of a model element or a system of elements, a function refers to the actual function of the corresponding element or system. The BIM Product ontology also defines the spaces inside a BIM model and differentiate among spatial regions (0D, 1D, 2D, and 3D) and model sites.

On the other hand, the BIM Process ontology presents a formal definition of a design activity as a BFO: Process having its start and end dates defined as a BFO: Process Boundary and its duration defined as a BFO: One-Dimensional Temporal Region. Also, the development history of an activity is defined as a BFO: History which is the sum-up of all related project’s instances throughout the design development process.

Also, a set of logical relations were developed to connect the different BIM ontology entities together as to capture important information about modeled elements and occurring processes throughout a BIM-based design project. These relations help formalize the connection among model entities at three different levels. At the Universal-Universal level, the “*is_a*” relationship is used to enable the systematic definition of different BIM model classes and to connect them across a logical hierarchy (ex: a Column is a Structural Element, a Structural Element *is_a* Model Element; thus, a

Column *is_a* Model Element). At the Particular-Universal level, the **instance_of** relation is used to connect a particular in a real-life BIM project to its ontology class (ex: column c in this model **instance_of** BIM: Column). At the particular-particular level, several relations were developed to represent different types of relations that can occur among continuants entities, occurrent entities, or between continuant and occurrent entities together (ex: design activity A **has_participant** column c **at** time t).

8.3 Key Findings

8.3.1 Design Planning

The results of the study show that the performance of a design project is highly affected by the characteristics of involved design stakeholders including: (1) the actual knowledge of the client about his project's value, (2) the ability of the AE teams to address and realize this value, (3) the quality of the design plan, and (4) the process setup underlying the design development; aligning with the results of several related studies in this field (Al Hattab and Hamzeh 2018, Cross and Cross 1995, Cross 1990). Ignoring these effects while planning for the development of a design project can lead to erroneous estimates about the expected project's duration and the needed man-hours; which may affect the quality of the generated design solution and the overall project's value.

In this regard, investigating the dynamics of a design project according to corresponding stakeholders' characteristics and project's setup can help design managers better anticipate the performance trends of the project before starting the actual design task. For instance, design managers can better expect the number of needed iterations in each phase, the possible amount of rework generated and wasted man-hours, the project's embedded risks that may cause changes in downstream phases, as well as the entire project's duration. In this context, the simulation model can be used as a tool to generate different model development scenarios to better decide on project's major milestones and budget; therefore, increasing the reliability of the corresponding plan.

8.3.2 Design Monitoring and Control

In addition to enhancing the quality of design planning by better anticipating the project's performance, this study develops a visual dashboard to enhance the monitoring and control of design projects by tracking the dynamics of corresponding BIM models. While the actual design thinking happening in the minds of involved designers is hard to observe, if not impossible, monitoring BIM model's dynamics is tangible. In this regard, the results of this study show that linking design development to actual BIM model dynamics can enhance the management of BIM-based design projects.

Based on defined and quantified metrics, the visual dashboard helps design managers better track the actual project's dynamics. In this regard, detecting important model changes in a timely manner allows the design manager to better control the development of design based on actual project's circumstances. For instance, if the architectural team is witnessing delays in developing some of its critical model categories, the design manager can adjust the architectural team's capacity to avoid delaying related disciplines or perform a root cause analysis to investigate the corresponding reasons hindering the architectural team from progressing. In this context, the dashboard is expected to increase the situational awareness among multi-disciplinary teams around the actual project's performance at different design fronts. Thus, the work progress achieved by each discipline can be transparently shared among involved stakeholders without uncovering specific designers' expertise, allowing for more collaboration and openness among different involved stakeholders.

8.3.3 Design Process Standardization

In addition to enhancing the planning, monitoring and control of design projects, this study suggests the use of ontology to represent BIM-based design projects at both the product and process levels. At the product level, the developed BIM Product ontology standardizes the definition of different BIM model entities based on a top-level ontology. This approach helps standardize the definition of different model entities from different domains and is expected to enhance interoperability among different BIM software.

Nonetheless, employing ontology to define the structure of BIM model's content can transform BIM from being a parametric modelling process, to a logical modelling process. So, in addition to relating model entities using conditional parameters as current BIM software do, the model content would be logically connected to each other using a defined set of logical relations. This approach can be further developed to enable semantic reasoning in BIM-based projects.

Moreover, relating BIM model's content to design activities by connecting BIM product and process ontologies together can help increase the situational awareness among different involved stakeholders. For instance, linking a category of model elements to a specific design process at a given time during project's development allows design participants to know what kind of design analysis this category is witnessing. This approach can increase the shared understanding among involved designers where experts of one domain are usually unknowledgeable about the different types of design processes other domains can be performing.

8.3.4 Design Management

The three modules can be employed to develop a comprehensive framework to manage BIM-based design projects. Starting from process standardization, design managers can employ the developed ontology to establish a standard representation of expected BIM models and corresponding design activities. Once established, the BIM dashboard can be employed to visualize the planning of the project development using the hierarchy established in the ontology at both the product and process levels. Therefore, the developed visual plan would form a baseline to measure project's progress throughout the process. In this context, design managers can investigate several project's development scenarios using the developed simulation model, while taking into account the actual characteristics of involved design stakeholders and the corresponding process setup.

8.4 Answers to Research Questions

This section summarizes the research questions and the way this study addressed them:

Q1: How do the characteristics of clients, architects and engineers affect the performance of BIM-based design projects?

This question is addressed in Chapter 5 by developing an agent-based simulation model that mimics the actual development of real design projects. Accordingly, agents to represent the client, the architect and the engineer were defined with a set of parameters and variables that represent their characteristics. In addition, agents that represent the architectural and engineering BIM model elements were developed to allow for the correlation between stakeholders' interactions and BIM model dynamics. In this context, different types of stakeholders were defined, and the simulation model was run under different project's scenarios. Results were then analyzed and discussed.

Q2: How does client engagement in the design process and the level of design planning affect the corresponding design workflows?

In addition to investigating the effects of stakeholders' characteristics on project's development, Chapter 5 also examines the effects of client's early engagement in the design process as well as the effects of design planning on design process performance. In this regard, metrics that describe these effects were developed and incorporated in the simulation model. Thus, a new set of corresponding design development scenarios were defined and tested accordingly.

Q3: How are design dynamics and BIM model progress correlated?

This question is addressed in Chapter 6 of this study. While different changes can be extracted from a BIM model, only changes that can be used to correlate between design dynamics and BIM model development were targeted. In this regard, a set of variables were defined to track changes at the level of BIM model elements. More specifically, changes related to element's type, geometry, attached information, and LOD levels were tracked. The developed framework was then applied on an actual case study project. Results were then analyzed and discussed.

Q4: How to visualize the development of BIM-based design projects?

This question is also addressed in Chapter 6. In this regard, the variables developed to track BIM model dynamics were visualized to represent the corresponding workflows. Accordingly, a visual dashboard is designed to represent the changes witnessed by these variables across the project's duration. Then, correlations between actual design dynamics and variables' changes were made. The different uses and applications of the dashboard were afterwards investigated and discussed.

Q5: How to standardize the representation of BIM-based design projects?

This question is addressed in Chapter 7 by developing a top-level BIM ontology to systematically represent BIM models and processes. In this regard, different methods used to create an ontology were investigated and a suitable method was selected. Then, the study sought an existing top-level ontology to start from. Accordingly, Basic Formal Ontology (BFO) was employed as a base point to develop the desired BIM ontology. Once developed, an illustrative example to show the application of the ontology was developed. Possible ontology uses were then analyzed and discussed.

8.5 Contributions and Recommendations

Although the design phase of construction projects is already acknowledged as a social process that involves several stakeholders from different domains, the actual effects of stakeholders' characteristics on the design process performance are still under-studied. More specifically, the micro dynamics occurring among the client, the architect, and the engineering teams while generating the design solution, especially at early project phases, are not fully investigated.

In this regard, this study contributes to the research knowledge on design management by addressing several aspects affecting the progress of design projects. Most importantly, this study presents design as a learning process affected by the client's understanding of project's value, by the AE teams' ability to shape and address this value, and by the collaboration setup underlying the process. Nonetheless, the study develops a method that can help design managers better anticipate a design project's performance by simulating its development under different scenarios.

At the practical level, this study contributes to current industry efforts directed to reap the full potentials of BIM in different construction phases. In this regard, a new visual dashboard is designed in this paper to enhance the monitoring and control of BIM-based design projects. While studying the overall process performance is important to understand the characteristics of BIM based design projects, developing practical tools is required to address the needs of practitioners to maneuver design project's while in the process. In this context, the developed dashboard provides the design manager with several guidance measures that can help him/her better monitor and control the project's progress, allowing him/her to take informed decisions.

This study also tries to fill the knowledge gap among different design stakeholders and to increase situational awareness among them by developing a new top-level BIM ontology that can be used to unify the representation of BIM models and processes among different involved domains. This approach, if successfully developed, can promote collaboration among different teams, reduce mis-interpretation of generated design information, enhance design workflow, and increase overall project's value.

Based on these findings, several recommendations for research and practice can be put forth:

(1) Invest more time in the pre-design stage to explore client's values and project's needs in order to enhance the performance of a design project and to increase the overall project's value.
(2) Acknowledge the importance of the design phase and dedicate more time and resources to it in the overall project's development process.
(3) Engage the client and different involved designers early in the process to enhance the performance of design projects and to reduce project's risks.
(4) Employ BIM to promote collaboration and sharing among different involved stakeholders, while properly dealing with the characteristics of design thinking.
(5) Track the dynamics of BIM model's content to better understand the corresponding design dynamics and to enhance the monitoring and control of design projects.
(6) Employ visual tools to better monitor and control the development of design projects.
(7) Standardize the representation of BIM model's content to reduce domain specific gaps among different BIM stakeholders, to reduce misinterpretation of design information, to enable better collaboration, to enhance the use of modelled data, and to promote transparency among involved stakeholders.
(8) Employ Design Science Research (DSR) for design management research which can help bridge the gap between theoretical research and practical applications.

8.6 Future Research

This study opens the door for several future research projects including the following:

- Develop new metrics and attributes to better model stakeholders' characteristics.
- Further investigate the effects of these new characteristics on design project's development under different project's conditions.
- Understand the nature of project's value and define metrics that can track its progress during the development of a design project.
- Understand the client's learning behavior about its project's value throughout the design development process.
- Further explore the effects of architects and engineers on project's value definition and realization.
- Increase the practicality of design planning, monitoring and control by employing visual management techniques.
- Develop a generic framework to standardize the development of BIM-based design projects.
- Increase the semantic richness of BIM models.

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APPENDIX

A: Average Project Duration for each Scenario

Scenario	Mean Project's Duration (days)	Standard Deviation (days)	% Deviation from Mean Value
1	832	96	11.50%
2	868	91	10.50%
3	1193	106	8.90%
4	1260	117	9.30%
5	1213	101	8.30%
6	1286	103	8.00%
7	2026	200	9.90%
8	2120	203	9.00%
9	922	83	8.23%
10	971	80	9.54%
11	1300	124	8.55%
12	1380	118	8.90%
13	1325	118	8.57%
14	1388	119	9.65%
15	2216	214	9.42%
16	2313	218	9.43%

B: Average Number of Design Iterations for each Scenario

Scenario	Average nb. of Iterations (CD Phase)	Standard deviation (CD Phase)	Average nb. of Iterations (PD Phase)	Standard deviation (PD Phase)
1	2.86	0.34	2.51	0.5
2	2.79	0.40	2.52	0.49
3	3.72	0.52	3.96	0.19
4	3.73	0.54	3.96	0.19
5	4.04	0.29	3.95	0.21
6	4.03	0.27	3.95	0.21
7	6.39	0.55	6.56	0.49
8	6.37	0.60	6.55	0.50
9	3.01	0.15	2.90	0.29
10	3.02	0.15	2.91	0.29
11	4.37	0.49	4.01	0.13
12	4.39	0.50	4.04	0.18
13	4.50	0.50	4.01	0.13
14	4.50	0.50	4.02	0.14
15	7.00	0.35	6.80	0.39
16	6.99	0.39	6.82	0.38

C: Average HVG and CCI Results for Each Scenario

Scenario	Average HVG	Standard Deviation	Average CCI	Standard Deviation
1	0.37	0.05	0.35	0.10
2	0.37	0.05	0.35	0.09
3	0.51	0.03	0.44	0.09
4	0.51	0.03	0.45	0.09
5	0.37	0.04	0.34	0.09
6	0.37	0.04	0.34	0.09
7	0.51	0.04	0.45	0.09
8	0.51	0.03	0.45	0.09
9	0.46	0.04	0.44	0.10
10	0.45	0.04	0.43	0.10
11	0.59	0.03	0.51	0.13
12	0.59	0.03	0.51	0.12
13	0.47	0.04	0.44	0.09
14	0.47	0.03	0.44	0.09
15	0.58	0.03	0.50	0.12
16	0.58	0.04	0.49	0.12

D: Average Number of Elements Witnessing Rework

Scenario	Architectural Elements (CD-phase)	Engineering Elements (CD-phase)	Architectural Elements (PD-phase)	Engineering Elements (PD-phase)
1	2264	2681	4450	1844
2	4759	5696	13097	4616
3	3381	4200	10263	3667
4	6778	8363	26587	7889
5	3583	4501	9330	3280
6	7236	9030	24449	7108
7	6625	8275	19303	6495
8	12451	15309	41215	13298
9	2739	3253	6063	2466
10	5469	6563	16846	5705
11	4374	5523	11273	3925
12	8410	10507	26931	7970
13	4436	5588	10267	3747
14	8537	10629	25613	7684
15	7648	9542	20930	7489
16	14074	17237	41827	14481