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DESIGN WORKFLOW ANALYSIS OF BIM-BASED PROJECTS: INTEGRATING SOCIAL AND PROCESS DYNAMICS

by
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AN ABSTRACT OF THE DISSERTATION OF

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The ongoing advancement and increasing complexity of design and construction requirements result in the rapid proliferation of information that needs to be properly integrated and coordinated among multidisciplinary parties. Inefficient planning, the abstract and interdependent nature of design tasks, and poor communication disrupt design workflow, which consequently increases cycle times, costs, rework, and degrades quality.

Workflow in design is the flow of information, deliverables, specifications and requirements, calculations and analysis, as well as solutions to design problems. Design concepts should be transformed into a value adding proposition for the client and be effectively translated into the desired facility during construction. Sub-optimal design workflow has captured research interests where researchers have developed several frameworks to either tackle design task structuring, measure information flow, or understand the organizational network involved. However, a formerly unexplored perspective of workflow is one that integrates both the process, i.e., flow of design information, and the social network, i.e., interactions among design teams.

To bridge this gap, this study approaches workflow at the intersection of the social and process aspects of design in order to understand, measure, and analyze the flow of design information within construction project networks. This research uses multimodal agent-based modeling and social network analysis to dynamically explore and analyze design workflow patterns resulting from the use of Building Information Modeling (BIM). The study presents a novel design management strategy that focuses, simultaneously, on interaction dynamics and information diffusion to assist design teams and managers in enhancing the flow, transformation, and value generation.

Cross-analysis of results from a case study show that using BIM-based design solely as a production tool in the absence of collaborative social interactions does not yield the desired design workflow improvements. Low BIM maturity with a traditional design delivery mind set counteracts the anticipated BIM benefits that research and industry foster. Collaborative teamwork, shared understanding, and harnessing the full potential of BIM are needed for better quality flow and exchange of information between design players so that rework and revision cycles can be decreased, errors can be reduced, and the overall design workflow process can be leveraged.

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To my cherished ones: this is the fruit of your timeless love, care, and encouragement.

CHAPTER 1

INTRODUCTION

1.1. Introduction

While manufacturing and other industries have been continuously experiencing a boom in labor productivity at a rate of 5-6% percent a year, the construction industry of the US and other countries has been suffering from a constant decline at a roughly 0.32% a year, equivalent to approximately a 16% total decline since year 1964 (Sveikauskas et al., 2014; Teicholz et al., 2001). These alarming trends are attributed to a misalignment between the goals and focus areas of different project teams, where the poor engagement of stakeholders with each other results in an uneven flow of project information (Stevens, 2012).

The design phase is considered to be one of the most challenging processes as it is concerned with the creativity and efforts of human minds in order to create, innovate, test, and transform ideas and inputs into value adding services, products, or facilities for clients or end users. Any deficiencies and complications resulting from design can have detrimental impacts on the overall productivity and performance of the project life cycle. In fact, the highest levels of effort and influence on the project are attributed to the early design stage (Macleamy, 2004), whereas the cost of changes is the least during early design (Boehm, 1976). Therefore, proper management of building design is critical for ensuring a successful delivery of projects as the impacts of design propagate and get augmented when moving downstream along the project's phases.

Building design is characterized by a high level of uncertainties due to the ill-defined nature of requirements, solutions, or outputs. Considering a relatively better scenario, design requirements can be well understood, whereas the solutions and resulting outputs cannot be defined in advance and are generally vague at the beginning. The more extreme yet common case is when the requirements, solutions, and outputs are all ill-defined, unpredictable, and poorly understood. This is known as the "wicked problem" (Whelton & Ballard, 2002). Moreover, design tasks and efforts are iterative in nature. Multiple alternatives are considered, developed, evaluated, and reconsidered or discarded in order to reach an unconstrained and satisfying set of solutions (Maier & Storrle, 2011). In addition to the intricate nature of design, the intensive interdependence of design information and tasks of several and sometimes an excessively large number of design trades, makes the design process even more highly complex. This lack of definition and comprehension of design needs as well as the iterative and complex nature of design processes makes the design phase ever growing in difficulty and variability.

In addition, the design environment is built on the interaction and collaboration of multi-disciplinary teams whose processes and information are intertwined. With the increase in interdependence and complexity of design tasks, the need for more synchronous communication becomes vital (Knotten et al., 2015). Failing to achieve the required level of cooperation among design players and related individuals can cause the design process to collapse. Therefore, design management should be targeted to address these specific characteristics of processes and teams involved for a proactive navigation of the project towards its successful completion.

Traditional project management is concerned with adhering to time, cost, quality, and safety standards and requirements. It is based on key tools such as planning, coordinating, executing, and controlling tasks to achieve the desired outcomes (Knotten et al., 2015). Although the tools and goals of traditional project management might be adequate for sequential design processes and construction operations, where time and cost expenditures as well as quality of delivery can be tracked, they come short when managing building design. The complexity and interconnectedness of design make real time information exchange, transparency, and flowing with changes a necessity for design management. Traditional project management has therefore ignored the needs for design management, specifically design workflow management, where upstream design disciplines are not fully aware of the needs of each other as well as the needs of downstream disciplines due to improper communication. Furthermore, project management is solely concerned with the transformation process and task completion with little to no attention given to workflow and value generation (Ballard, 2002). In this approach, total transformation is broken down into smaller tasks or transformations that are then managed separately and independently from other tasks (Ballard & Koskela, 1998). Since design phases are comparably different from construction phases, the latter being more structured and defined, relying on the same management techniques can be counterproductive especially with the highly iterative design processes (Ballard, 2000b). The efficacy and challenge of design management is rooted in appropriately managing its work flow.

Managing design workflow has to do with managing the people involved in the design process as well as the flow of information between them to enable for design solutions to progress. When planning design tasks, the lack of consideration of their interrelatedness often leads to tasks being planned with insufficient, obsolete, or faulty information, leading to poor productivity, delays, cost overruns, and an inferior ability to generate value for the client or end user. Design concepts should be transformed into a value adding proposition for the client and effectively translated into the desired facility during construction.

The ongoing advancement and increasing complexity of design and construction requirements result in the rapid proliferation of information that needs to be properly integrated and coordinated among multidisciplinary parties. Failing to plan and relate information flows to the respective tasks and responsible parties, delays in sharing the right information can result in delaying the progress of design task completion, out-dating existing information, and causing design deliverables to have missing data necessary for their conformance with requirements or completion. Unfortunately, such issues are usually concealed and only appear in later stages of construction, where the cost, time, and resources required for changes and rework are high (Tilley, 2005). Therefore, the inability to effectively plan and manage the design process can lead to less streamlined processes and inefficient flow of information, thus preventing the design process to progress appropriately.

While poor flow of information and design errors plague the design process resulting in delays, increased fees, and compromised design quality, available literature target such issues without accounting for inherent problems in design communication networks and behaviors. Previous research studied methods for improving the traditional ways of solving the mentioned problems. In this regard, advancements in design and construction technologies, planning, and management strategies are continuously being developed to meet the rising complexities in the industry. Building Information Modeling (BIM) is a virtual process for project lifecycle modeling and management developed to improve the sub-optimal and fragmented administration of construction projects. The proper flow, processing, and use of information helps prevent errors in design, ensure continuous flow, and steer the project towards the desired goals.

Sub-optimal design workflow has captured research interests where researchers have developed several frameworks to either tackle design task structuring, measure information flow, or understand the organizational network involved (Baldwin et al., 1999; Lopez et al., 2002; Parraguez et al., 2015; Parraguez & Maier, 2015; Pryke, 2004; Tribelsky & Sacks, 2010). However, a formerly unexplored perspective of workflow is one that integrates both the process, i.e., flow of design information, and the social network, i.e., interactions among design teams. To bridge this gap, this study approaches workflow at the intersection of the social and process aspects of design in order to understand, measure, and analyze the flow of design information within different collaborative network setups. This research uses multimodal agent-based modeling and social network analysis to dynamically capture the impacts of Building Information Modeling (BIM) on design workflow and collaboration. The study presents a novel design management strategy that focuses, simultaneously, on interaction dynamics and information diffusion to assist design teams and managers in enhancing the flow, transformation, and value generation through the design phase.

1.2. Research process

A research process is a plan designed to conduct the dissertation study from initiation to completion. It serves as a guided strategy to identify problematic issues and limitations in the area of study, pose and answer a set of research questions, achieve the objectives of the study, and provide clarifying conclusions through employing different sources of evidence and following a well-developed research methodology.

The primary step of the process presented in Figure 1.1 involves a revision of available literature on design workflow in order to underline the problems faced by the industry and gaps in the current body of knowledge. The identified problems and limitations form the motivation for this work and help set the objectives of this research. After setting the research questions and hypotheses to be tested, specific research questions in relation to the research goals can then be specified. These questions guide the design of the research methodology to be adopted in order to bridge the gaps in both research and practice. Based on the methodology, the experimental setup, data collection, and model development will be performed following the design of the methodology. Results from case studies will be presented, analyzed, and discussed. Recommendations and contributions of this research work will finally be put forth.

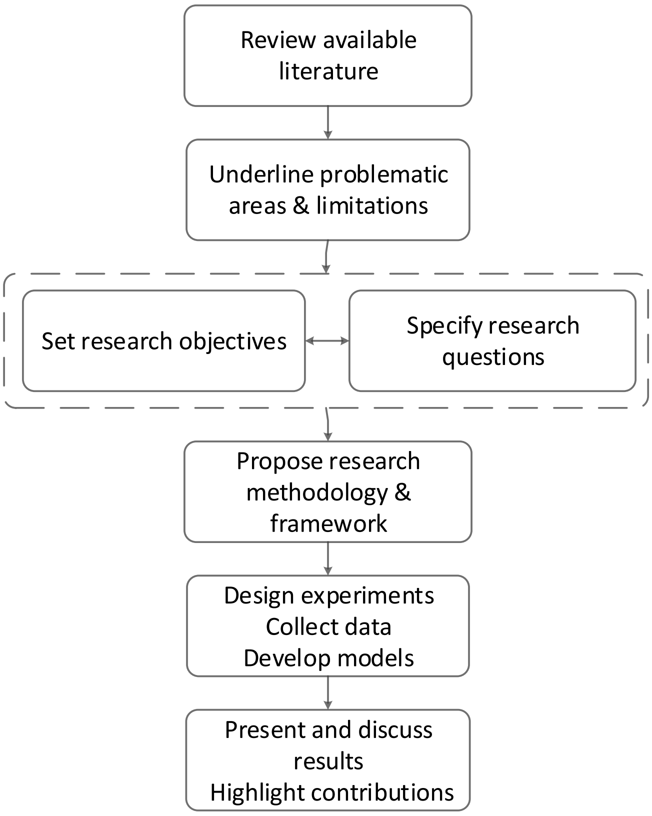

Figure 1.1 - Process for research design

1.3. Organization of the dissertation

The organization of the dissertation is presented in Figure 1.2. Chapter 2 provides research background on the topics covered in this study mainly design management and workflow in traditional and BIM-based design, simulation and agent-based modeling, Building Information Modeling (BIM), and social network theory. Chapter 3 presents problematic areas and gaps in current research which are the drivers for this ongoing research work. The research objectives and questions are also highlighted to guide the design of the research methodology. Chapter 4 presents and explains the research methodologies developed. Theoretical frameworks, experimental setups, and simulation models are explained in Chapter 5. Chapter 6 presents the application of the models to a case study. The results of the case study are then presented, analyzed, and discussed in Chapter 7. Chapter 8 concludes with a summary of the work presented, recommendations for research and industry, and future research.

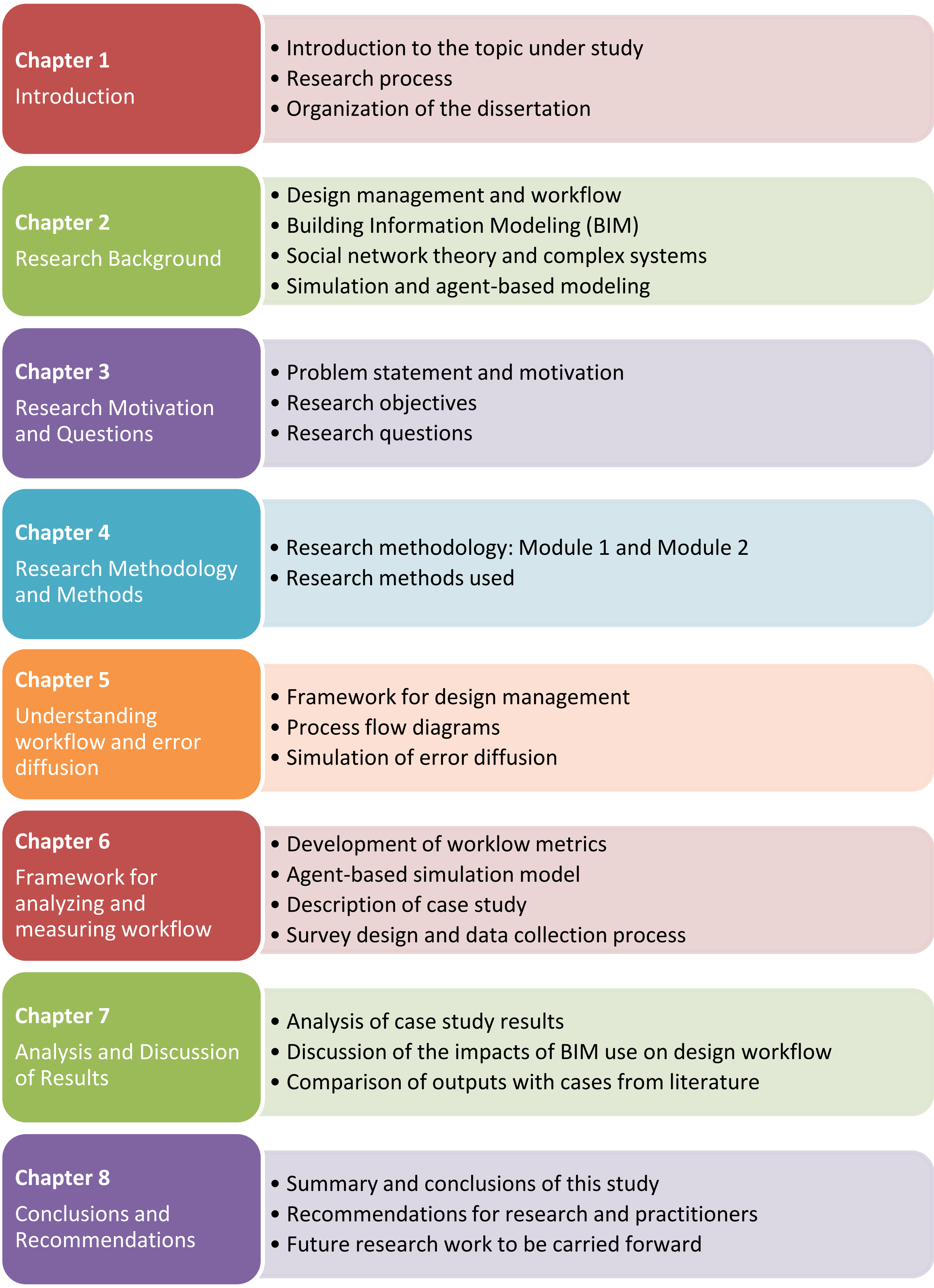

Figure 1.2 - Organization of the dissertation

CHAPTER 2

RESEARCH BACKGROUND

2.1. Traditional design and workflow management

The management of the design process is innately different from the design act itself. Decisions taken by design managers have a profound influence on the design process (Gray & Hughes, 2001). However, separating the act of design and management no longer holds as a proper way of design management. Management is the conduct of people and things in order to achieve a certain end and involves the coordination, organization, planning, motivation, leadership, and other facets of accomplishing goals through people. Initially, design was thought to achieve design management by implementing the notions of management to design, such as decision making, controlling processes, generating profit, etc. (Cooper et al., 2011). However, a new perception is that design management is a field of practice and research aimed at providing methods that bring design to the consciousness of management. In this regard, design management became the process of product and service development, standardizing work, performing quality and design audits, evaluating design concepts and competencies, developing best practice models, and delivering design contributions effectively (Cooper et al., 2011).

Design management can be perceived through three paradigms: the first paradigm is concerned with ideas and concepts of design practice, how design is performed and what it deals with; the second paradigm revolves around design management, the attributes of the design manager and the issues that can and need to be managed; the third paradigm is about the design capability, the principles, methods, and practices of design dealing with the people aspect of design as well as the environmental and the organizational characteristics (Cooper et al., 2011). In light of this perception, design management lends itself to the management of design processes as well as the involved individuals and establishing a communication structure to ensure design information and requirements can properly flow between teams so that respective processes can be executed continuously and successfully.

The traditional approach to design management resembles regular project management, where the focus is on transforming inputs into outputs with minimal regard to the flow of information and resources or the creation of value for clients and end users (Ballard, 2002). While this approach might be sufficient for more stream-lined and well-defined processes such as construction operations and sequential design tasks, it is incompatible when dealing with the non-streamlined and less defined nature of the design phase. In order to understand the shortcomings of traditional design workflow management approaches, a review is conducted on the literature pertaining to the characteristics and problems of the traditional design process and workflow as well as the research works aimed at understanding and leveraging design workflow management efforts.

2.1.1. Characteristics and problems with design and workflow

Design is the creative and personal activity of designers where the outcomes of their intellectual efforts can only be seen after design completion (Gray & Hughes, 2001). These thoughts and innovative processes are not visibly detectable at the beginning, and can only be evaluated as design progresses. This is known as the incubation time in design where the thought process is implicit and not defined as a design task. This matter creates a challenge for design managers to understand what designing entails, how designers think, what designers need, and how these aspects can be assessed and whether the design processes are yielding the desired outcomes.

Design attributes, whether in the building sector or product engineering fields, converge towards the same understanding of their processes. These characteristics are described based on research conducted by several studies and summarized in Figure 2.1 (Ballard, 2000a; Bolviken et al., 2010; Gray & Hughes, 2001; Knotten et al., 2015; Koskela, 2000; Maier & Storrle, 2011; Reinertsen, 1997; Thompson, 1967):

- Design is *ill-defined*: requirements and/or solutions are not known in advance, not understood, and not clearly defined. When both requirements and solutions are ill-defined, the case is known as a "wicked problem".
- Design is *iterative*: due to its ill-defined nature, approaching solutions and decisions require back and forth iteration in design thinking and production, where feedback loops are inevitable between design tasks and responsible individuals. Iterations can be positive (add value to the end design) or negative (do not add value and are considered as waste).
- Design is *complex*: complexity arises with the lack of proper definition of design needs and tasks, the iterative nature of processes, the inherent difficulty of design creativity and approaching solutions, sophistication of requirements of products, services, or facilities, and the input and interactions of multiple disciplines and teams providing various services during design.
- Design involves *multiple trades and skills*: design comprises a combination of efforts and thought processes of individuals and teams with different backgrounds. With the increase in project complexity, more skills and specialized services need to be outsourced as they can no longer be provided in-house. This requires the proper coordination of work among different teams with different backgrounds and needs.

- Design is *non-repetitive*: as opposed to manufacturing and production lines, design is a one-time endeavor specific to the project. Although knowledge can be transferred to new projects, the processes, people, and requirements are always changing, rendering design a specific and non-repetitive effort requiring new thought processes every time.
- Design is *expandable*: many solutions and alternative options exist for a single design requirement. There is always room for improving design and searching for better solutions, making design an expandable process. With requirements also constantly changing throughout design, decisions need to be taken and design schemes need to be selected. Taking such decisions is not quite simple.
- Design is *uncertain and variable*: since changes are always introduced into the design phase, such changes can be value adding or disruptive to the design process. Moreover, with the involvement of multi-disciplinary teams, and since design is fundamentally a human endeavor, there is a lot of variability embedded in design. Uncertainty is a manifestation of the unpredictable outcomes of design, the ill-defined nature of requirements or solutions, the constant changes, as well as influences from the environment and exterior parties. Moreover, dependencies and commitments between tasks make design even more uncertain and variable.
- Design is a *transformation, flow, and value generation process*: inputs, needs, and requirements are converted into a service, product, or facility through problem solving and decision making. Although the conventional understanding and practice of design is only concerned with transformation, design should be also seen as the flow of information, where information is transformed, queued, shared, moved, or inspected. Generating value occurs by

capturing needs and requirements of the client or end user and allowing design ideas to be transformed into those needs, where flow can help reduce wastes and allow for improvement.

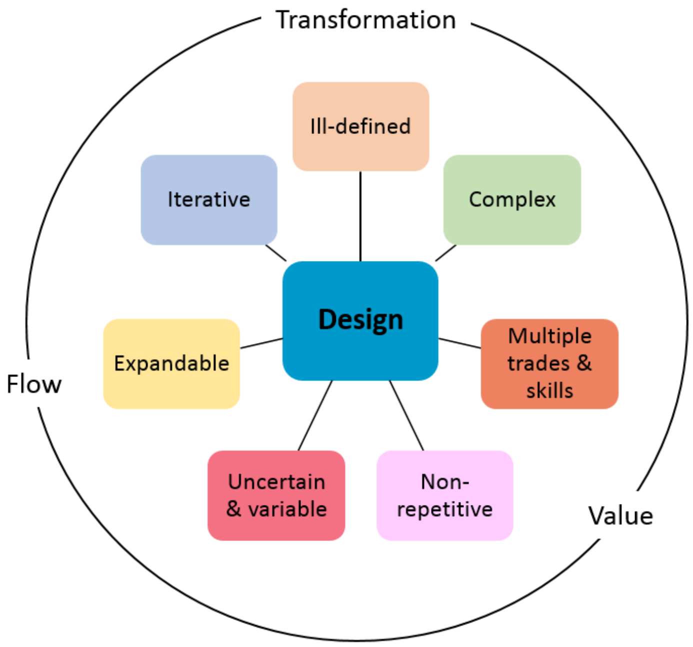

Figure 2.1 - Design phase characteristics

Design tasks and information exhibit different kinds of interdependence. Thompson (1967) examines these interdependencies and classifies them into three types, *pooled*, *sequential*, and *reciprocal*, along with three types of coordination, *by standardization*, *by plan*, and *by mutual adjustment*, suitable for each kind of interdependence. Bell and Kozolowski (2002) introduce a fourth dimension of interdependence called *intensive* interdependence. Figure 2.2 shows a schematic description of each type of interdependence.

- *Pooled* interdependence coordinated *by standardization*: under such interdependence, each individual or team contributes separate parts to the whole design and the whole design supports each individual design. This kind of dependence requires coordination by standardization through the establishment of a set of rules and routines to synchronize these processes.

- *Sequential* interdependence coordinated *by plan*: under such group, design tasks follow a consecutive order. Task A needs to be completed before Task B can proceed. If a task stops for any reason or fails to provide the required information for its successive tasks, the design process will exhibit delays and bottlenecks. This type of dependence requires coordination by plan which establishes schedules defining durations, critical hand-offs, and logical sequencing.
- *Reciprocal* interdependence coordinated *by mutual adjustment:* this kind of interdependence is described as having the outputs of each task feed as input for other tasks. It is best understood as a chain of input and output loops between tasks. This requires coordination by mutual adjustment where parties negotiate alternatives and agree on trade-offs so that design can progress and information can be smoothly transmitted.
- *Intensive* interdependence coordinate *by mutual adjustment*: similar to reciprocal interdependence, intensive interdependence is characterized by adhocracy of highly complex dependencies and little formalization. Tasks and information form a web of input and output loops that require high levels of coordination and integration among responsible entities.

These interdependencies and coordination vary depending on the stage of design (Knotten et al., 2015). Early design stages that are conceptual and abstract are highly reciprocal and intensive requiring trade-offs, negotiation, and assessment of different design alternatives. As design progresses and decisions are made, tasks become better defined and stream-lined following a more sequential type of dependency. Therefore, the intensity and synchronicity of communication and integration of work is vital for supporting design progression and its proper flow for value generation.

Given these specific attributes, interdependencies, and requirements for coordination and communication, building design in its conventional forms of practice experiences a lot of problems. Gray and Hughes (2001) state that the nature of the building design problem lies in the client's inability to clearly or fully define requirements at the outset. Each problem and facet of design is handled by a group of people, where each party will have a different set of requirements and responsibilities that make the decision-making process very complex. There will be a lot of overlaps and gaps, which will require a lot of trade-offs and compromises. Traditionally, separate groups do not discuss their needs and requirements early on, which results in teams imposing their ideal solutions on other teams and creating conflicts and deviation from the client's value. Gray and Hughes also argue that if design in typically interactive, iterative, and reflective, then adopting methodical and analytical approaches to the design management is difficult.

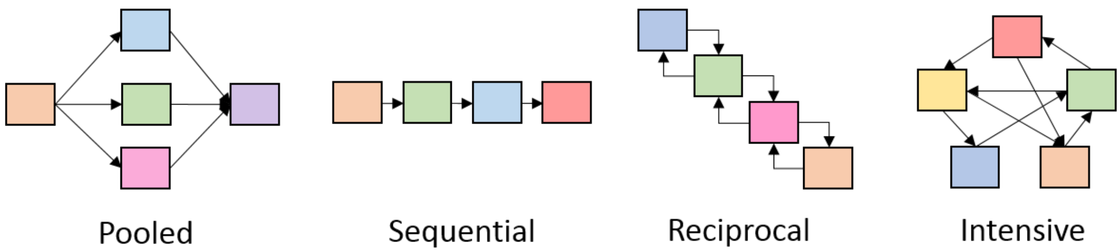

Figure 2.2 - Types of task information dependencies (based on Knotten et al., 2015)

Ward et al. (1995) characterize the traditional design methodology as a point-based design, where participants in the project are engaged only based on their scheduled work. This segregation of design efforts into separate stages leads to having feedback from later design specialists that conflict with earlier decisions and also turn to be unfeasible. This in turn results in re-exploring those alternatives and repeating parts of the design process, known as negative iterations (Ballard, 2000b). Tilley et al. (2002) identified design briefing, detail design, and constructability as major problem areas within design. In addition, they identified that information deficiencies and poor coordination between design disciplines are the main causes for problems with project documentation. Barret & Barret's (2004) study supports these findings where it highlights that design documentations often look professional but in fact do not properly specify or describe design solutions and requirements. Moreover, the most frequent causes for design deviations are deficient planning and/ or resource allocation, deficient and missing input information, and changes (Sverlinger, 1996). In his study, Josephson and Hammarlund (1996) attributes lack of coordination between disciplines as the main cause for design-caused defects.

Variability is embedded in the design process. It results from inefficient planning strategies, sub-optimal levels of operation, lack of coordination, and poor flow of information and resources. Variability is the imbalance or unevenness or non-uniformity in processes and resulting products where planned and performed work have wide discrepancies (Arashpour & Arashpour, 2015; Hamzeh, Saab, et al., 2015; Hamzeh, Zankoul, et al., 2015). This inherent variability causes interruptions in workflow through unreliable exchange of information, generation of design errors, lack of knowledge of specifications and required deliverables, weak transmission of work and tasks, and poor coordination between different disciplines. Interruptions resulting from variability cause rework, increased costs, time delays, inferior quality, and inefficient productivity.

Based on the previously mentioned issues with the traditional design approach as well as the mentioned attributes of design nature, managing the design process in such a way that considers these important aspects is vital for the successful execution of design and the fulfillment of the client's value. The following section reviews conventional design and workflow management attributes and approaches.

2.1.2. Conventional workflow management

Complexity in building design is not solely the result of using sophisticated technology or designing large scale facilities (Gray & Hughes, 2001). In fact, complexity results from the need for multiple trades and specialized skills to come together and deliver the project within a set budget, schedule, and quality requirements. These multi-disciplinary teams, which can reach hundreds and be geographically dispersed on some projects, have different needs and requirements that need to be coordinated and integrated with each other. This leads to a high degree of fragmentation and organizational complexity that will continue to increase if conventional ways of design administration persist.

Lahdenpera and Tanhuanpaa (2000) state that design is generally managed by traditional project management methods resulting in poor design performance. Project management is performed through traditional functional elements: planning, organizing, staffing, budgeting, controlling, leading, and evaluating to achieve organizational objectives (Chapman, 1984; Dessler, 1982; Kotter, 1990). Following this line of thought, traditional project management is concerned with adhering to time, cost, and quality requirements (Eynon & Building, 2013). In fact, the main problem with project management is the exclusive focus on transformation and task completion and neglect of flow and value generation (Ballard, 2002; Koskela, 2000). This approach might be convenient for the pooled and sequential interdependencies in design that required standardized and planned coordination, but is not effective when managing reciprocal and intensive dependencies of design tasks and people that require more complex coordination approaches (Knotten et al., 2015).

Therefore, what design management really entails is the management of people and the flow of information between individuals and teams (Tilley, 2005). The transformation process that practitioners and researchers focus on only involves the conversion of input into output, leaving a vague understanding of what happens during that process. Koskela (2000) developed the TFV theory which highlights the important role of flow in the transformation process for generating value adding results. Due to the resulting inefficiencies in productivity, inferior quality and design errors, rework, improper communication, and non-value adding design that does not meet the client’s needs, there is an urgent need for ensuring that design workflow is instilled during the design phase to avoid interruptions and wasteful transformation processes.

In manufacturing, workflow has been managed by the routing of products, elements, and production lines through the adequate sequencing of operations and processing steps (Ballard, 2002). In addition, business models and product development strategies have been incorporating workflow management as a mechanism to facilitate the teamwork and development environments, even remotely (Basu & Kumar, 2002; Huang et al., 2000). Moreover, systematic approaches have been developed to create a balance between quality and performance in workflow systems through dynamic work distribution (Van-Der-Aalst & Verbeek, 2002).

Workflow in design is the flow of information, handoffs of design deliverables, requirements, specifications, calculations, and design solutions between individuals and teams. In contrast to a more predictable outcome of construction activities, design tasks and process are very iterative, jumbled, and involve a thought process that accounts for multiple alternatives to be assessed at the same time. Moreover, the complexity of managing design is the management of multiple individuals and teams with different specializations and geographical locations. Therefore, the main challenge in design projects is how to manage work flow and people.

2.1.3. Current workflow management

Research efforts have since been examining new ways of managing design taking into consideration the involved workflow and/or the interactions among design participants. Data flow diagrams (DFD) design structure matrices (DSM) were used to map and model design processes to explicitly identify the information dependencies (Austin et al., 1996b; Austin et al., 1996a; Austin & Steele, 2001). A study by Al Hattab and Hamzeh (2013) developed swim-lane process flow diagrams to show the different design stages, the output deliverables of each stage and how they flow while linking them to their respective teams. In addition, parameter-based DSM's were used for modeling detailed information flows pertaining to the product architecture rather than design activities (Pektas & Pultar, 2006). These authors also developed discrete-event models and DFD's to simulate design tasks and their information requirements and how design information flows during the design stage (Austin et al., 1995; Baldwin et al., 1998, 1999). Similarly, Chua and Hossain (2011) develop a simulation model to study the impact of early information sharing on design duration and redesign. An interesting study develops lean indices for measuring information flow on construction projects by mapping sharing trends of data collected from database logs of the detailed design phase (Tribelsky & Sacks, 2010, 2011). These trends can help identify bottlenecks and faults in the design process. However, these studies, among others, do not consider the human behavior and interactions when analyzing or measuring the flow of design information.

On the other hand, the activities of design were reconsidered from a networked perspective, where the people performing those activities are considered and how their behavior can affect performance (Parraguez & Maier, 2015). In their study, the design activity network (i.e., the DSM) and organizational social network of people are integrated where the responsible people are mapped to their activities. This study was then expanded to analyze design activities through the stages of complex engineering design using different social network analysis (SNA) metrics characterizing the impacts of human interactions on these activities (Parraguez et al., 2015). Yet, their work does not present the information dependencies of such activities. Moreover, social network structures are analyzed in hierarchical organizational setups to study the impacts of such compositions on the flow of information to different members of the hierarchy (Lopez et al., 2002). A research article by Durugbo et al. (2011) develops a mathematical model of information flow for analyzing collaboration in organizations by developing social network metrics pertaining to collaboration, teamwork, and decision-making. Although these studies provide insight into a member's position within non-engineering organizational networks and the amount of information reaching them, they do not demonstrate the actual flow of information between these individuals, but are only based on mathematical relationships.

Accordingly, it seems that there is a tendency to separate workflow from the human interactions involved. Yet, the studies that included the social networks only considered the integration with design activities and disregarded the information requirements and dependencies within these processes. Therefore, it is important, for design to be successfully delivered, to integrate design information with social networks to analyze and measure how such information is diffused as a result of human interactions and collaborations. Such analysis is fundamental for design management in order to detect underlying problems and propose methods for resolving them to enable a smooth design phase that builds for an overall successful project management.

2.2. Building Information Modeling (BIM)

The acronym BIM can be used to mean a "Building Information Model", a parametric n-dimensional model which compiles, links, and computes information of interrelated elements of a building or facility. One might confuse a BIM to a regular 3D model; the latter, however, does not contain any smart information as it is just a 3D representation tool. On the other hand, BIM can be used as “Building Information Modeling” referring to the process of using the provided model and building information to virtually represent, analyze, simulate, and manage the project through its entire life cycle (Eastman et al., 2008). However, BIM is widely perceived as an upgraded 3D approach to the traditional 2D drafting process. In fact, the strength of BIM, which many users have not yet realized as they think of BIM as just a “software” rather than a “process”, lies in the collaboration that BIM allows and requires between the stakeholders throughout the project’s life cycle (Azhar, 2011). Although the model is a very powerful method for project development, BIM goes beyond the notion of a 3D model or drafting tool. BIM is a project life cycle process using the provided model and parametric building information to virtually simulate and manage the physical, functional, and task related attributes of a project. It helps stakeholders make educated decisions and execute the project with reduced costs, schedules, rework, and better quality (Azhar, 2011; Eastman et al., 2008; Redmond et al., 2012).

Since a building information model integrates information that describes geometrical configurations, quantity and cost related estimates, material related characteristics, analytical and behavioral attributes, geographical locations and spatial relationships, schedules, and other project related information, several functionalities are made possible through this virtual design and construction aid. Besides using the model for visualization of the project, a BIM can be used to easily generate shop drawings for on-site construction and fabrication (Azhar, 2011). Moreover, a BIM model can facilitate the process of performing quantity take-offs and producing cost and schedule estimates due to the integration of parametric data that helps automate the process of retrieving the required information. When models from different disciplines are incorporated into a central BIM model, clash detection and automated code checking allow users to perform comprehensive and simplified checking for design compliance and conflict resolution within and between trades (Eastman et al., 2008). Virtual 4D (3D + time dimension) and 5D (4D + cost dimension) simulations are enabled in order plan and analyze in advance the construction process and the expected project performance to proactively implement the desired and optimal performance.

Researchers and industry stakeholders have investigated and employed various uses and applications of BIM in multiple studies and on diverse projects. Researchers studied the automation of rule-based checking of building designs and their applications on projects (Eastman et al., 2009; Tan et al., 2010) and the detection of root causes of clashes and conflicts in building information models (Hartmann, 2010; Love & Edwards, 2011; Tommelein & Gholam, 2012). Another study simulates and compares the diffusion of design errors between traditional and BIM-based projects for better design management and error reduction resulting from BIM use (Al Hattab & Hamzeh, 2015). Moreover, several studies targeted the analysis of construction process simulations and safety analysis through BIM and sensing technologies in order to enhance performance and site safety (Hu et al., 2008; Turkan et al., 2012). The integration of BIM practices has also been investigated to bring about a synergistic approach for their applications (Sacks et al., 2010).

It has become commonly realized that planning and managing the design and construction process can enhance project productivity and client satisfaction. In this regard, the strength of BIM lies in enabling collaboration between participants throughout the project's life cycle, and adding value by reducing waste and optimizing involved operations (Demian & Walters, 2013; Eisenmann & Park, 2012).

2.2.1. BIM practices, standards, and maturity

Looking at the adoption levels of firms across different countries, the US seems to be in the lead of BIM implementation where 71% of its firms are using BIM or BIM related tools with a 158% growth from 2007 to 2012 accordingly (G. Lee et al., 2012). South Korea also experiences a high fraction of BIM use by 58% of its firms (G. Lee et al., 2012). Australia and New Zealand have 51% of their firms using BIM on 30% of their projects, and this number is expected to increase in the upcoming years (SmartMarket, 2014a). European countries, such as Germany and France, as well as Scandinavian countries, have an average of 36% of AEC firms employing BIM on their projects. Similarly, 35% of firms in the United Kingdom are using BIM, where mostly architects are implementing it at 60%, followed by engineers and contractors at 39% and 23% respectively (Kassem et al., 2012). On the other hand, the government of Singapore has mandated a British Level 3 adoption by all firms using BIM to be established by 2015. Surveys conducted by Building Smart (2011) in the Middle East show a much lower adoption rate of only 25% of AEC firms using BIM at underdeveloped competencies. These figures show wide discrepancies in BIM adoption between different countries and an overall slow implementation. Moreover, collaboration and project management are still mainly based on 2D deliverables.

Several countries and organizations have developed standards, mandates, and policies for more efficient BIM use and wider implementation on projects and by firms. Governmental mandates as well as public and private BIM initiatives are continuously being established to foster BIM's growth worldwide. Table 2.1 summarizes some reported governmental mandates and initiatives by private or public organizations in different countries (SmartMarket, 2014a, 2014c).

The BIM Industry Working Group (2011) in the UK state four BIM maturity levels. A maturity model has been devised to ensure clear articulation of the levels of competence expected and the supporting standards and guidance notes, their relationship to each other and how they can be applied to projects and contracts.

Table 2.1 - BIM standards and mandates in different countries

Country	Governmental Institutes - Standard	Description	Private/ Public Institutes - Standard	Description
UK	The Cabinet Office of Government Construction Board (BIM Task Force) - Government Construction Strategy for UK National BIM Standard	Requires all national public projects to use BIM at Level 3 by 2017	RIBA – National Building Specs- Outline Plan of Work; British Standards Institution – BS 1192	Publishes research about BIM adoption; Provides guidelines to support collaboration & BIM application
USA	National Institute of Building Sciences - US National BIM Standard (NBIMS); General Services Administration - National 3D-4D BIM Program; Naval Facilities Engineering Command – ECB 2014-01: NAVFAC's BIM Phased Implementation Plan; U.S. Army Corps of Engineers - ECB 2013-18: BIM Requirements On USACE Projects	Require BIM on all national public projects, or new buildings costing $750,000 or more, major renovations of $2.5 million or greater	Associated General Contractors of America (AGCA); American Institute of Architects (AIA)	Developing modeling standards, documentation specifications, and tools for BIM deployment
Australia	Australasian Procurement and Construction Council - National BIM Guide	Developed by NATSPEC to support BIM fluency for the construction industry and Maintain competitive advantage	Air Conditioning and Mechanical Contractors' Association - BIMMEP^{AUS}	Provides instructions and requirements for performing particular operations and using standards
New Zealand	Ministry of Business, Innovation and Employment – New Zealand BIM Handbook	Started a BIM acceleration committee to achieve 20% effectiveness by 2020	NATSPECT &buildingSmart - Australian & New Zealand Revit Standards	Targets the need for better quality content for Revit users across
France	Ministry of Ecology, Sustainable Development & Energy, & Ministry for Territories & Housing	Developing a BIM Road map in draft form expected by end of 2014	French Federation of Building & French arm of buildingSmart	Promote the use of BIM in France

Germany	Federal Office for Building and Regional Planning – BIM Guide	Developing a guide to provide structure for national BIM mandate	-	-
Canada	-	No official national standard yet but is underway	The Institute for BIM in Canada; Canada BIM Council	Work to adapt UK National BIM Standard as a basis for a Canadian one
Brazil	-	No official national standard	-	BIM use is rising faster than other markets
Sweden	-	No official national standard	The BIM Alliance	Promotes open standards, processes, and best practices
Denmark	Building & Property Agency under the Ministry of Climate, Energy and Building - Executive Order No. 118	Requires BIM on 5M kroner & higher national projects; 20M kroner & higher regional & municipal projects	-	-
Finland	Senate Properties - Common BIM Requirement 2012	All national public projects should use BIM	-	-
Norway	Statsbygg - Statsbygg BIM Manual 1.2.1	Requires BIM on all public projects	-	-
China	Ministry of Science and Technology - NA	National BIM Standard by 2016	-	-
Japan	Ministry of Land, Infrastructure, Transport, & Tourism - Guidelines for arch. BIM models	No official national standard	Institute of Architects; Samsung	Created BIM guidelines; requiring BIM on projects in Japan
Singapore	Building and Construction Authority - Road map & e-submission requirements	Mandates all new buildings over 20,000 sq. m. to use BIM and report performance metrics	-	-
South Korea	Public Procurement Service - BIM Guide Version 1.2	Mandates BIM on all public buildings costing over $27.6M	-	-
UAE	Dubai Municipality – BIM Mandate	Requires BIM on 40 stories high,>300,000 sq.ft., hospitals, universities, buildings delivered by international parties	-	-

The levels are Level 0, Level 1, Level 2, and Level 3 explained as follows:

- *Level 0:* Unmanaged ad-hoc CAD based on 2D documentations
- *Level 1:* Managed CAD based on 2D and 3D format using BS1192:2007 with a collaboration tool providing a common data environment, possibly some standard data structures and formats. Commercial data managed by standalone finance and cost management packages with no integration.
- *Level 2:* Managed 3D environment held in separate discipline "BIM" tools with attached data. Commercial data managed by an ERP. Integration on the basis of proprietary interfaces or bespoke middleware program data are could be regarded as "pBIM" (proprietary). The approach may utilize 4D and 5D cost elements as well as feed operational systems.
- *Level 3:* Fully open process and data integration enabled by web services compliant with emerging IFC/ IFD standards, managed by a collaborative model server. Could be regarded as iBIM or integrated BIM potentially employing concurrent engineering processes.

However, when referring to BIM maturity, it is not sufficient to solely consider the BIM levels or stages as indicators of an industry's or organization's BIM maturity. Studies on BIM maturity were undertaken to delineate the underlying knowledge structures and present frameworks for BIM's implementation and assist organizations as well as industries in assessing their maturity and improving their performance through a BIM maturity matrix (Succar, 2009a, 2009b).

The framework Succar (2009b) developed is a tri-axial model representing BIM Fields, BIM Lenses, and BIM Stages for organizing domain knowledge through a systematic investigation of the BIM domain. The BIM Fields identify the interlocking processes, technologies, policies, as well as the involved players and deliverables. The

BIM Stages define milestones, or minimum capability benchmarks, to be achieved by players while adopting BIM over 3 stages: Stage 1 which is object-based modeling, Stage 2 which is model-based collaboration, and Stage 3 being the network-based integration stage. The third dimension of the tri-axial framework is the BIM Lenses. These lenses represent different views of analysis that filter the scopes of knowledge so that researchers or practitioners can filter or isolate aspects of their interest at different levels of complexity.

A maturity matrix for assessing and improving a firm's or industry's BIM performance has also been developed (Succar, 2009a). The components of the BIM maturity matrix include many BIM Framework components defined earlier such as the BIM stages, BIM maturity levels reflecting the extent of BIM abilities from the initial ad-hoc level through an optimized BIM level, BIM competency sets categorized as BIM fields regarding policy, process, and technology, as well as the organizational hierarchy scale reflecting a global market level analysis or a micro level of a member at an organization.

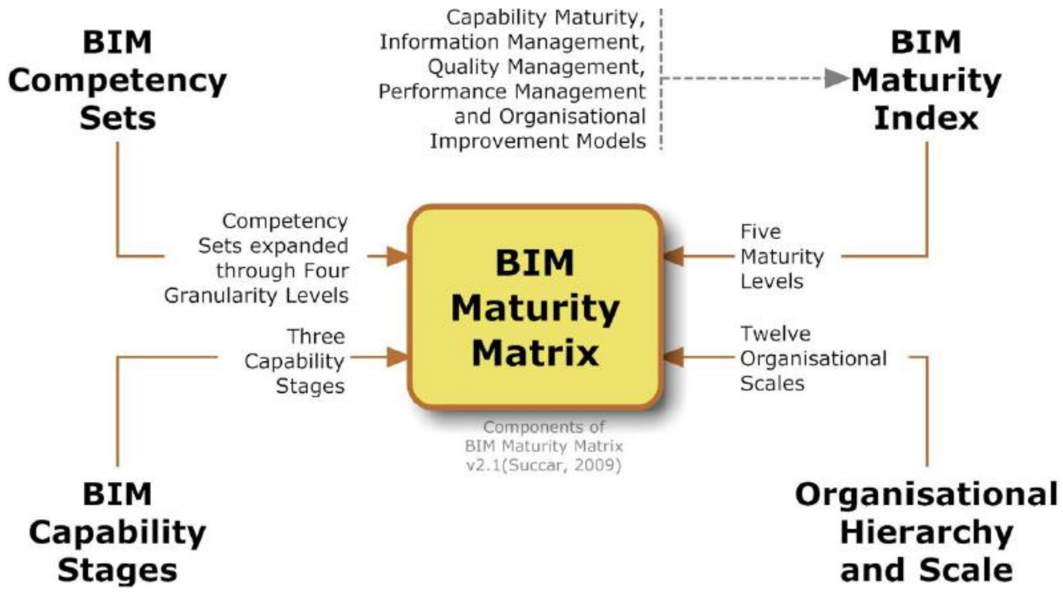

Figure 2.3 - Components of the BIM Maturity Matrix v2.2 (from Succar, 2009a)

The matrix can then be applied at the required granularity level depending on the purpose of BIM assessment and the scale of application. The developed framework and matrix serve to assess and improve BIM capability across teams and organizations to reach desired BIM performance standards and expectations (Succar, 2009a, 2009b). A study by Kassem et al. (2013a) proposes three metrics to augment survey collected data and establish the overall BIM maturity of countries. The metrics also allow highlighting gaps in BIM knowledge content and identifying fields that need more exploration and development.

2.2.2. Adoption barriers and enablers

When it comes to studying BIM adoption, it is important to explore barriers to adoption and strategies to overcome these barriers for a more widespread adoption. Based on literature review on BIM barriers and challenges, the barriers can be categorized into three main groups: (1) product and technology, (2) process and policy, and (3) people and organization. Although they are divided into separate categories for the sake of classification and explanation, they are tightly related and affect each other resulting in a compounded impact on BIM's implementation.

With respect to BIM as a product and technology, surveys show that interoperability has been a major issue (Kassem et al., 2012). However, with the advancement of BIM technology, it is longer the main concern. Yet, "meaningful interoperability", where specific information requirements of various users need to be transferred between different platforms through purpose-built conduits, is still a challenge as it is highly dependent on the risks, rewards, and responsibilities associated with applying such information transfer controls (Bernstein & Pittman, 2004). Moreover, most users are generating pictorial data rather than computable data due to the lack of understanding of the uses and importance of computable data (Bernstein &

Pittman, 2004). This in turn limits the realization of BIM's full potential for analytical computations and prevents its understanding by practitioners. It also inhibits the efforts of Industry Foundation Classes (IFC's) in enabling more stream-lined information transfer. A second challenge relates to a firm's return on investment (ROI) when deploying a new strategy. The benefits should outweigh the costs of investment; however, with the high costs of BIM software, hardware, and staff training required, the absence of tangible and measurable benefits, as well as the lack of understanding of BIM outcomes and expectations, justifying the business case for BIM implementation may prevent a firm or project from employing it when ROI cannot be predicted or realized (Bernstein & Pittman, 2004; Kassem et al., 2012; Lindblad, 2013).

A construction project includes multiple trades and stakeholders that have different needs, expectations, understandings, and demands on the BIM technology (Lindblad, 2013). Therefore, finding and choosing a platform or a set of systems that supports the various purposes and services for the project's whole lifecycle management needs might be a challenge and create problems between the different stakeholders and processes. Moreover, the choice of BIM needs to support a firm's long term business strategy. Yet, with the limited knowledge about BIM and its functionalities, BIM projects might be contra-productive if BIM is poorly implemented. Also, the lack of a universal supply chain buy-in and implementation might prevent entities willing to adopt it from actually taking that step due to the lack of upstream and downstream support or demand (Eadie et al., 2014).

Regarding BIM barriers pertaining to the involved processes and policies, upon implementing a new strategy, workflows and streams need to be redesigned to cater for the new process. However, the lack of clear workflow definitions and the lack of business process integration can create conflicts with existing traditional work processes (Bernstein & Pittman, 2004; Kassem et al., 2012). This is augmented when obligations, risks, and rewards are not redefined for the new system. Hence, the processes associated with BIM should be clearly delineated in terms of developing process modeling standards, Level of Development (LOD), how information will be exchanged, who has the access to proprietary information, and how to model for lifecycle information use (Dawood & Vukovic, 2015). If these matters are not tackled in advance, it would be hard for firms or projects to properly deploy BIM and realize its potential instead of experiencing complications.

Traditionally, clear lines can be drawn between responsibilities, roles, and data management protocols. However, with BIM's integration of work and information, these lines start to blur and it becomes difficult to properly redefine these aspects. As a result, there is a critical effort in setting up legal matters and spelling them out in contractual setups. In fact, existing contractual arrangements become obsolete with BIM use and they will fail to support collaboration initiatives. Unless legal frameworks, standards, and contracts are tailored for BIM use, existing ones will create barriers again the investment in BIM-based approaches (Dawood & Vukovic, 2015; Eadie et al., 2014; Kassem et al., 2012).

At the core of all these barriers are the forces driven by human skills. Assuming BIM processes and products are problem free, if the industry and people are not initially educated about BIM, the whole BIM philosophy will fail to progress. The lack of skilled labor for BIM use, the lack of understanding of BIM uses and benefits, the absence of measurable and tangible benefits, and the deficiency of historical data of successful BIM cases make it hard for clients, organizations, or stakeholders to be willing to invest in BIM (Kassem et al., 2012). In addition, the building sector is a complex supply chain, requiring a massive scale of cultural change for a traditionally risk and change-averse mind sets. With the high fragmentation and contacts that boost adversarial relationships instead of collaboration, and a conventional trend of reluctance in open sharing of information, collaboration might be hard to achieve. Consequently, these matters, along with the unawareness and lack of support of management, are inhibiting a more widespread BIM adoption (Eadie et al., 2014; Lindblad, 2013).

Based on these critical issues, there is an urging need to not only develop, but also implement strategies to counteract these challenges and facilitate BIM's deployment worldwide. Improving collaboration is key to BIM's successful implementation due to BIM's holistic integration of diverse building information from everyone. Thus, the collaboration and input from all stakeholders can leverage BIM's capabilities. Moreover, involving courses on BIM in higher education curricula can help improve awareness and instill the needed skills. This consequently reduces costs associated with acquiring competent talent and training staff.

On the other hand, new project delivery approaches such as Integrated Project Delivery (IPD) and Project Alliances (PA) can foster collaboration while balancing risks and rewards (Kassem et al., 2012). This will help encourage stakeholders to cooperate and gain the support of clients, industry, and governments, which is critical to BIM's more widespread adoption. Defining workflows, responsibilities, and developing measurement frameworks for quantifying BIM's outcomes can make benefits more realizable and understandable, and accordingly, put a step forth towards better BIM utilization.

2.2.3. BIM design workflow management

Several studies and initiatives are undertaken to organize and manage the design phase of building projects. The Royal Institute of British Architects's (RIBA) 'Outline Plan of Work' and 'BIM Overlay to the RIBA Outline Plan of Work' in the UK are developed for the revision and modification of information at various stages depending on project requirements and changes considering the BIM overlay (RIBA, 2012). While such BIM workflows and frameworks are intended for adoption at industry level or use in large enterprises, Kassem et al. (2013b) developed a practice-oriented BIM framework and workflows considering BIM processes, methodologies, and technologies that can be applied at project level while being aligned with the standard design practices. The developed framework and workflows, when tested on case studies, proved to increase the efficiency of the workflow of the design process between stakeholders.

The impact of BIM on inter-organizational communication in construction projects has been examined through a social network analysis (SNA) approach, where results show that BIM can facilitate information exchange and improve communication (Diamantidou & Badi, 2015). However, the study does not consider the dynamic aspects and the flow of information in the social networks. On the other hand, a study aiming at challenging the BIM utopia adopted the SNA approach as well to examine the interactions within an organization where a BIM platform has been applied (Azouz et al., 2014). Results of their study show that within this organization, the expected benefits of BIM enhancing workflow failed to be realized due to team members preferring the more traditional design management and data exchange processes. However, this only applies to a one case project that can have multiple underlying causes for the observed results, where such results are also not generalizable to the industry BIM workflow and practices.

Existing information flows and technologies under BIM applications are studied to assess or develop means for enhancing information exchange and integration. Cloud BIM, for example, is analyzed as an information exchange mechanism that enhances the possibility of many disciplines collaborating on the same platform by sharing and exchanging data to provide more effective key decisions at the early design stage where most costs are estimated and upon which early investment decisions are made (Redmond et al., 2012). Another study proposes an integrated design system based on functional integration, integrated information management, and integrated process support that can enhance conventional BIM-based collaborative design (Oh et al., 2015). Similarly, two patterns, defined as reusable design templates for facilitating synchronous BIM-based communication, are suggested to help system analysts and designers to focus on tackling recurring problems in the design phase (Isikdag & Underwood, 2010).

Research on measuring design workflow as the flow of information between project participants on BIM-based projects has not been deeply studied. Therefore, this study embarks on modeling the design workflow in attempt to improve the communication and exchange of information between members of different team disciplines. While many studies and practices state that BIM can enhance the overall project experience, quantitative assessment alongside qualitative analysis is needed as a starting point to implement and realize actual improvements to existing design processes.

2.3. Social Network Analysis (SNA)

Social network analysis (SNA) is an approach for focusing on the relational structures of systems within which entities exist. It is a method for studying interactions and relationships among agents which can be people, cars, communities, etc. It provides both visual and quantitative analyses for the interpretation of human associations. Sociologists and scientists have been researching and applying the theory of social networks since the early years of the 20th century in diverse fields, mainly sociology, anthropology, biology, communication studies, economics, and political studies (Klijn & Koppenjan, 2000; Simmel & Wolff, 1950; Tichy et al., 1979). Not only does SNA examine the structure of the relationships between the individuals, it also studies the natural mechanics occurring within (Chinowsky et al., 2010). The visual graphs used to map social networks consist of nodes, representing the individuals or any component under study, which are connected via links representing the relationships, connections, or modes of interaction. SNA helps researchers understand the network data visually, convey the results of the analysis, and reveal any hidden properties that might not have been captured through qualitative measurement (Alarcon et al., 2013). Quantitative analysis can also be performed to relationships, connections, and characteristics pertaining to an individual node and to the network structure as a whole. Network metrics translate complex visual analysis into quantitative values for interpreting hidden existing behaviors and node features. Some of these metrics are defined in Table 2.2.

Table 2.2 - Social Network Analysis (SNA) metrics

Metric	**Definition (this metric describes)**
Degree centrality	Measures the number of links an individual has with others (Alarcon et al., 2013)
Betweenness centrality	Measures the number of node pairs that an individual connects or bridges (serving as a broker or intermediary) (Hickethier et al., 2013)
Closeness centrality	Measures the number of links from an individual to others; how reachable a person is by others (Haythornthwaite, 1996)
Density	Measures how many actual links exist between nodes divided by the number of total possible links to reflect cohesiveness of the network (Alarcon et al., 2013)
Clustering coefficient	Measures how clustered groups of people are compared to the rest of the network indicating existence of closed triads and small communities (Hickethier et al., 2013)
Average path length	How many steps, on average, nodes require to reach each other (Haythornthwaite, 1996)
Modularity	How dense the connections between nodes within groups as compared to nodes with other groups (M. E. J. Newman, 2006)

SNA has been gaining momentum in fields other than social sciences. In communications engineering, the SNA has been adopted to develop patching schemes to contain the spread of worm and viral applications in cellular-phone networks (Zhu et al., 2012). Recently, SNA is also being employed in organizational behavior studies (Easley & Kleinberg, 2010; Hatala et al., 2009). The application of SNA is increasing in the construction domain to examine how communication and interactions occur within project teams (Al Hattab & Hamzeh, 2015; Alarcon et al., 2013; Azouz et al., 2014; Chinowsky et al., 2010; Chinowsky & Taylor, 2012; Diamantidou & Badi, 2015; Priven & Sacks, 2013), how safety and resilience are related (Wehbe et al., 2016), how contractual setups are formed on projects and their impact on information flow (Chowdhury et al., 2011; Hickethier et al., 2013; Pryke, 2004), and how industry coalitions are formed (Akhavan & Brown, 2011; Alarcon et al., 2013; Y. S. Lee et al., 2016; Park et al., 2011).

This research paradigm is continuously being reinforced in the construction industry to examine formal and informal relationships of network-based project organizations at the inter and intra organizational levels (Turner & Muller, 2003). The main purpose of these studies is to establish a coordination mechanism to facilitate project execution and enhance collaboration and communication among project players and teams.

Social networks present a static analysis of relationships as a single snapshot within a time interval. Therefore, in order to analyze changes that occur within the construction environment, where coalitions are constantly changing along a project and between organizations, several snapshots in time are required to present the dynamic nature of real life network formations. Agent-based modeling, presented in the following section, is a simulation approach for modeling such interaction between agents or entities of a system.

2.4. Complex systems in building projects

Complexity in systems arises when the dependencies between its components become important (Maier & Storrle, 2011; Miller & Page, 2007). Complex systems have several common traits, primarily: (1) *aggregation*: groups can form; (2) *non-linearity*: extrapolation is invalid; (3) *flow:* resources and information can be transferred and transformed; and (4) *diversity:* agents or entities can behave differently and exhibit different characteristics (Bertelsen, 2003; Son et al., 2015). Under complex systems, the system-level behavior emerges from the interactions of its lower-level components; however, it is not the sum of its sub-components (Miller & Page, 2007). This is known as *emergence* which is the development of new and coherent structures, trends, and characteristics during the process of self-organization in complex systems (Goldstein, 1999). Under the notion of emergence, system-level is a robust and powerful force resilient to changes occurring to the low-level components (Miller & Page, 2007). The traditional approaches such as the "Heroic Assumption" cannot be used to explain complex systems (North & Macal, 2007). Under this assumption, levels of detail of the systems are simplified by reducing interactions between components, which often result in an incomplete and unrealistic depiction of the system's behavior (Son et al., 2015).

Construction projects are becoming more complex systems with the increase in the involved uncertainties, the scale of works, and the number of project teams as well as the resources required. In this respect, construction projects become intertwined networks with high complexity and dynamic interdependencies as they exhibit some characteristics of complex systems, such as autonomous agents (evolution and learning of agents), non-linearity (the outcome of processes is emergent and not equal to the sum of the sub-elements), and undefined values (design and project values keep evolving through the project) (Bertelsen, 2003). Using traditional methods to understand complex construction projects fall short when studying the effect of communication and coordination on team performance. By simply assuming that team members interact based on hierarchical relationships and work independently of each other, a lot of existing communication channels and network interactions will be concealed (Son et al., 2015). Therefore, to capture the emergent behavior of the design phase, a more holistic approach such as agent-based modeling of a social network perspective is needed to capture more realistic and comprehensive dynamics of the construction system.

2.5. Simulation and Agent-based Modeling (ABM)

Modeling can simply be described as a form of imagination or projection of an event, occurrence, behavior, or situation in an implicit manner in an individual's mind before it is explicitly written down and formulated (Epstein, 2008). In order to represent these models and explain the relationships between its components or its relationship with surrounding systems, different techniques can be used such as mathematical models (algebra, probability theory, calculus, etc.) to reach analytic solutions. Analytical approaches apply mostly to models or systems whose relationships are not very complex and can be expressed through mathematical relationships that can reach exact solutions (Law, 2014). However, most real-world systems are too complex to be evaluated through analytical approaches and thus require the use of simulation. Simulation is a broad collection of methods used to mimic a real-life system by creating simplified models or replicas of it that are evaluated numerically to better explain the system and provide understanding of underlying mechanisms (Kelton et al., 2010).

A lot of misconceptions revolve around modeling and simulation being techniques used majorly for prediction only. In reality, modeling can be used to explain how and why systems behave the way they do, highlight certain concepts and core dynamics, and raise new questions and horizons beyond the observable. Moreover, systems are simulated to measure their performance, improve their operations, aid in decision making, experiment with them to test the impact of changes or varying certain conditions, or design them if they don't exist (Kelton et al., 2010). Computer simulations have become very popular modeling tools due to the software advancements that provide quick, cheap, and valid decision making as compared to the more error-prone and tedious programming and analytical techniques. Simulation models can be classified along the following three dimensions (Kelton et al., 2010):

- *Static vs. dynamic*: time doesn't play a natural role in static models but does in dynamic models that change with time.
- *Continuous vs. discrete*: continuous systems are those that are changing continuously with the flow of time; on the other hand, changes occur at specific time instances in discrete models.
- *Deterministic vs. stochastic*: models that have exact and no random input are deterministic, whereas models that have random input are stochastic. Most models, due to the nature of real-life systems that involve uncertainties and variabilities, are stochastic in nature. These models also result in random output.

Simulation can also be classified into several types depending on the abstraction level of the system and the purpose of analysis. For instance, (1) discrete-event (process-based) simulations are mainly used to describe processes such as manufacturing and queueing theories of systems with a medium level of abstraction that require tactical level analysis with medium details, (2) system dynamics can explain the changes in a system's equilibrium and balance at a higher abstraction level with minimum details for a strategic level of analysis such as stock fluctuations or customer behavior changes due to marketing/ promotions, and (3) agent-based modeling (ABM) is used at low abstraction level with a lot of details so that micro level observations and occurrences can be modeled and understood, such as modeling the local behavior of individual entities and analyzing their local interactions (Macal & North, 2010).

This research study adopts agent-based modeling for analyzing and simulating the flow of information between design project participants. Agent-based modeling is a new approach for modeling and analyzing complex systems composed of interacting agents (Macal & North, 2010). The behavior of each agent, the dynamic interactions between agents, and their resulting emergent behavior are modeled through ABM. ABM has been gaining momentum over the past decade due to its diverse areas of application and its ability to capture individual behaviors as well as interactions among agents that lead to the behavior of the system as a whole. While systems have been usually presented as homogeneous, ideal, and maintaining long-term equilibrium so that problems under study can be computationally and analytically manageable, the two distinguishing features of ABM is that it models the heterogeneity of agents across complex systems as well as the emergence of its behavior (Macal & North, 2010). Agents in a system can be humans, organizations, or viruses, as long as they exhibit the properties of agents presented in Table 2.3; a brief description of agents in project teams are also presented.

Table 2.3 - Agent properties

Properties	Description of Agents in Project Teams
Autonomy	Acts independently within its environment based on acquired information and interactions with other agents
Discrete Identity	Is identifiable and discrete with a set of characteristics with decision-making ability
Interaction	Can interact with surrounding agents based on a set of protocols of communication and information exchange
Environment	Its behavior is situated and depends on project environment conditions and interactions with other agents
Goals	Works towards a goal, i.e., satisfying design requirements and modifying behavior based on outcomes
Learning and Adaptation	Adapts to collective environment attributes and can possess memory to adjust future behavior
Resources	Has information, trust, collaboration levels, tendency to share,

Different network topologies exist, but no matter what topology is used in the agent-based model to connect agents, the local interaction and information transfer between agents is essential. This means that agents can interact with a limited number of agents within the population at a given time, where global information exchange does not exist (Macal & North, 2010). ABM systems are built from the ground-up perspective rather than a top-bottom approach; it starts by identifying the agents, their behaviors, and their interactions with other agents. These behaviors and interactions of agents eventually define and form the entire system. ABM is most useful when the system under study is naturally composed of autonomous interacting agents forming a network, when decisions and behaviors can be defined, when agents have behaviors that can also adapt and change, and when agents dynamically interact and relationships form, change, or decay. Several ABM models have been developed for various ranges of applications such as air traffic control, energy analysis, biomedical research, and organizational decision making (An & Christley, 2011; Grether et al., 2013).

Design and construction projects are the most complex and comprehensive multi-disciplinary problems as they involve social and human aspects as well as spatial and temporal interactions of different participating organizations (Chen, 2012). Under design projects, collaboration is of high importance. Several ABM tools have been developed to support collaborative design processes (Hao et al., 2006; Liu et al., 2004; Tang, 2004). An ABM-CAD system using internet and web-technologies was developed where different users can have different views of the design and make modifications synchronously and dynamically (Rosenman & Wang, 2001). Anumba et al. (2002) applied ABM to the design stage to support collaborative design by negotiations of intelligent agents. Their study showed that ABM flexibility can integrate negotiation and design information argumentation to facilitate the design process. A 3D virtual environment was developed where modifications and updates of design in the virtual world can be transferred to the CAD system by communications of agents in the virtual world (Maher et al., 2005). The research results show that ABM tools can facilitate synchronous collaboration and design reasoning. Modeling virtual interactions for enhancing real world design processes was further explored as augmented reality in architectural design (Wang, 2009), and modeling complexity of human interactions was explored through ABM (Gao & Gu, 2009).

In this regard, ABM and social network analysis are used in this study to model the exchange of design information between the members of different teams in order to capture a holistic view of the complex interactions and processes involved in the design process of construction projects. Moreover, it allows to measure the potential changes to the design process resulting from the use of BIM as a facilitator of collaboration and design information exchange.

CHAPTER 3

RESEARCH MOTIVATION AND QUESTIONS

3.1. Problem statement and motivation

Studies about construction project management highlight the negative outcomes of variability and acknowledge the importance of ensuring flow of resources and information (Ballard, 2002; Koskela, 2000). However, there is insufficient focus on the mechanisms involved in the flow process and therefore the management of workflow was not explored in depth. Without developing a thorough understanding of the problem under study and methods for measurement and control, traditional sub-optimal approaches cannot be changed in order to boost the current declining status of the industry. This section will highlight some problems and limitations in both research and practice for design information workflow.

3.1.1. Gaps in workflow research and practice

Design management practices and research efforts acknowledge the importance of generating superior design quality that satisfies requirements and specifications. Therefore, the focus has always been on transforming information into the required output (Koskela, 2000). While this premise is a corner stone in the design process, the poor performance during this phase has yielded undesirable cost increases, delays, defected designs, and rework (Ballard, 2000b). When addressing design workflow, some studies, presented in the literature review section, tend to isolate the topology of team interactions from the flow of information between individuals by only considering design task transformation while neglecting the flow of design information, or by targeting the social network structure of involved individuals and ignoring information diffusion, or by analyzing information diffusion and ignoring team coalitions. Some gaps in design management research and practice are presented below and summarized in Figure 3.1.

- Research and industry do not commonly consider the importance of information flow between designers which results in poor workflow practices. Informal surveys conducted with design teams revealed that negative iterations (rework) constitutes an approximate 50% of design time (Ballard, 2000b). Obsolete or missing information that was not promptly shared can result in such rework. During conventional design, individuals and teams work in isolation without realizing that information they are withholding is useful for other team members and the overall design requirements.
- The drawbacks of poor workflow are not clearly understood or observed which limits instilling flow into design practice. Some studies developed flow diagrams to qualitatively map the flow of design deliverables through different stages of the design process (Baldwin et al., 1999). However, this flow has not been mapped across multi-disciplinary teams to highlight the interactions between trades with diverse needs and outputs. Therefore, the impact of these relationships on information flow was not thoroughly evaluated.
- Current methods for quantifying flow metrics are not very comprehensive nor sufficient, making it hard to measure performance. Measuring performance is an important step to assess design workflow and implement the required changes. Tribelsky and Sacks (2011) developed metrics to measure design information flow rates on projects by tracking database logs and showing trends of indices reflecting design workflow. Such studies provide important metrics to understand information flow patterns based on database logs, yet they neglect a

critical controlling factor in the process of information flow: individual and team interactions. Social network structures and their impact on flow of design work and design quality are not taken into account when measuring information flow.

- The intersection of flow dynamics and interactions between design individuals is not fully considered when studying workflow. Some studies highlight the importance of realizing design and construction projects as social networks constituting design players and their communication (Pryke, 2004), whereas others extend this notion to develop a modeling method that links design tasks to the responsible people within a social network (Parraguez et al., 2015). Some efforts developed metrics of collaboration and team work and related them to the ability of information to reach people depending on their position in hierarchical networks (Durugbo et al., 2011; Lopez et al., 2002). Although these studies give insight into the integration of design activities and people involved, they do not model the information exchange necessary for performing tasks, which prevents the realization of workflow patterns within such networks.

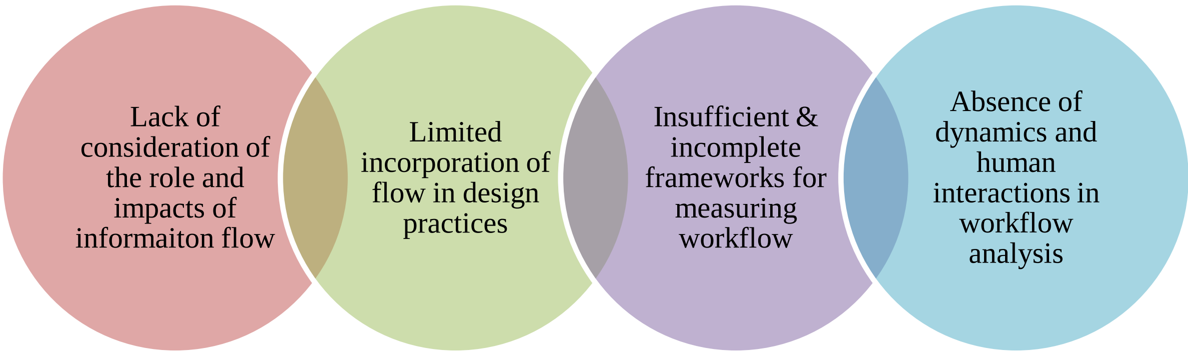

Figure 3.1 - Gaps in design workflow research

The combined effects of the mentioned limitations result in an un-streamlined design delivery process whereby productivity, quality, and client satisfaction are jeopardized (Koskela, 2000). As a result, this study is driven by the urging need to address these problematic areas and advise on improvements that can be made by exploring the dynamics of information flow within social networks. It also puts forth a way to explore how BIM use impacts workflow and what are the underlying factors influencing workflow characteristics that need to be addressed.

3.2. Research goals and objectives

The characteristics, underlying mechanisms, and dynamics of design workflow should be adequately addressed and thoroughly examined. With new approaches in management, planning, technical and collaborative aspects of a project, namely BIM, simulation, and SNA, the major goal of this research is to explore and analyze design workflow of BIM-based projects. The integrated approach models the dynamics of workflow as well as the underlying organizational structure to reveal and measure communication patterns across teams. Modeling and measurement can allow researchers and practitioners to better understand current involved dynamics in order to develop improvement schemes and implement the desired changes.

3.2.1. Research objectives

The specific objectives of this research are as follows:

- Understand the attributes and interrupters of design workflow
- Explore the error diffusion process within design social network structures
- Visualize the process of information flow across multi-disciplinary teams
- Develop a measurement framework for design workflow
- Understand, measure, and analyze the patterns of BIM-based design workflow
- Assess the impact of BIM and collaboration on the flow of design information

3.3. Research questions

Reviewing the literature and assessing the research gap, holding discussions with experts in the fields of design and construction, and attending conferences that present multi-disciplinary studies have resulted in several research questions that this study aims to answer. The questions proposed are based on the 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

Below are the research questions to be answered throughout this study:

- What are the main attributes and leading interrupters of design workflow?
- How do teams interact and what are the deliverables generated at each design stage?
- How do design errors diffuse within traditional and BIM-based social networks?
- What metrics can be used to measure workflow?
- How do the social network topology and collaboration impact workflow dynamics?
- What is the impact of BIM use and maturity on the flow of design information?

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

CHAPTER 4

RESEARCH METHODOLOGY AND METHODS

4.1. Research methodology for design workflow management

Enhancing work flow reliability can be achieved by ensuring required information and handoffs between participants and tasks to be transmitted timely, correctly, and as needed. Human factors, such as the mental thought process, communication with others, and level of trust, are the most unpredictable, but through exploring and understanding the personnel's interactions and underlying dynamics, their behavior and actions are made more predictable and relations between them are made stronger. Design workflow can be thought of as the flow of design tasks whose output and time frame cannot be clearly defined. This design flow comprises the flow of information, handoffs of design deliverables, requirements, specifications, calculations, and design solutions, etc. In contrast to a more predictable outcome of construction activities, design tasks and processes are very iterative, jumbled, and involve a thought process that accounts for multiple alternatives to be assessed at the same time. Therefore, the main challenge on design projects is how to better manage work flow. To explore the impacts of BIM on workflow, a thorough understanding of the mechanisms and dynamics of information flow is needed and a measurement technique is required to better analyze the outcomes of BIM use.

Before developing the methodology for assessing the impacts of BIM on design workflow, a few attributes and interrupters of design workflow are suggested in Table 4.1 to guide the research framework development. Design workflow is an inherently chaotic process that involves multiple iterations and assessment of alternatives. Due to the interdependent nature of design tasks, using the concept of productivity tracking and independently defining tasks can become inaccurate with complex designs. Therefore, workflow can better be measured and handled as the flow of information and exchange of data between project participants. Since the flow of design information occurs between project participants, workflow should be assessed from a human-to-human social interaction perspective. Such workflow can be measured and analyzed in terms of underlying processes such as the rate of designing, reworking, sharing of information, reviewing, and work-in-process (WIP). Such processes can reflect the quality of workflow and help understand problems with it. Moreover, measuring workflow at different time intervals is necessary to have a more complete visualization of its attributes and capture its dynamic nature.

However, design workflow suffers from several interrupters that disrupt the smooth exchange of design data between project participants. Accumulating information in inventories (WIP) before sharing them causes a disruption of the continuous flow. Such inventories can cause the data to become obsolete, resulting in design errors that cause rework and negative iterations. On the other hand, acquiring new information and requesting changes causes the flow to be interrupted where this new data and changes need to be incorporated into existing designs. The traditional tendency in design is to withhold information until it is complete and ready to share which results in idle time experienced by others who are waiting on this needed information. Workflow can be interrupted also by long cycle times and slow processing of design information by individuals creating bottlenecks in the system and disrupting the flow of data. At the core of these issues is the lack of coordination and collaboration among the involved individuals and teams. The lack of teamwork prevents the establishment of shared understanding between members and therefore the timely and correct exchange of information is jeopardized.

Table 4.1 - Attributes and interrupters of design workflow

Attributes of design workflow	Interrupters of design workflow
Design workflow is innately chaotic	Accumulation of information in inventories
Tasks are hard to define independently, thus tracking productivity rates and completion dates is inaccurate	Acquisition of new information and requested changes
Workflow can be measured in terms of information flow and data exchange	Design errors and obsolete design causing rework and negative iterations
Design flow should be assessed on a network basis and human interactions	Idle time waiting on needed information from others
Workflow can be measured in terms of its internal processes such as design, share, rework, WIP rates, etc.	Long cycle times and slow processing causing bottlenecks (Tribelsky & Sacks, 2011)
Multiple measurements of flow need to be performed at different intervals in time	Lack of coordination and collaboration between individuals

The research methodology developed for the study of design workflow is summarized in Figure 4.1. The methodology consists of two major modules: (1) understanding design workflow and error diffusion and (2) developing a framework for analyzing and measuring design workflow.

4.1.1. Module 1: Understanding workflow and error diffusion

Module 1 of this study aims at gaining an understanding of design workflow and how errors, as main interrupters of such flows, diffuse through design social networks. First, existing problems with traditional design workflow management are highlighted, and, accordingly, a framework for a proactive management of workflow is proposed. The core of the framework, explained in chapter five, is to have a holistic vision of information flows between different teams during the design phase of construction projects. Based on the conducted literature review and discussions with design professionals, such flows within and between team members are preliminarily and qualitatively modeled into swim-lane diagrams. Two diagrams are presented, one describing the traditional design flow and the second presenting BIM-based workflow.

The process models, presented in Chapter 5, not only show the sequence of information exchange in the conceptual and schematic design phases, but also show the information flow between the cross-functional participants. They also present the data deliverables generated by the cross-functional teams design processes in order to highlight potential design iterations, rework, delays and idle time, and unnecessary repetitive processes.

In order to model the flow of information in the BIM-based design phase, research work on BIM collaboration and the roles of participants in the modeling process are reviewed, after which a preliminary process model is generated. Design professionals in the BIM field are then consulted for their feedback on the preliminary process model and interviewed to further develop it. The interviewed design professionals have over 20 years of experience working at major architectural/ engineering firms in the Middle East and the US. These firms use BIM on medium sized residential buildings, large complex structures such as stadiums and convention centers, as well as universities, airports, hospitals, and governmental facilities. Moreover, to validate the data in the process model of the traditional 2D CAD design phase information flow, the design professionals are also asked to provide their feedback on the process model targeting the roles of the cross-functional teams, the data deliverables of each stage, and the interaction and exchange between teams.

With design errors being major interrupters of workflows and main contributors of failures on construction sites, the mechanisms of their occurrence and diffusion through social networks are explored in this module. Previous studies on design error management only focused on exploring design errors from a static cognitive perspective and on solutions targeting individuals' actions in isolation. Research so far has answered the questions of “How” and “Why” errors occur but ignored two fundamental contributors to errors: improper information flow, and the relations between the influencing factors and contributors.

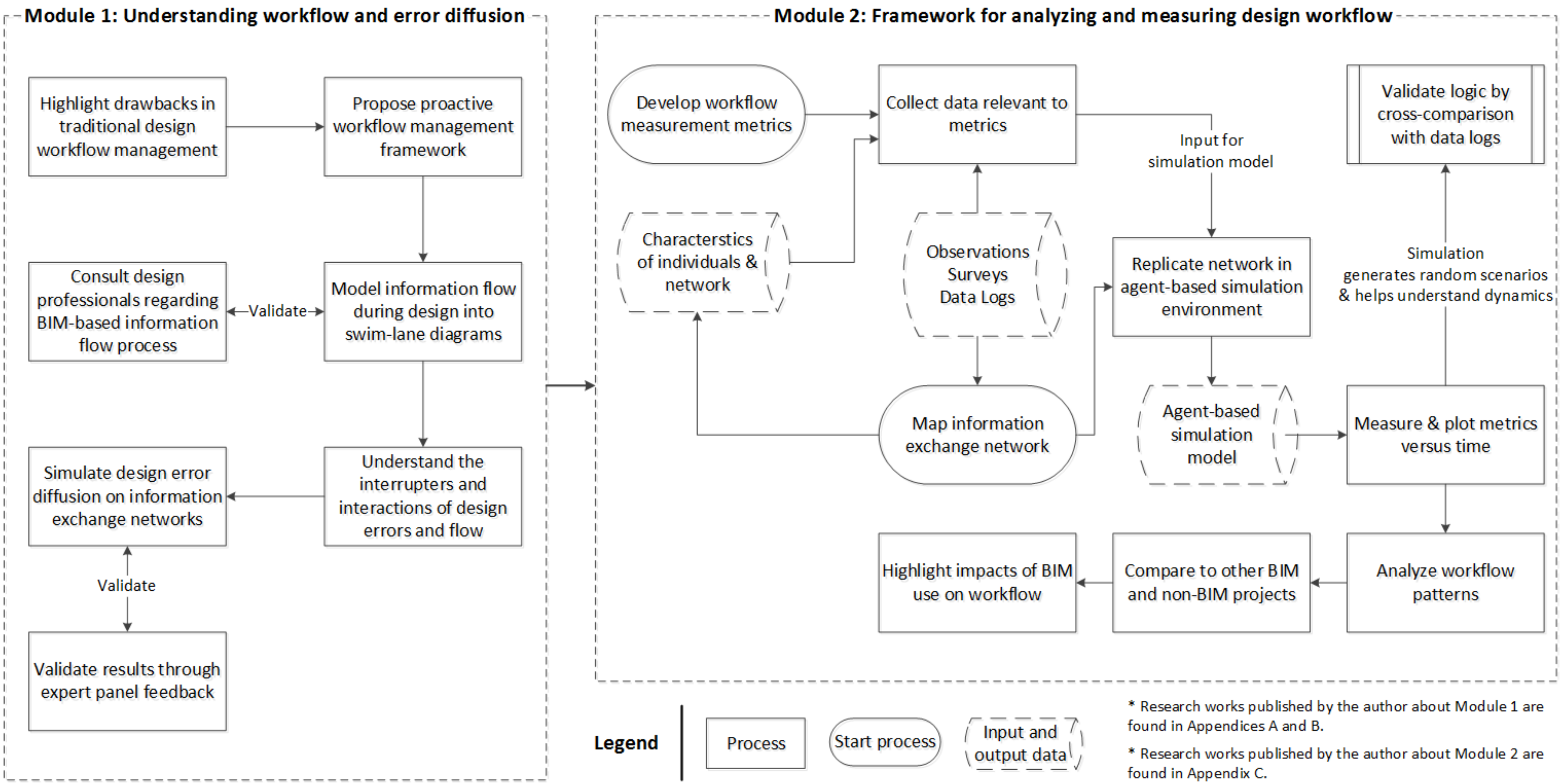

Figure 4.1 - Research methodology

A schematic model is proposed to connect the "How" with the "Why" and highlight the interactions between design errors and information flow as an interconnected chain rather than separately examining the causes and effects.

In order to explore the diffusion of errors through design networks and the impact of such network structures on shaping the dissemination of errors, social network analysis and agent based modeling are adopted in this regard. Two hypothetical networks of a traditional 2D design system and BIM-based design system are developed for the purposed of assessing how errors diffused under these different network structures. Social network theory is used to qualitatively and quantitatively assess the characteristics of the network structures. Gephi (Jacomy et al., 2009), a network analysis and visualization software, was used to map the interaction and information exchange networks and calculate the respective metrics. The resulting structures and metrics for the traditional and BIM-based setup are compared against each other to help understand the underlying differences in their communication environments. The structures present a static understanding of the governing relationships at one point in time.

Second, to map the dynamic nature of error generation and propagation, agent-based modeling performed through NetLogo software, is used to simulate the diffusion of the design errors in these structures under different conditions. The resulting configurations of both structures from Gephi are used as input for the NetLogo simulation. NetLogo is an agent-based simulation tool for modeling the actions and interactions of agents (in this case the agents are project players) and to evaluate their impact on the system (Wilensky, 1999). The values of parameters used in the simulation models are based on theoretical assumptions in order to better represent a generic range of different possibilities and scenarios. Agent-based simulation also allows tracing design errors throughout the network. It is a convenient tool for multiple experimentation and assessment of BIM impacts in providing defense and reduction mechanisms against design errors. The dynamics of this procedure help measure the severity of outbreaks of errors and assess the impacts of the proposed design error management strategy.

In order to compare the impacts of traditional and BIM practice on the reduction and mitigation of design errors, agent-based simulation is used to model four theoretical scenarios of error transmission between the individuals under each environment, measure the time it takes for errors to disperse and be remedied, as well as the percentage of the individuals receiving these errors and learning from them. The scenarios represent combinations of different theoretical ranges of parameters used in the simulation model. The simulation results for each scenario are plotted and analyzed to highlight the impact of BIM practices on design error management. Afterwards, an international panel of experts in the fields of lean, BIM, and social network analysis was consulted to seek their feedback on the inputs and the results of the experiments performed in this study in order to validate their theoretical basis and rationale. The detailed experimental setups and analysis are presented in Chapter 5.

4.1.2. Module 2: Measuring and analyzing workflow

The second module develops a framework for the measurement and analysis of design workflow of a BIM-based case study project by considering information flow aspects and interactions among individuals as a dynamic social network. In order to quantitatively measure and analyze the impacts of BIM and its social network structure on the flow of design work, a social network structure map and workflow metrics are developed. The study not only considers how BIM-use impacts workflow, but also how the design communication structures of members and teams can shape and influence the resulting workflows.

Therefore, the first step is mapping the communication network structure through social network analysis (SNA). Gephi is used as a tool to map and show how teams and members of different design disciplines are connected and how frequently they communicate. It allows collecting metrics that describe the structural setup of such networks and the inherent dynamics and interactions of its teams and members. To map this network in Gephi, a survey is prepared to gain insight into network mechanism and structure. Based on the literature discussed earlier regarding social network analysis, the questions of the survey are prepared as shown in Appendix A. The survey is conducted with certain personnel involved on a design project. The survey asks participants to list the people with whom they communicate for design purposes, how frequently they do so, why they communicate and what they use the exchanged information for, the type and amount of deliverables they exchange, and the modes of communication. Collected survey data from each member and general observations are then used as input for Gephi to setup the communication structure. The analysis of metrics in Gephi is then performed. Afterwards, collaboration metrics developed by Durugbo et al. (2011) are used to assess collaboration during the design phase.

The second step is developing workflow metrics to assess flow criteria such as designing, sharing, reworking, and revision rates, as well as the amount of work-in-process (WIP). In addition, the daily time division between designing, reviewing, reworking, sharing, and collaborating efforts are also metrics developed. These metrics reflect the nature and attributes of workflow during the design phase. In order to measure these metrics, an agent-based simulation model is developed to simulate the dynamics of information exchange between the mapped agents and teams on the case-study project. Not only does ABM model the behavior of individual agents, but shows the emergent behavior of the design system as a whole; thus capturing the overall resulting workflow interactions within the system. Based on observations of members and teams, social network and collaboration metrics collected earlier, as well as data collected from the surveys, an agent-based model is developed to model organizational and process dynamics of design workflow. Simulation allows experimenting with a multitude of scenarios, variations, and making use of stochastic input to test out different behavioral setups. As a result, the ABM allows to output the workflow metrics of interest while integrating both the social and process dynamics, which have not been considered in earlier research. Some features of the model are validated using data logs extracted from the project's data base to ensure the model is credible and reflects reasonable behavior of individuals and the system.

After running the simulation model, the obtained metrics are plotted and resulting trends are analyzed to explore the workflow trends and BIM's impact in the light of the social network structure, collaboration levels, and BIM maturity. The resulting patterns are then compared to other BIM and non-BIM projects extracted from literature to further highlight the role of BIM maturity and collaborative structures in shaping workflow.

The case study used, surveys and data collection process, development and explanation of the metrics, setup of the social network structure, as well as description and development of the agent-based model are presented in detail in Chapter 6.

4.2. Research methods used

Using multiple sources of evidence when collecting and analyzing data is necessary to develop a process of triangulation of several congregating methods. Accordingly, this study employs the following types of triangulation (Meredith, 1998; Stuart et al., 2002; Yin, 2014):

- Data triangulation utilizing several sources (questionnaires, interviews, models)

- Theory triangulation (analyzing and comparing data across different case studies and perspectives)
- Methodological triangulation (employing quantitative and qualitative methods)

The choice for each research method is discussed and justified. Table 4.2 presents the research tools and the validation techniques used in both studies.

Table 4.2 - Research tools employed and validation techniques

Tools used	**Validation techniques**
Process mapping	Case study
Social network analysis (SNA)	Expert panels
Agent-based modeling (ABM)	Data base records
Case studies	
Questionnaires and interviews	

4.2.1. Questionnaires and interviews

A structured questionnaire is a research instrument used to collect data by the presence of the interviewer instead of online or mailed surveys. The interviewer provides a background about the survey, reads the questions to the interviewee, and explains any aspect if needed. The questionnaire should be discussed in the same way to every participant to avoid bias or subjectivity in the answers. Structured questionnaires provide higher participation from the targeted group, less bias and errors in answers, and better data consistency (Bryman, 2012; Creswell, 2003; Dipboye, 1994).

Interviews with researchers and practitioners can help guide the research work and gather new insights into the areas being studied. Aside from questionnaires, open ended interviews and discussions open floors for new ideas and research questions. Moreover, observations at the work place can help clarify misconceptions and gain a deeper understanding of natural behavior and processes (Bogdewic, 1999).

4.2.2. Expert panels

The focus-group method is a qualitative research approach to collect perceptions and feedback from a group of individuals regarding a certain product, service, application, etc. within a group discussion environment (Parker & Tritter, 2007). An Expert panel is one form of a focus group; however, it is more reliable and reduces biases or influences as it is carried individually. In this research study, panels of experts in the field of design management are asked to provide their perceptions regarding the methodologies and models developed in Module 1. The feedback provided by the individuals serves to enhance or modify these processes and models. The aim of soliciting feedback from experts is to validate the rationale of the research procedures, inputs used, and outputs generated in order to add credibility and reality to the study.

4.2.3. Case-study application

A case-study is used to provide more compelling evidence and contribute to the robustness of the study. Case-studies have the ability to capture "lived reality" by retaining more aspects of real life than other types of research methods, which becomes of high importance when it comes to social and behavioral studies (Hodkinson & Hodkinson, 2001). Moreover, case-study research can help explain the complexities of real-life situations, how, and why certain behaviors occur which may not be captured by experimental research (Zaidah, 2007). The case-study project is selected to address the questions of this research; additionally, cases collected and analyzed from literature will be used for comparison and replication. Replication takes two forms: (1) literal replication, which takes place when two case-studies produce close and comparable results and (2) theoretical replication, which occurs when results between two cases contrast under contrasting conditions(Yin, 2014). The combined use of a project case-study and multiple simulation scenarios can provide the literal replication, whereas the use of case studies from literature will be used for theoretical replication. The case-study project was selected as a good testing ground for data gathering, have accessible data records and practices, and have interesting attributes that can serve as comparable basis to draw certain inferences and relationships. The case-study project selected for this study is part of a large ongoing airport construction project. The design phase under study was at the conceptual and schematic design levels, and the case was selected accordingly because it was still at the early phases where the design is most iterative and requires a lot of collaboration. Moreover, the design was "live" during the data collection process which enabled conducting surveys with the designers and observing the ongoing work processes and interactions in real-time.

4.2.4. Simulation and modeling

Simulation is a representation of a part or parts of a universe, where important aspects and behaviors are of interest to the study. Simulation has many roles depending on the situation under study, where it can be used to solve problems, improve status of the system, understand otherwise complicated relationships, analyze behavior, or measure performance(AbouRizk, 2010). Moreover, simulation can be a faster, cheaper, and more exhaustive alternative than regular analytical or qualitative procedures. Different scenarios and conditions can be experimented with, where it might be hard, impossible, or time and cost consuming to perform in real life.

In design management, assessing individual's behavior within a network of interactions and communications, and analyzing the dynamics at a micro and macro level is hard to capture in real life observations alone. Therefore, social network modeling and agent-based simulation are used to recreate the environment and reflect such interactions, where variables and parameters can be controlled, measured, and manipulated. This allows to analyze, measure, and understand design workflow trends. Simulation also helps fill gaps in data collection and missing time spans during measurement to give a more comprehensive coverage of the phenomena under study (D. Newman, 2003).

4.3. Research limitations

Research limitations involve the adopted methods, data collection process, and analysis of results. Data and required input are not abundantly available or accessible, which requires theoretical assumptions and validation by expert panels. Consequently, the data used does not reflect the characteristics of all project types and conditions. Similarly, case study analysis is project specific where results are not necessarily generalizable to the entire industry, even though they can provide important insights and inferences. Moreover, results from the case study reflect a specific project type, a unique contractual arrangement and delivery approach, as well as a specific culture of the organization and country. Therefore, different project types, contractual setups and delivery approaches, as well as the underlying cultures and backgrounds of individuals can yield different results and observations. Questionnaire responses are subject to the interviewees' bias and subjective feedback even if they were asked to be fully objective and honest. Finally, simulation techniques require validation of the model's logic. This imposes limitations where it is hard to measure performance in reality or validate complete aspects of the model, which prevents the full comparison of real-life and simulated environments. Further model limitations are listed under the relevant sections in the model description.

CHAPTER 5

UNDERSTANDING WORKFLOW AND ERROR DIFFUSION

5.1. Design workflow management

The following sections detail the frameworks and experimental setups involved in the methodology adapted for assessing the impacts of BIM on improving design workflow.

5.1.1. Proactive framework for management practices

The first module of the research methodology provides an understanding of traditional design workflow, its drawbacks, and interrupters. Accordingly, a proactive framework for better design workflow management strategies based on a BIM environment is proposed.

Figure 5.1 is a representation of the traditional approach of design workflow. The initial status of the workflow system under a traditional approach is based on a fragmented environment with poor coordination and communication. The lack of

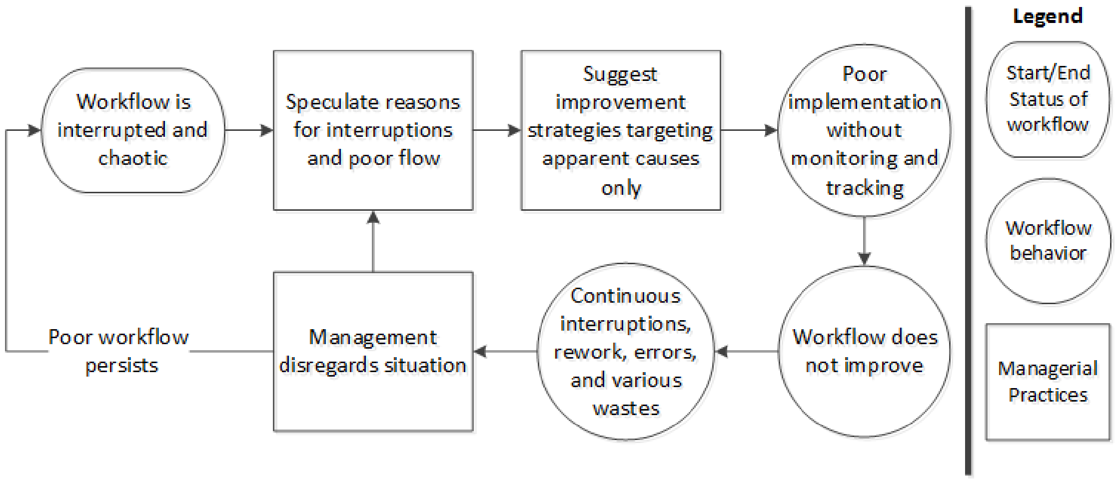

Figure 5.1 - Traditional approach for workflow management

continuous exchange of information in a timely manner, the generation of design errors, and rework cause workflow to be interrupted and chaotic where design information is unorganized and jumbled. If managers and coordinators realize this situation, they usually speculate reasons for the poor flow of design work in order to rectify the flow; however, they base their suggested improvement schemes on superficial and apparent causes only without targeting the core problems (Al Hattab & Hamzeh, 2015).

The framework in Figure 5.2 proposes an attempt to bridge the gaps and drawbacks of the reactive traditional approach. It is a combination of suggested steps that build from general proactive management principles tailored to preemptively manage workflow in the design phase. The initial step in the framework requires management and users to observe qualitatively the characteristics of design workflow and how teams and individuals interact during design. Accordingly, issues that hinder and interrupt the flow of design work need to be identified with rooms for potentail improvements, followed by root cause analysis in order to determine the fundamental causes of these apparent problems.

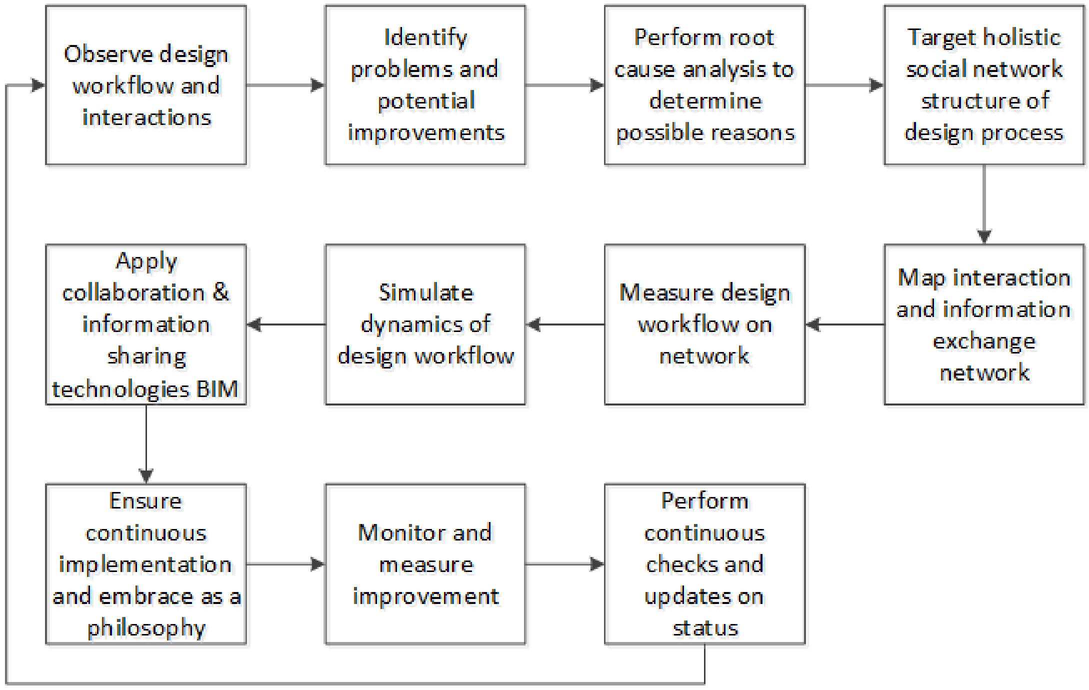

Figure 5.2 - Proactive approach for workflow management

Since design work flow has the term "flow" at its core, assessing individual design work execution does not allow to observe and evaluate the work flow in order to improve it. Therefore, it is important to analyze design workflow by targetting the entire social network structure involved in the design process. In this regard, the information flow and exchange network are mapped in order to understand the structures through which design work flows, and accordingly provide an insight into the underlying mechanics of the flow system. In order to improve the system, meaurement of certain attributes through developed metrics is required to implement desired imporvements and track the progress. Simulation of the dynamics through which information flows between teams and structures allows to highlight drawbacks in the traditional approach and benchmark the role of information technologies and collaboration, such as BIM, in streamlining the design workflow.

Implementing changes and improvements is only effective when it is continuously employed and embraced as a key principle and mindset within an organization. Finally, measurement on regular basis enables to monitor and control desired output and update behavior and status of the system accordingly with timely feedback.

5.1.2. Process-flow diagrams of information flow

In order to visually delineate the impact of BIM, process-flow diagrams for traditional (2D CAD) designing and BIM-based design production are developed.

The traditional (2D CAD) design phase information flow was modeled in cross-functional (swim-lane) diagrams. The choice of swim-lane diagram is for the fact that it helps present three things simultaneously: (1) information flow, (2) clear information exchange between the different disciplines, and (3) data deliverables resulting from each design process.

The swim-lane diagram shown in Figure 5.4 is divided horizontally into three lanes (architect/designer, structural/civil engineer, and MEP engineer). Vertically, the diagram is divided into four phases. The first phase is the conceptual design phase, followed by review and iterations (rework) period when the conceptual design phase tentatively ends, and once the review period and any rework has been performed and accepted by the owner, the schematic design phase is triggered. In a similar fashion, it is followed by a review and iterations period once the schematic design phase tentatively ends. After receiving the approval of the owner, the design teams can then proceed to design documentation, which is usually more stream-lined as design is more developed and clearer than earlier stages.

The architects start by developing the design concept and then generate information deliverables like preliminary massing and orientations of the project. These deliverables are collected as documents, and after the architect concept design ends tentatively, they are then passed on to the structural/ civil engineers who have been waiting to receive these documents and experience delays and idle time. Similarly, the structural/ civil engineers proceed with developing their concept design and generate information deliverables. Meanwhile, the MEP engineers after waiting to receive the data deliverables from the architects, start developing their concept design as well. Only after the teams have finalized their preliminary concept designs, silos of information documents can then be shared in iterative feedback loops between the different teams to perform the necessary adjustments.

Traditionally, the teams submit their information deliverables to the architects and owners for their decision, which results in either the acceptance (with comments) or rejection of the design concept documents. In the case of rejection, which normally comes late as it waits for the complete design input, the structural/ civil, MEP engineers, and architects have to perform adjustments and rework in the design process and go back again through several iterative loops before the design finally gets accepted. Upon the owner's approval, a final concept design report is generated to proceed with the schematic design phase. This phase proceeds in a similar manner as the concept design and includes several iterative and feedback loops, idle time and delays, rework and adjustments until the approvals of the architects and owners are received.

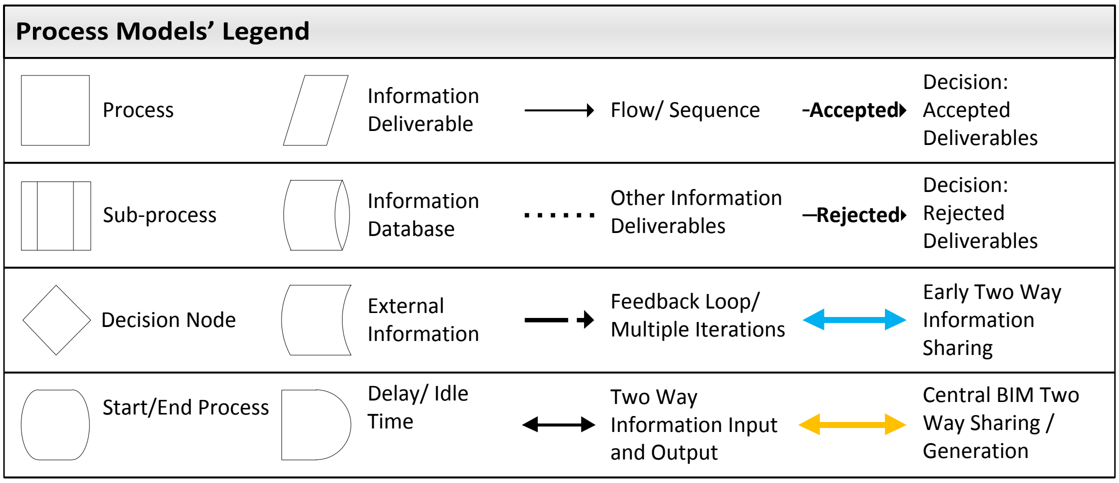

Figure 5.3 - Legend of components for process models in Figures 5.4 & 5.5

The swim-lane diagram shown in Figure 5.5 represents the model for the BIM-based design process. It is divided horizontally like the traditional 2D CAD design phase information flow swim-lane diagram. However, vertically, only the conceptual and schematic design phase are present as the information coordination, sharing, and owners' feedback happen during each of these phases and do not have to wait till the design is complete.

The concept design phase starts by developing the architectural concept in the BIM environment and generating deliverables that are incorporated into the building information model. Unlike the traditional 2D CAD design phase, the structural/civil and MEP engineers do not have to wait until the completion of the architectural design.

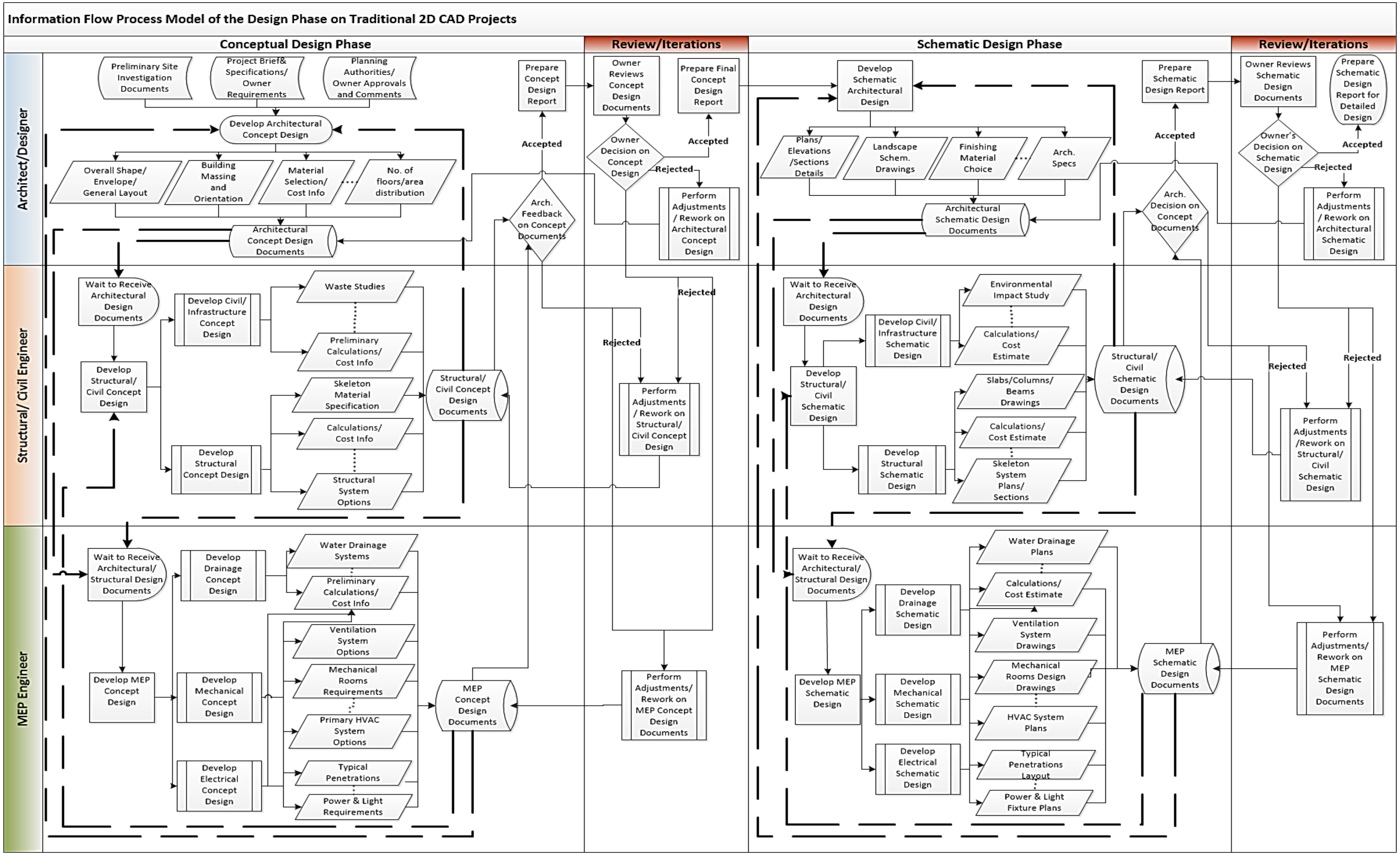

Figure 5.4 - Traditional 2D information flow process diagram

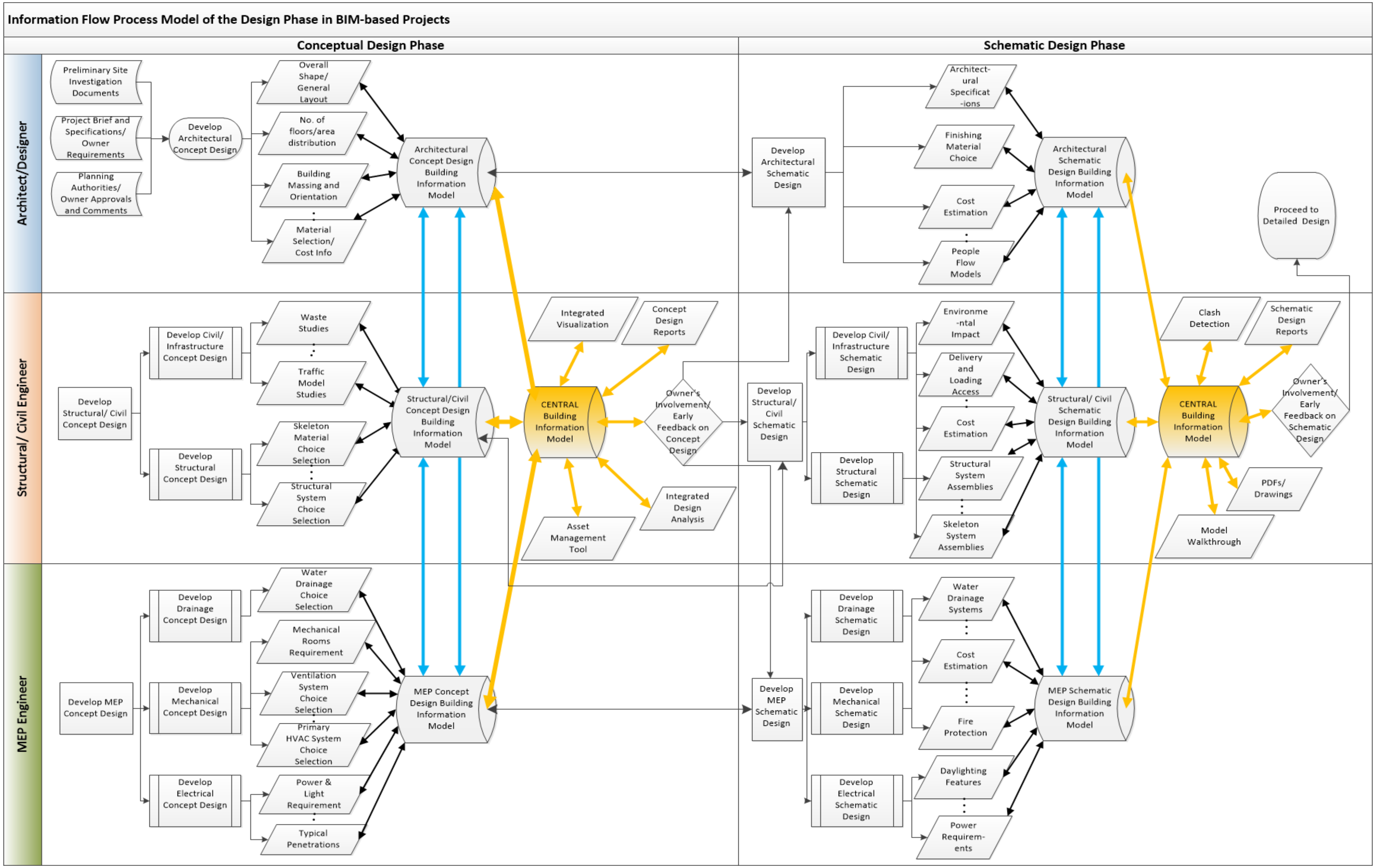

Figure 5.5 - BIM-based information flow process diagram

Instead, early and easy data sharing is possible before data completion, thus the three cross-functional teams can develop their design concepts simultaneously. These concepts are modeled in the BIM environment, and result in individual comprehensive building information models that are integrated into one central model (Al Hattab & Hamzeh, 2013).

This central model and individual models allow two-way information sharing between the different design participants in real-time as well as prompt adjustments of the model information after integrating and coordinating all the data. In addition, the owner can get on board during the design concept development to provide his early feedback on the design criteria as the required deliverables can be extracted from the building information models at any time. This avoids the late "acceptance or rejection" decisions which result in massive time and cost consuming rework and countless design iterations as it happens on projects not using BIM.

After the completion of the conceptual design phase, there is no need to start over and generate new models to develop the schematic design process. Instead, the previous individual building information models are further detailed in accordance to the required level of development (LOD) of the schematic design phase. This in turn saves time of starting over and wasting time. The schematic design process then proceeds in the same logic of the previous design phase.

5.2. Simulation of design errors

Design errors play a major role in controlling the workflow of design, and as explained earlier, it is important to analyze how errors disseminate and how they impact flow of information under each structure. Research so far has answered the questions of "How" and "Why" errors occur, but they ignored two fundamental contributors to errors: improper information flow, and the relations between the influencing factors and contributors. Unless the information exchange channel and its relation to the interactions of design errors are examined, the required interventions to improve the performance of the design process are difficult to attain.

Figure 5.6 proposes away to connect the “How” and “Why” and incorporate the role of information flow into what has been studied earlier. The squares represent the factors (“Why”) and the failures (“How”), and the circles represent sub-categories or different types of these factors and failures. The idea behind the model is to combine what previous researchers have studied separately into linked factors and failures. The model shows how information flow influencing factors are connected to workplace and organizational factors. These factors are related to coordination, culture, social, cognitive, and informational aspects of the design process. If the individuals fail to communicate or exchange the right data needed to perform their design adequately, errors are more likely to be generated and dispersed among the teams.

On the other hand, information flow failures are the core of the contributing factors and are tightly linked to direct (mistakes appearing directly in design) and latent failures (hidden errors that propagate and result in failures). Such failures are manifested, for instance, when designers are not being aware of the needs of other project participants or all the requirements of design. The lack of proper information exchange and shared cognition creates a medium for the incidence of failures. However, the design data are traditionally piled in silos before they are exchanged between the design teams. The reasons behind the design failures and the ways in which they occur are highly intertwined. In fact, classifying factors or manifestations into discrete categories independent of each other conceals the actual continuum that links causes with effects, and hides the synergistic product of the interacting factors and interacting contributors, at which improper information flow is the core. Therefore, the reasons and effects of underlying problems should not be examined separately, but should be analyzed as a whole interconnected chain as suggested by the model in Figure 5.6.

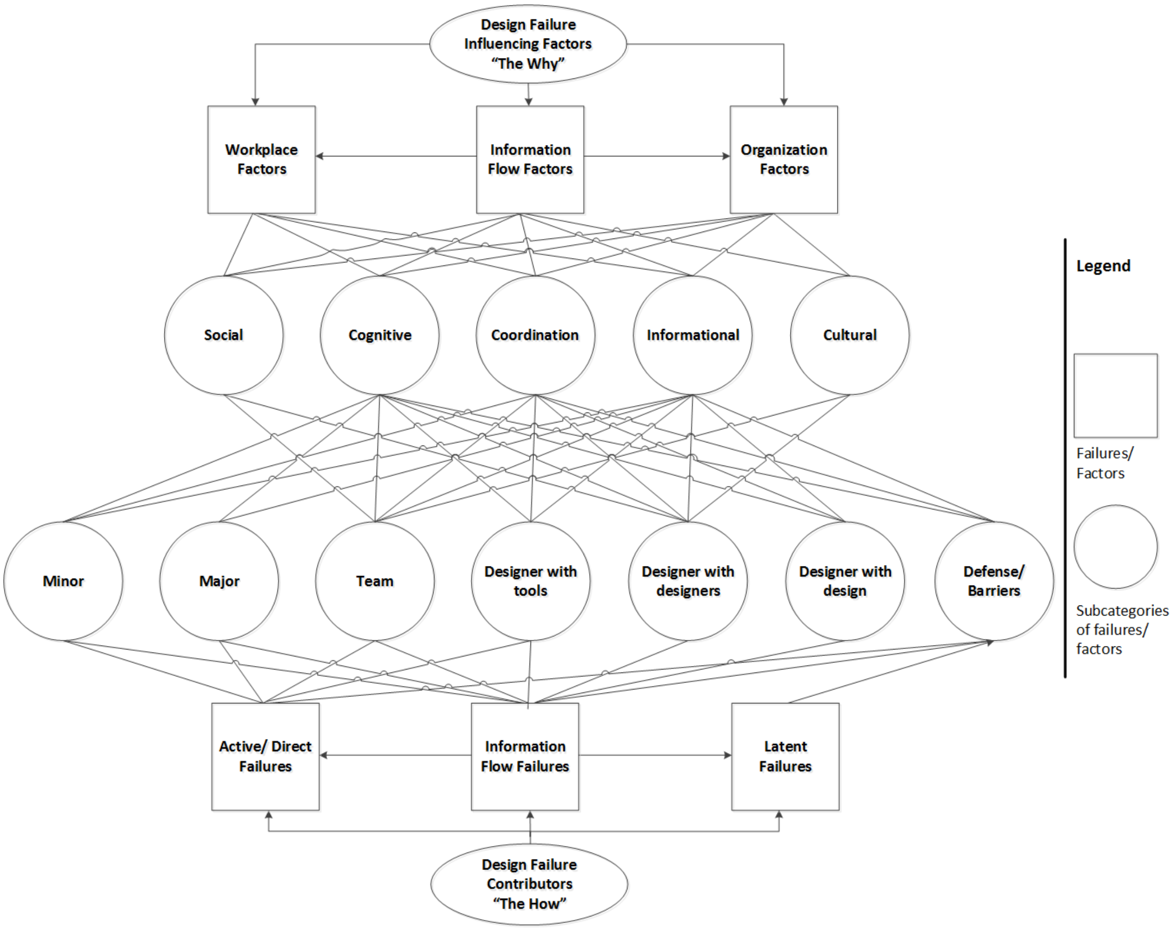

Figure 5.6 - Interactions of information flow and design errors

5.2.1. Experimental setup for error simulation

The social network theory approach can serve as a means for the mitigation of the design errors by examining a broad diversity of interaction channels, which was limited previously to separate the individuals and the small groups of designers. Since many errors are manifestations of wrong and improper exchange of information or lack of transparent communication, studying information and interaction networks form the basis for understanding and managing errors. Gephi was used to map the interaction and information exchange networks for both traditional, and the BIM network. Figure 5.7

and Table 5.1 present generic structures of each network and the list of abbreviations/annotations of the nodes.

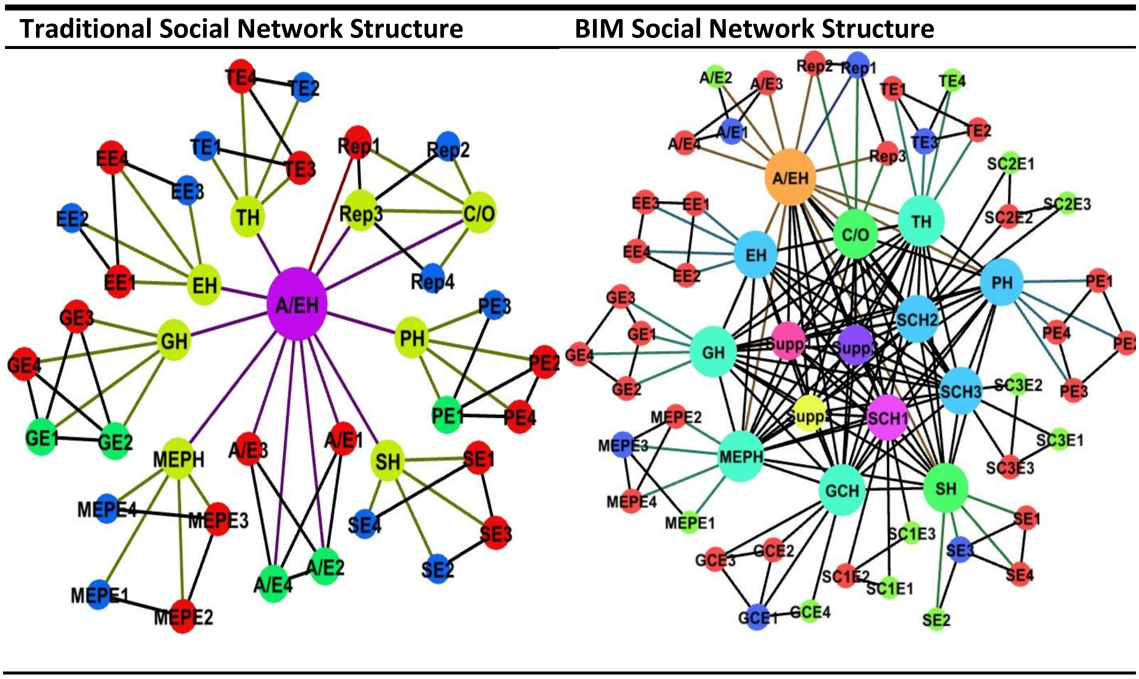

Figure 5.7 - Hypothetical structures of traditional and BIM social networks

Table 5.1 - Abbreviations for design and social network structures

List of Abbreviations		
A/EH: Architect/ Engineer Head	MEPE: MEP Engineer	TE: Transportation Engineer
A/E: Architect/ Engineer	GH: Geotechnical Head	GCH: General Contractor Head
C/O: Client/ Owner	GE: Geotechnical Engineer	GCE: General Contractor Eng.
Rep: Client Representative	EH: Environmental Head	GCH: General Contractor Head
SH: Structural Head	EE: Environmental Engineer	SCH: Sub-contractor Head
SE: Structural Engineer	PH: Planning Head	SCE: Sub-contractor Engineer
Supp: Supplier/ Manufacturer	TH: Transportation Head	

The construction industry under traditional systems is highly fragmented, where each team strives to increase their own benefit and profit at the expense of other teams (Al Hattab & Hamzeh, 2015). This situation reflects a lack of awareness among project participants of the needs of each other, what is required to add value to the project, in addition to poor information exchange and transparency. The design phase in traditional project delivery is mainly driven by the Client/Owner (C/O) and the A/E. The involved disciplines depend on the scope of the project, and traditionally consist of the architectural, structural, mechanical/electrical/plumbing (MEP), conveying systems, environmental, geotechnical, and planning disciplines, where each discipline team is usually formed of the head/ manager and the team engineers.

A suggested example of a small/medium sized design firm (the left network in Figure 5.7) was assumed for mapping a generic structure based on interviews with design professionals with 20 years of experience working at major architectural/engineering firms, observations of authors of behaviors within these firms, and previous research (Alarcon et al., 2013; Chinowsky et al., 2010; Linderoth, 2010). The provided structure example consists of 8 groups, each including the head/manager, and 4 team individuals (engineers or representatives). It is also assumed here that the individuals within separate teams work closely, but there is no interaction between teams, and contractors or builders are not involved earlier in the design phase. The A/E normally plays the role of the coordinator and the link between the C/O and the rest of the project participants. Therefore, A/E is the central and largest node given that he has most connections with the rest of the teams. The other players are clustered within their own isolated teams as separate webs.

Under a BIM configuration, early involvement of contractors, sub-contractors, and suppliers allows the integration of construction experience early on. This reaps benefits such as providing constructability analysis, performing value engineering, and providing accurate manufacturing details with least errors and assumptions. The proposed structure presented (the right network in Figure 5.7) builds on principles of integration and information exchange, as well as the early involvement of key project participants (Ilozor & Kelly, 2012). The structure shows the addition of new nodes representing the general contractor, sub-contractors, and suppliers, with their engineering teams. More importantly, the different teams are integrated, where there are more ties between the different teams, and the A/E is no longer the sole coordinator between the disciplines and the C/O. The two suggested structures are hypothetical examples out of many other possibilities as they would differ according to each project, country/location, culture, work environment, etc.

The limitation of the static structures generated by Gephi is that they fail to provide the required means to determine which of the traditional or BIM structure is favorable for error dissemination or error containment. This matter is supported by a dynamic simulation tool, NetLogo. For the purpose of this study, a NetLogo model, Virus on a Network, is modified and customized to be used to simulate different scenarios for the diffusion of design errors generated by designers under both structures. The aim of the simulations is to observe the dynamics of error transmission between individuals based on each structure, measure the time it takes for errors to disperse and be remedied, as well as the percentage of individuals receiving these errors and recovering from them. Figure 5.8 shows a sample of the NetLogo interface.

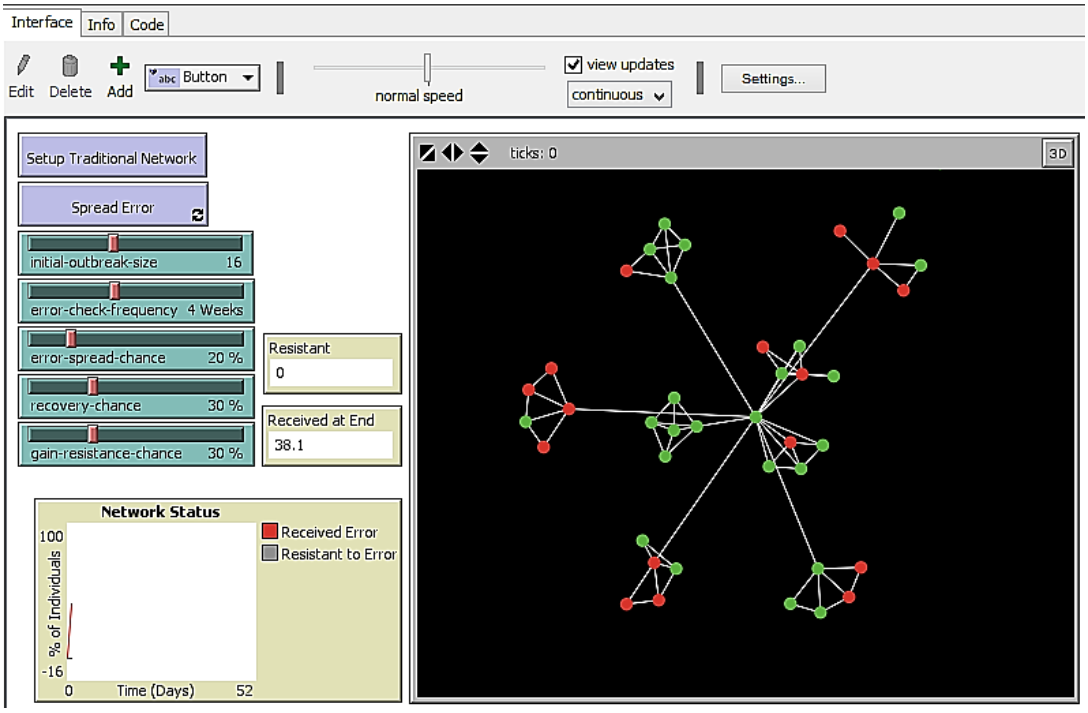

Figure 5.8 - NetLogo interface for error simulation

Table 5.2 defines and specifies the values of parameters used in NetLogo for traditional and BIM structures. At each step, and given a specified error spread chance, an error generated by an individual (colored red) attempts to spread to all connected individuals. However, individuals receiving an error or generating an error are not immediately aware that they have done so. Only when design checks are conducted would individuals become aware of having errors in their design. In addition, the individuals receiving an error have the tendency to fix it, representing a sort of error healing energy, which is defined through the “recovery-chance” parameter. Also, individuals have the ability to learn from the design error they have detected and prevent its future occurrence. This is translated as the “gain-resistance-chance”. Gaining resistance resembles a shield and defense mechanism against errors, and reduces the chance of generating a similar design error or allowing it to diffuse into the network.

Table 5.2 - NetLogo input parameters for both structures

Parameter	**Definition and Purpose**	**Values for Traditional**	**Values for BIM**
initial-outbreak-size	Number of individuals generating design errors	40% of individuals	40% of individuals
error-check-frequency	Frequency of design checks to detect an error	4-5 weeks	1 week
error-spread-chance	Probability for error to diffuse to linked individuals	20%	50%
recovery-chance	Probability that an individual fixes a design error before or after it diffuses (expelling energy)	10% to 40% (in 10% increments)	20% to 50% (in 10% increments)
gain-resistance-chance (resistivity)	Probability that an individual does not commit an error due to learning effect (shield)	10% to 40% (in 10% increments)	20% to 50% (in 10% increments)

For traditional structures, design checks are not frequently conducted as opposed to regular checks under a BIM environment. Moreover, since individuals under traditional networks are not closely connected to each other and their interactions are limited to a few number of individuals within their teams, the probability for an error to propagate is lower than that in BIM social networks. As for resistance and recovery chance, BIM networks are assumed to maintain a higher rate given several defense schemes to be discussed in later sections. A 10% difference is assumed between the ranges of recovery and resistance chance of each structure as specified in Table 5.2. The input values are hypothetically selected and do not reflect any specific project. Further research and applications on real case studies is required to provide actual values.

5.2.2. Results of social network and simulations

The quantitative social metrics defined in Table 2.2 are calculated for both traditional and BIM structures. Results were calculated by Gephi software and are summarized in Table 5.3. They are divided into structure, node, and network metrics.

For the structure metrics, the graph type is selected to be “undirected” for both networks, where information exchange can happen both ways between individuals and does not follow a specific direction. Under the traditional structure, less players (nodes) are involved during the design phase as opposed to a more integrated BIM project environment early in the design phase. Nonetheless, the number of existing edges (existing connections between individuals who interact and exchange information) is higher for the BIM network as there is more collaboration and team work between and within the involved teams as opposed to traditional projects. The node metrics are averaged over the total number of nodes for each network. They represent average characteristic pertaining to every individual node such as their closeness to the rest of the nodes or their centrality (or importance) within a network. On average, the degree centrality and betweenness for nodes in the traditional structure mark lower values as compared to BIM-based networks (3.51, and 39.85 vs. 6.21 and 41.83 respectively). This indicates that individuals in a BIM environment are more equally connected to each other and can more easily reach others within their network. While the closeness metric has a higher value for traditional (3.04) compared to (1.79) in a BIM structure, but this value does not mean individuals are closer, but instead, the higher the “closeness” metric is, the more edges or hops are required to reach the rest of the nodes. The network metrics are related to the overall structure composition.

Table 5.3 - Gephi metric results for both structures

Type	Metric	Traditional	BIM
Structure	Number of Nodes	40	59
	Number of Edges	70	183
	Graph Type	Undirected	Undirected
Node (Averaged)	Degree Centrality	3.51	6.21
	Betweenness	39.85	41.83
	Closeness	3.04	1.79
Network	Density	0.09	0.11
	Avg. Clustering Coefficient	0.76	0.79
	Average Path Length	3.04	2.44
	Diameter	4	4
	Modularity	0.74	0.40
	Number of Groups	8	11

For the traditional structure, the average path length and modularity values (3.04 and 0.74 respectively) are higher than those for the BIM network (2.44 and 0.40 respectively). This indicates that, on average, an individual requires more edges and connections to reach to another individual in a traditional network, and that there are more connections within a team than there are be-tween teams. On the other hand, the BIM structure ranks higher on density, average clustering coefficient, and number of existing groups than the traditional structure. This relates to the existence of more nodes and more connections between project players in a BIM network as compared to a traditional network. As for the diameter metric, the value is the same for both structures as the size of the networks are not drastically different to be notable in the results.

Agent-based models that simulate the diffusion of design errors are prepared and run for both structures. To compare the error dispersion and containment between both networks, the simulations are conducted as per the parametric set up shown in Table 5.2. Four different combinations were performed for each structure, hence a total of eight scenarios were conducted for both networks. For each scenario, the initial-outbreak-size, error-check-frequency, and error-spread-chance (defined in Table 5.2) were fixed. The variation was performed over the recovery-chance and gain-resistance-chance under each scenario as shown in Table 5.4. For example, when the traditional structure has a recovery chance and gain resistance chance of 10%, it is compared to four BIM setups respectively having 20%, 30%, 40%, and 50% for both parameters. The minimum difference of recovery and resistance chance is suggested to be 10% for both structures, with BIM having the higher values in all scenarios. For each scenario, thirty-five manual iterations were performed, averaged, and plotted. Table 5.5 summarizes the results obtained from the plots in Figures 5.10, 5.11, 5.12, and 5.13.

Table 5.4 - Parameters for design error diffusion scenarios

Scenario	**1 (Figure 5.10)**	**2 (Figure 5.11)**	**3 (Figure 5.12)**	**4 (Figure 5.13)**
BIM	**Traditional**			
	10% recovery-chance 10% gain-resistance-chance	*20% recovery-chance 20% gain-resistance-chance*	*30% recovery-chance 30% gain-resistance-chance*	*40% recovery-chance 40% gain-resistance-chance*
20% recovery-chance 20% gain-resistance-chance	✓	-	-	-
30% recovery-chance 30% gain-resistance-chance	✓	✓	-	-
40% recovery-chance 40% gain-resistance-chance	✓	✓	✓	-
50% recovery-chance 50% gain-resistance-chance	✓	✓	✓	✓

Each iteration presents different sources of errors and different diffusion paths. The results of interest are the percentage of individuals the errors spread to and who are able to gain resistance and recover thus avoid repeating similar errors. The results also show the time (in weeks) it takes for the errors to diffuse and to be contained. The comparisons were arranged accordingly to allow mapping several combinations of each traditional error diffusion scenario under the given parametric range versus all possible BIM ranges. The plots represent the overall diffusion of errors and not only the initial outbreak. Results show that it takes more time for errors to diffuse and peak under a traditional environment (solid lines), but the percent of individuals who receive the error is always higher than those under the BIM configuration. Although errors spread and peak at a slower rate under the traditional structure, the time for recovery and gaining resistance (dotted lines) is slower than the BIM network.

Additionally, the plots within the BIM/ lean structure show that the higher the recovery and resistance chances are, the faster the error spreads and dies out, and the faster the recovery and resistance processes are. Not all individuals are able to become resistant and recover since the learning process and human capabilities vary between individuals. Thus, 100% error containment is an ideal to be pursued.

5.2.3. Model validation

An international panel of experts in the fields of lean, BIM, and social network analysis was consulted to seek their feedback on how well the models represent the characteristics of each environment and the validity of results of the experiments performed. The experts were asked to rank 8 aspects on a scale of 1 to 5, where 1 indicates the aspect being unreasonable and 5 being very reasonable. The aspects pertain to the inputs and outputs of the Gephi and NetLogo models. The responses are averaged and summarized in Figure 5.9. The averaged ranks for all aspects indicate that the inputs and outputs are fairly to highly reasonable, thus providing theoretical validity to the assumptions and results.

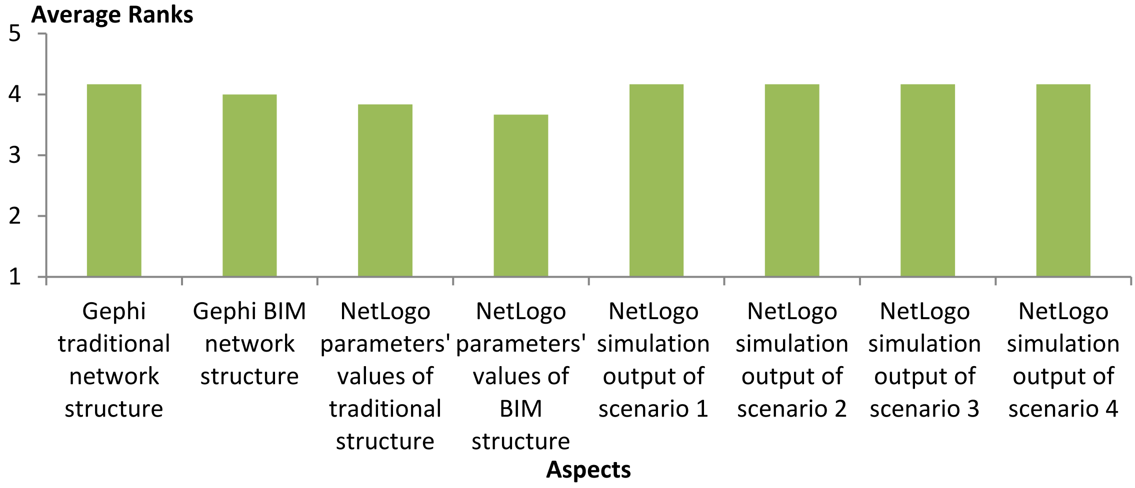

Figure 5.9 - Responses of expert panel members

Table 5.5 - Summary of simulation results of error diffusion scenarios

	Scenario Results	Peak time & % of individuals receiving errors	Peak % individuals gaining resistance	Time for error to be resolved and individuals to gain resistance
1	**Traditional** *10% recovery; 10% gain resistance*	84% after 16 weeks	70%	204 weeks
	BIM/lean *20% recovery; 20% gain resistance*	69% after 4 weeks	80%	82 weeks
	BIM/lean *30% recovery; 30% gain resistance*	56% after 3 weeks	80%	43 weeks
	BIM/lean *40% recovery; 40% gain resistance*	47% after 2 weeks	76%	26 weeks
	BIM/lean *50% recovery; 50% gain resistance*	41% after 1 week	76%	18 weeks
2	**Traditional** *20% recovery; 20% gain resistance*	63% after 12 weeks	70%	65 weeks
	BIM/lean *30% recovery; 30% gain resistance*	56% after 3 weeks	80%	43 weeks
	BIM/lean *40% recovery; 40% gain resistance*	47% after 2 weeks	76%	26 weeks
	BIM/lean *50% recovery; 50% gain resistance*	41% after 1 week	76%	18 weeks
3	**Traditional** *30% recovery; 30% gain resistance*	51% after 8 weeks	77.5%	45 weeks
	BIM/lean *40% recovery; 40% gain resistance*	47% after 2 weeks	76%	26 weeks
	BIM/lean *50% recovery; 50% gain resistance*	41% after 1 week	76%	18 weeks
4	**Traditional** *40% recovery; 40% gain resistance*	42% after 7 weeks	82.5%	28 weeks
	BIM/lean *50% recovery; 50% gain resistance*	41% after 1 week	76%	18 weeks

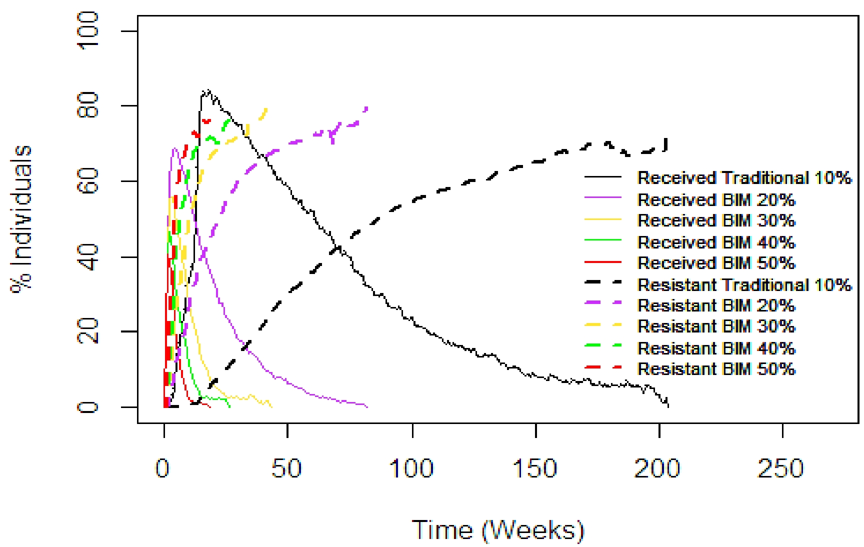

Figure 5.10 - NetLogo scenario 1 plots

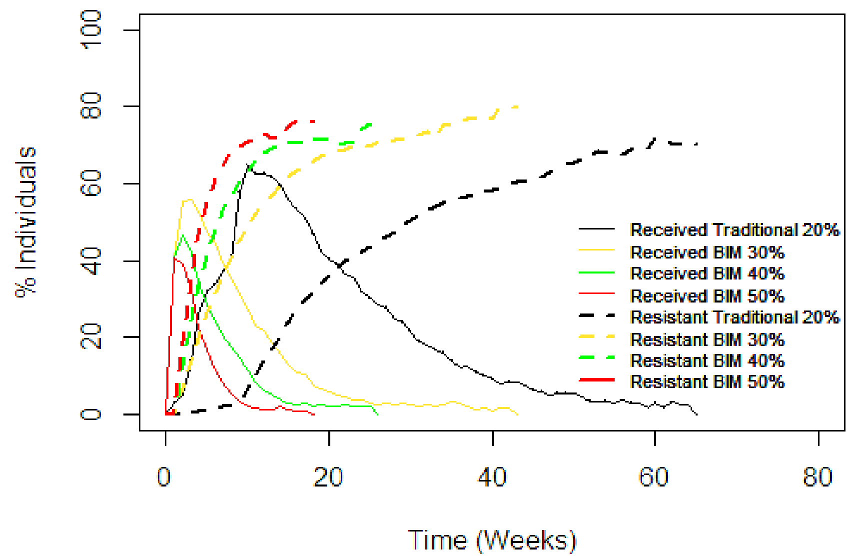

Figure 5.11 - NetLogo scenario 2 plots

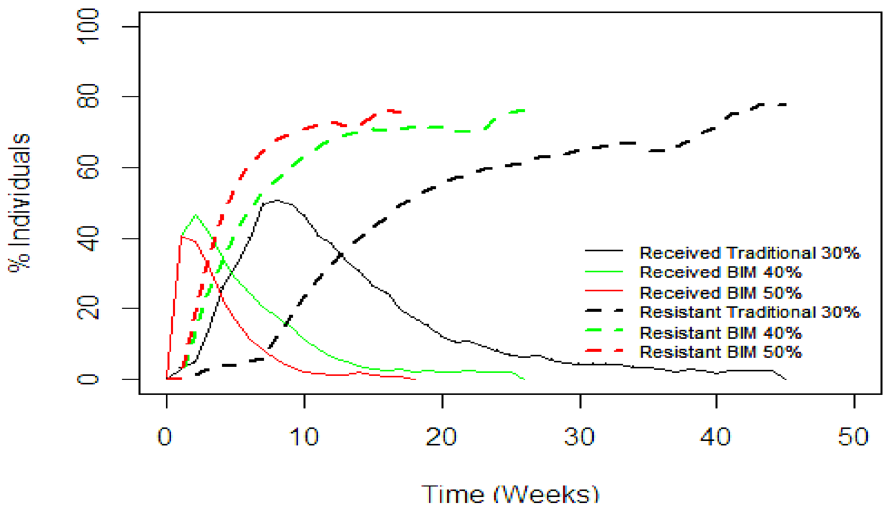

Figure 5.12 - NetLogo scenario 3 plots

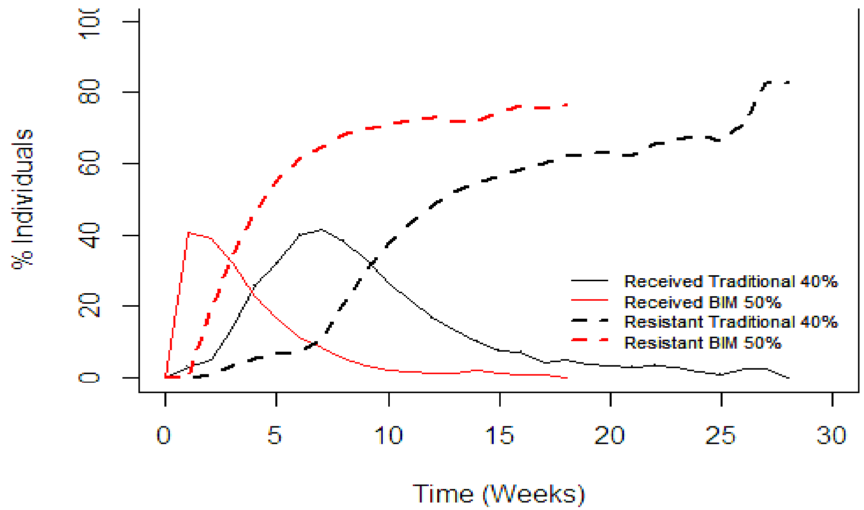

Figure 5.13 - NetLogo scenario 4 plots

5.2.4. Analysis and discussion

Social network structures

Early design collaboration and integration of construction expertise enabled by BIM are the main reasons for the different composition between both networks. For a traditional project structure that does not adopt BIM, only the architect and engineers are present during the design phase, where teams usually collaborate within their internal department. This explains the lower number of individuals present, the lower number of edges (lower connection across teams), and the higher network modularity as connections are only denser within teams but not between them. Within a BIM and collaborative environment, contractors, suppliers, sub-contractors, and other specialty engineers are involved earlier in the design phase, which helps merge the input and requirements of downstream players with those of the upstream in an information pull strategy. Not only more participants are present, but sharing information and collaboration, with the help of BIM to enable and facilitate this process, allows teams to connect to players external to their discipline and to decentralize the exchange of information and decision making. This justifies the higher network density and number of groups in the BIM structure. As opposed to the centralized control through the A/E on a traditional project, the process becomes decentralized when implementing BIM, which helps remove bottlenecks, stream-line data exchange, and increase the autonomous work of teams and individuals.

The resulting node metrics show that participants in a BIM-based structure are more equally central on average as they are almost connected to everyone else without one central player. In addition, the betweenness and closeness metrics show that in a BIM network, individuals are closer to each other and can reach the rest of the players in a shorter path, as opposed to the traditional network where an individual requires to pass through several connections to get to the person they need. This justifies why the average path length of the network, similar to the closeness metric, is higher for a traditional network. The comparison of both structures indicates that a BIM network is favorable for the exchange of information, with a faster ability to reach a larger number of individuals due to enhanced communication and collaboration. While the BIM structure is an adequate environment for the diffusion of useful information, the question of concern is how design errors would spread in a similar environment. One would assume that this structure would similarly allow design errors to disperse quickly and reach many individuals, which is not a favorable condition. This assumption is justified by the results showing that for a BIM structure, errors spread to the maximum number of individuals at a much faster rate as compared to traditional network behavior.

<u>Error diffusion simulation</u>

However, by examining the plots, we find out that errors die out at a faster rate in a BIM network as individuals detect and resolve errors by through frequent checking and communication. On the other hand, when comparing traditional and BIM structures at the same value of the recovery-chance and gain-resistance-chance (i.e. 20% for both parameters of traditional structure versus 20% for both parameters of BIM structure; 30% for both parameters of traditional structure versus 30% for both parameters of BIM/lean structure; etc.), the BIM simulation results show poor performance in design error management as summarized in Table 5.5. This shows that if the communication and information exchange patterns in a BIM/lean network are the same interactions as in a traditional environment, the system resembles a virus or disease spreading quickly in an environment of well-connected and interactive individuals with weak defensive mechanisms, as opposed to a less connected and interactive cluster of individuals where the virus slowly spreads and infects less people until it fails to find a host to multiply and spread. Therefore, the lesson learned from these results is that BIM should not be used under a traditional mindset of poor communication and fewer design-checks but instead exploit the several functionalities of BIM and inherent collaboration that can reduce design errors.

5.2.5. Conclusions on error management

Techniques enabled by BIM such as clash detection and automated code checking can serve as possible defense lines against the diffusion of design defects. By conducting regular design re-views, more accurate and faster approach of conflict detection, and code compliance checking, errors that could have easily passed undetected in the traditional approach would more probably be discovered through proper team work and high levels of BIM utilization.

Big-room meetings, design charrettes, and collaborative design under a lean environment, real-time visualization, and decision making enabled through BIM (Eastman et al., 2009; Love & Edwards, 2011) might be potential reasons for faster and smoother resolution of errors and mending information deficiencies between teams. This is in contrast to traditional structures, where individuals and teams do not perform continuous checking and design communications, thus allowing more defects to pass unseen and manifest in several deliverables. In addition, several human errors remain concealed and pass downstream un-checked. Hence, individuals assume the design is valid and pass it on to others who build the rest of their design on deficient inputs.

A long-term solution to design defects require addressing the root causes, which are human-based errors. Even if BIM technology enables automated checking procedures, individuals and teams need to develop and improve defense mechanisms within them. When a defect is detected, root-cause-analysis should be performed to find the fundamental causes, solution should be developed to remove these causes or mitigate their consequences, learn from these errors, and prevent their future occurrence. The resistance to errors as a recourse action emerges from a continuous learning attitude and instilling the quality at bay principle where each individual is made responsible for ensuring his/her design to be error free. Therefore, the use of BIM justifies the results of the simulation where resistance is gained faster.

CHAPTER 6

MEASURING AND ANALYZING DESIGN WORKFLOW

6.1. Integrating organizational and process dynamics

Maintaining a smooth flow of design information is key to a value adding transformation of design input into the client's value proposition, i.e., what the customer wants from the project. However, designers, planners, engineers, and constructors only focus on the transformation process, from input to output, ignoring what happens within the vague box of transformation source. While poor flow of information and design errors plague the design process resulting in delays, increased costs, and compromised design quality, available literature do not provide an in-depth study of problems in design communication networks.

In fact, perceiving the design process as a flow of information rather than a rigid segmentation and sequencing of design tasks can lend itself to a better design management approach (Ballard & Koskela, 1998). Such conceptualization is the foundation to finding ways to reduce the queued time for information before it is used, minimize time spent on reworking design information to meet requirements, and avoid unnecessary overproduction of obsolete data. More importantly, this perspective of design as information flow is crucial for the integration and coordination of multi-disciplinary information at a current time of increasing design complexity, sophisticated client needs, and a rapid proliferation of information from multiple geographically dispersed teams. With the presence of different project procurement approaches that call for more collaboration among project teams, and with the utilization of modern technologies, namely BIM, the need to evaluate their impacts on design workflow and to compare their performance to more traditional delivery approaches calls for a new perspective to better understand design workflow. Although defining what better design management entails and addressing workflow needs have been highlighted, a practical analysis of workflow characteristics and the influence of human interactions that shape these workflows in the context of BIM-based design processes and collaborative deliveries have not been considered or examined in depth.

A formerly unexplored perspective on workflow is one that integrates both the process, i.e., flow of design information, and the social network, i.e., interactions among design teams. The dynamics of information flow and interactions between design individuals are not considered when measuring design workflow. Some studies highlight the importance of realizing design and construction projects as social networks constituting design players and their communication (Pryke, 2004). Other studies develop a modeling method that links design tasks to the responsible people within a social network using network analysis (Parraguez et al., 2015), and also develop metrics of collaboration and team work and link them to the ability of information to reach people depending on their respective position in the hierarchical networks (Durugbo et al., 2011; Lopez et al., 2002). Although these studies give insight into the integration of design activities and people involved, they do not model the exchange of design activity information as input and output deliverables, which prevents the realization of design workflow patterns within such networks.

The integration of these segregate approaches remains absent resulting in incomprehensive analytical methods that fail to capture a realistic image of information flow within design networks. Considering this integration and communication between teams can reveal underlying mechanisms that impact information flow dynamics. Accordingly, the remaining part of this study approaches workflow at the intersection of the social and process aspects of design to understand, measure, and analyze information flow within a BIM network. ABM and SNA are used to dynamically capture the impacts of BIM on communication and workflow.

Some studies tend to isolate the topology of team interactions from the flow of information between individuals by only considering design task transformation while neglecting the flow of design information, or by targeting the social network structure of involved individuals and ignoring information diffusion, or by analyzing information diffusion and ignoring team coalitions. Figure 6.1 schematically describes the perspective of integration employed in this study that incorporates not only the communication structure, but also investigates what flows in the vague box of transformation where inputs are turned into outputs.

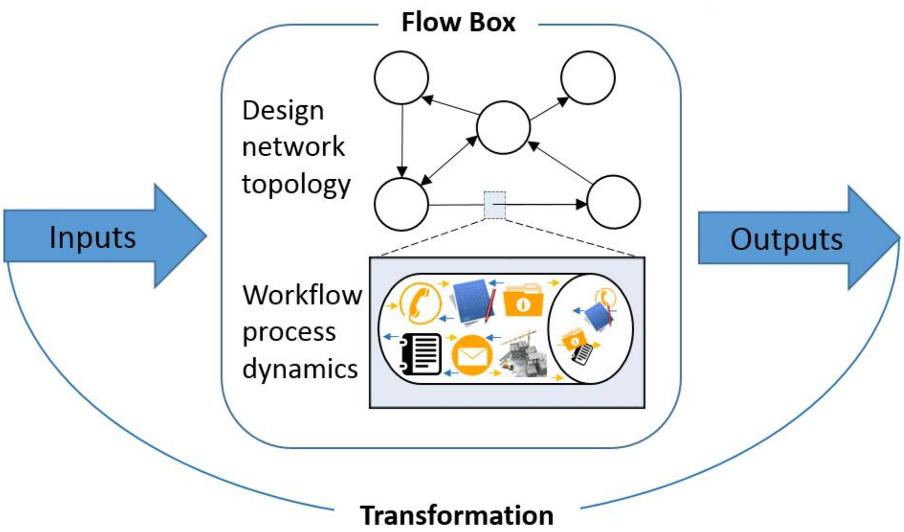

Figure 6.1 - Flow box of transformation

Module 2 of the methodology outlines the steps needed to measure and analyze workflow on BIM-based projects. Accordingly, the next sections present the framework setup that involves (1) the description of social network topology mapping process, (2) the modeling setup of the agent-based simulation model, (3) the development of workflow measurement metrics, and (4) the setup of the simulation experiments. These steps are explained based on a real-life case study of a design project.

6.1.1. Case study description

The case study selected for this research is a sub-project of an ongoing airport construction project in the Middle East. This building facility serves as a check point for all the airport staff when accessing from and to the air side. The contract type is a traditional design-bid-build type. The design phase under study was at the conceptual and schematic design levels, and the case was selected accordingly because it was still at the early phases where the design is most iterative and requires a lot of collaboration. Moreover, the design was “live” during the data collection process which enabled conducting surveys with the designers and observing the ongoing work processes and interactions. The design team is composed of 8 different disciplines such as the architectural, transportation, mechanical, and structural departments, a BIM development and support unit, as well as the managerial board. The project is BIM-based, where teams model their design using Revit. Given that most of the team members do not have a prolonged experience in the use of BIM software, the BIM development unit members assisted the designers with software related inquiries.

The social network topology of this project will be mapped using Gephi to determine the characteristics of its structure and assess the degree of collaboration. An agent-based model is then developed based on collected surveys and observations in order to measure workflow metrics and assess the impact of BIM on design information flow. The resulting workflow patterns of the case study are then compared to cases collected from the literature of BIM and non-BIM based projects to highlight the role of BIM use and maturity in affecting workflow outcomes.

6.2. Mapping the network topology

The design process of construction projects is a complex system consisting of a large number of individuals working within geographically dispersed teams with multiple backgrounds and trades who are all gathered to deliver a project with limited resources such as time, cost, and information. With current shifts in traditional design and project delivery and introduction of BIM-based design and life-cycle management, it becomes obsolete and ineffective to analyze design workflow independent from the interactions of these teams that bring about the design delivery process.

Using social network analysis, these interactions and the topology of connections between designers help to visually understand some characteristics of the social network structure. Not only does SNA help examine the structure of the relationships between the individuals, but also aids in studying the natural mechanics occurring within. SNA helps researchers understand the network data visually, convey the results of the analysis, and reveal any hidden properties that might not have been captured through qualitative measurement source. Quantitative analysis can also be performed to relationships, connections, and characteristics pertaining to an individual node and to the network structure as a whole. Metrics such as degree centrality which measures the number of links an individual has with others, the average path length that reflects the number of nodes required to reach the desired node, the betweenness metric that reflects a node's role in connecting nodes to each other, and other metrics defined earlier in Table 2.2, are used to analyze the structural attributes of the design network.

Such metrics reflect the environment of communication, where individuals might work as collaborative teams or as isolated entities, exist as segregated clusters or one coherent network unit, work within a centralized or decentralized decision making hierarchy, facilitate the flow of information or make it interrupted based on their interactions. Other insights can be obtained through the observation and analysis of network topologies.

In order to map the topology of the case study selected for this research, questionnaires were conducted with each member of the various design teams. There are 8 design teams: architectural, structural, mechanical, electrical, transportation, landscape and signage, resources and environment, and geotechnical, the BIM development and support unit, as well as the project and sustainability managers. A total of 38 members were interviewed. The questionnaires were administered face-to-face separately to each member in the same way to avoid biases, clarify all questions, and have open-ended discussions about their design processes and interactions. Moreover, the author was able to observe real-time design work of the participants and gather more insight about matters not addressed in the questionnaires.

6.2.1. Questionnaire design

The questionnaire, provided in Appendix A, consists of four main sections:

- *Section 1*: includes basic demographic question such as the profession, education, and years of experience of each person.
- *Section 2*: includes questions about the building information modeling process, the deliverables used for coordination and design information exchange, the design coordination and collaboration process, and what BIM is used for. This section is used for calculating collaboration metrics of the network.
- *Section 3*: asks each participant to list the people with whom he/she interacts within the scope of the design work. For each person listed, a set of information is required regarding the interaction and information exchange occurring, such as the modes of communication, the frequency of interaction, the use of information exchanged, etc. The names of the people, including the participant’s, remain confidential and will not be disclosed in any private or public analyses, and instead will be given alphanumeric codes (i.e., Name = EPE1, B9, etc.). The resulting data from this section are then used to map the social network topology in Gephi and calculate collaboration metrics, where links represent communication channels for each

person, the weight of each link reflects the frequency of communication, and the node size represents the role and importance of each member in the network.

- *Section 4*: includes questions that help gather information about the participant's design process: types of deliverables produced, time spent designing, reviewing and reworking deliverables, time spent collaborating and communicating with others, and other relevant information. The data gathered are used as input for the agent-based simulation model.

Figure 6.2 shows how the different sections of the survey are used for analysis, setting up the social network and calculating collaboration metrics, and as input for the agent-based simulation model.

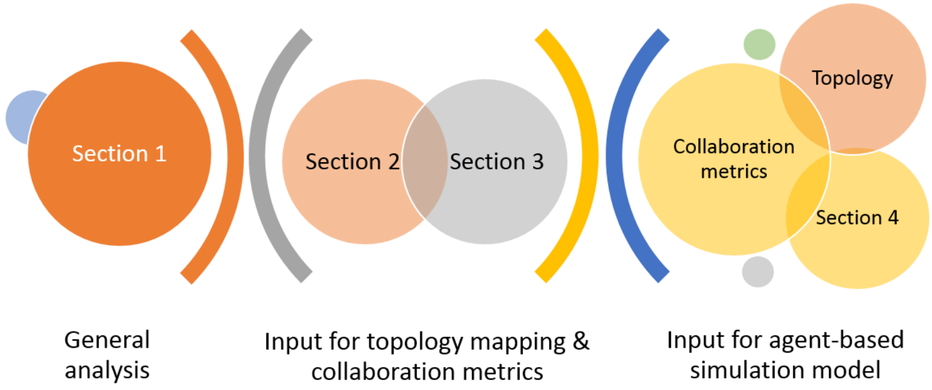

Figure 6.2 - Survey sections and uses

6.2.2. Collaboration within networks

Collaboration in design social networks requires a network where members and teams are interconnected and communicating often. Moreover, collaboration in design is needed to integrate experiences and backgrounds of different members to solve problems while contributing towards a common goal (Durugbo et al., 2011). Collaboration during early design stages is key to providing a shared understanding of common project goals and requirements. Collaboration plays a vital role in information exchange and achieving quality where collaborators can shape the structure and behavior of organizations by pooling their knowledge and expertise (Durugbo et al., 2011). Research interests have recently been directed to collaboration as modern day businesses are increasingly becoming dependent on collaboration and cumulative knowledge.

In order to measure collaboration attributes of the teams and individuals in the design project case study, indices developed by Durugbo et al. (2011) are adopted and implemented in this study. Teamwork scale, decision making scale, and coordination scale are used to measure the collaboration scale of each individual or the network as a whole. The scales are derived from social network measures for clustering coefficient (CC), closeness (C), and degree centrality (DC) because they reflect interconnectedness within groups and individual relationships. These scales are explained in Table 6.1.

Table 6.1 - Collaboration indices based on Durugbo et al. (2011)

Scale	Definition	Individual scale	Network scale
Teamwork scale (τ)	Reflects the activity of a person and connectedness within a cluster for teamwork	$\tau_i = (CC + DC) * \gamma_i$ where γ_i is teamwork constant based on ability of an individual to pool resources	$\tau = \frac{\sum_{i=1}^{N} \tau_i}{N}$
Decision-making scale (δ)	Reflects the ease with which a person can make decisions based on network relationships	$\delta_i = (CC + C) * \beta_i$ where β_i is decision-making constant based on ability of an individual to make choices	$\delta = \frac{\sum_{i=1}^{N} \delta_i}{N}$
Coordination scale (χ)	Reflects the ability of a person to harmonize interactions and activities	$\chi_i = (C + DC) * \alpha_i$ where α_i is collaboration constant depending on ability of an individual to harmonize interactions	$\chi = \frac{\sum_{i=1}^{N} \chi_i}{N}$

For each individual, these scales are calculated based on the resulting Gephi social network metrics of the case study to reflect the extent of collaboration present in the network. This collaboration is reflected by the ability of each individual to engage in teamwork by forming teams, to make decisions based on his/ her relations and interconnectedness in the network, and to coordinate activities with other individuals based on his/ her ability to harmonize work for maintaining or updating the flow of resources and information (Durugbo et al., 2011).The collaboration scales are then averaged for the entire network to reflect how the network's structure as a whole can foster or prevent collaboration. These scales combined describe the characteristics and level of collaboration at the organization where teamwork reflects the ability of members to coordinate work between each other as well as their ability to take decisions based on their collaborative knowledge and interactions.

6.3. BIM maturity score

A BIM maturity score is measured in this study in order to evaluate the level of BIM use and its maturity at the organization. Measuring the organization's BIM maturity will enable better understanding of its impacts on the design workflow patterns. The maturity matrix for assessing and improving a firm's or industry's BIM performance has been developed by Succar (2009a). The components of the BIM maturity matrix include many BIM Framework components defined earlier such as: (1) the BIM stages, (2) BIM maturity levels reflecting the extent of BIM abilities from the initial ad-hoc level through an optimized BIM level, (3) BIM competency sets categorized as BIM fields regarding policy, process, and technology, as well as the (4) organizational hierarchy scale reflecting a global market level analysis or a micro level of a member at an organization. The matrix can then be applied at the required granularity level depending on the purpose of BIM assessment and the scale of application. The developed framework and matrix serve to assess and improve BIM capability across teams and organizations to reach desired BIM performance standards and expectations (Succar, 2009a, 2009b).

For this research, the BIM maturity matrix is used in order to assess the BIM maturity of the design firm handling the case study project. The BIM matrix, in its expanded data-base driven form, includes all Capability Stages, Maturity Levels, and Organizational Scales and their respective maturity levels. The matrix is presented in Appendix B. BIM Capability and Maturity assessments can be employed at either one of three Capability Stages, one of twelve Organizational Scales, and at one of four Competency Granularity Levels (Succar, 2009a). .An assessment and reporting workflow has been developed by Succar (2009a) to manage these configurations as depicted in Figure 6.3.

In order to get a basic assessment of the firm's BIM maturity, the workflow is adopted to compute a BIM maturity score. The selected Organizational Scale is the organization (scale 9) reflecting the design firm responsible for the design of the case study project. The selected Granularity Level is discovery (level 1) for a basic and low-detail assessment of BIM Capability and Maturity at the design firm. The Capability Stage is modeling-based collaboration (stage 2) where multi-disciplinary interchange of models occurs between different departments. The Discovery scoring system is used for a simple and basic non-formal scoring of the organization's BIM maturity. This system follows a simple model:

- There are twelve individual scores relating to ten Competency Areas, one Capability Stage and one Organizational Scale (as detailed in Appendix B)
- Maturity Levels are assigned a number of points: "Initial" Level a (10 points), "Defined" Level b (20 points), "Managed" Level c (30 points), "Integrated" Level d (40 points), and "Optimized" Level e (50 points)
- The Maturity Discovery Score is the average of total points divided by twelve

The minimum Maturity Discovery Score is 10 while the maximum achievable score is 50. This scoring system is applied on the design firm of the case study and results are presented in the next Chapter.

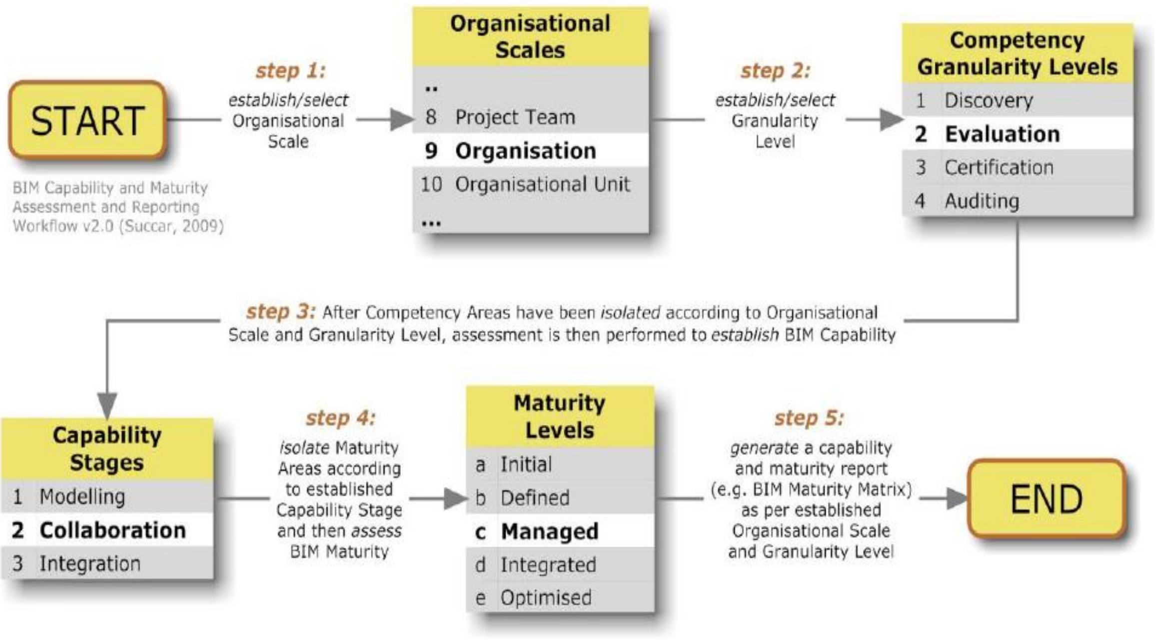

Figure 6.3 - BIM capability and maturity assessment (from Succar, 2009a)

6.4. Modeling workflow dynamics through ABM

After mapping the topology of the design social network, the dynamics of information exchange between design participants are modeled through agent-based simulation. Since these design processes and interactions are too complex, non-linear, and hard to capture through regular analytical mathematics, agent-based modeling will be used for this purpose. ABM specifies the rules or relationships of individual agent behaviors, the rules of their interactions, and results in an emergent behavior of the overall network of agents and their interactions (Macal & North, 2010).

While ABM takes a reductionist approach that transforms the real world into a simplified model, it more importantly allows to capture emergent behaviors of the overall network behavior that cannot be obtained by simple observations or assumptions of individual agent behavior, better understand how design information flows between participants, and underline the role of the social structure in influencing the diffusion of design information.

The environment considered in this research is the design social network topology, with a hypothetical schematic depiction in Figure 6.4, consisting of two types of agents: (1) the person (or individual within the design network) agent and (2) the design information deliverable agent. This topology represents the nodes as the people performing design or involved in the design decision-making process, the links (edges) representing interactions and communication between the people agents. The individual agent has attributes such as demographic information, number of connections he/she has, frequency of information exchange, time spent working, etc. The links, in earlier studies, have been regarded just as mere connections and what flows within them has been disregarded. These interactions as well as the exchange and interdependence of information create an emergence of new information and behaviors.

In order to account for information flow dynamics within these links, an information deliverable agent is created representing design information deliverables such as BIM models, design drawings, calculations, etc. The time spent under rework, design, review, or being queued, are also attributes that can be determined for a deliverable. The figure also shows the overall project social network attributes such as the type of the project, contractual setup, number of teams involved, and the network structure characteristics, which are important in understanding and justifying network behaviors and outcomes. The resulting simulation dynamics and trends of information flow can be obtained such as the total number of deliverables shared over the project duration, the amount of rework, and work-in-process present in the system.

The following sections describe the model setup using the AnyLogic® Simulation software, the empirical data collection process, the workflow metrics developed for assessing design workflow, as well as the uses and limitations of the developed model.

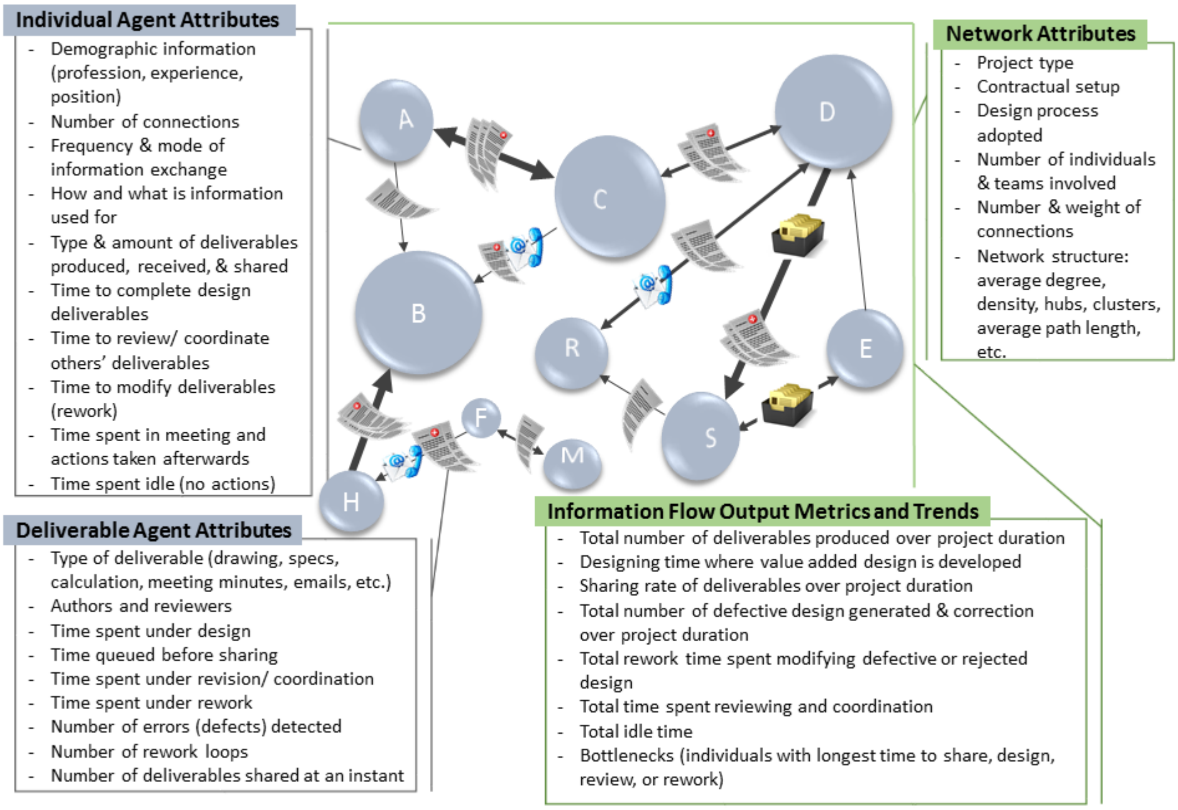

Figure 6.4 - Schematic depiction of topology and process dynamics

6.4.1. Agent-based simulation model setup

AnyLogic® is a simulation tool that performs discrete-event simulation, system dynamics, and agent-based modeling (Borshchev, 2013). AnyLogic® is used in this study to develop an agent-based simulation model for understanding and measuring design workflow under BIM-based design network topologies. To first understand the interface and process of the agent-based modeling approach, Figure 6.5 represents a schematic explanation of the environments, agents, and a brief setup process of the model.

The main environment is where all the agent groups and agents exist. In reference to the case study, the main environment mimics the design firm where the design participants perform their work. The sub-level of the main environment is the agent group or agent population, which represents a specific department team such as the architectural team or the structural engineering team. In each agent group environment, single agents representing a design team member exists. Finally, an embedded agent belonging to each single agent exists in the environment of the single agent. The embedded agent in the case study represents a design deliverable that is created by each design team member. Therefore, the ABM environments form different levels, the main environment being the macro level and reduces down to the micro level of embedded agents.

To setup the ABM model environments, the first step is to create the different agent groups in the main environment and define the connections (communication channels) between the groups. In order to collect output metrics for the entire project level, project level metrics are defined in the main environment. The next step is to define the number of team members in each agent group, setup communication channels for each member with the other agent group members, and define the cumulative output metrics for each agent group. The third step involves defining the behavioral states of each agent member throughout design and the conditions for transitioning from a behavior to another. The behavioral state chart will be discussed in more detail in upcoming sections. Moreover, the rules and conditions of interactions between agents are defined. In order to measure the resulting workflow of each agent, output metrics are also defined at this level. The final step regards the embedded agents (design deliverables) that are created by each design team member. The different states that the embedded agent goes through (to be detailed in the following sections), the conditions of moving from a state to another, as well as output metrics specific for each design deliverable generated are defined.

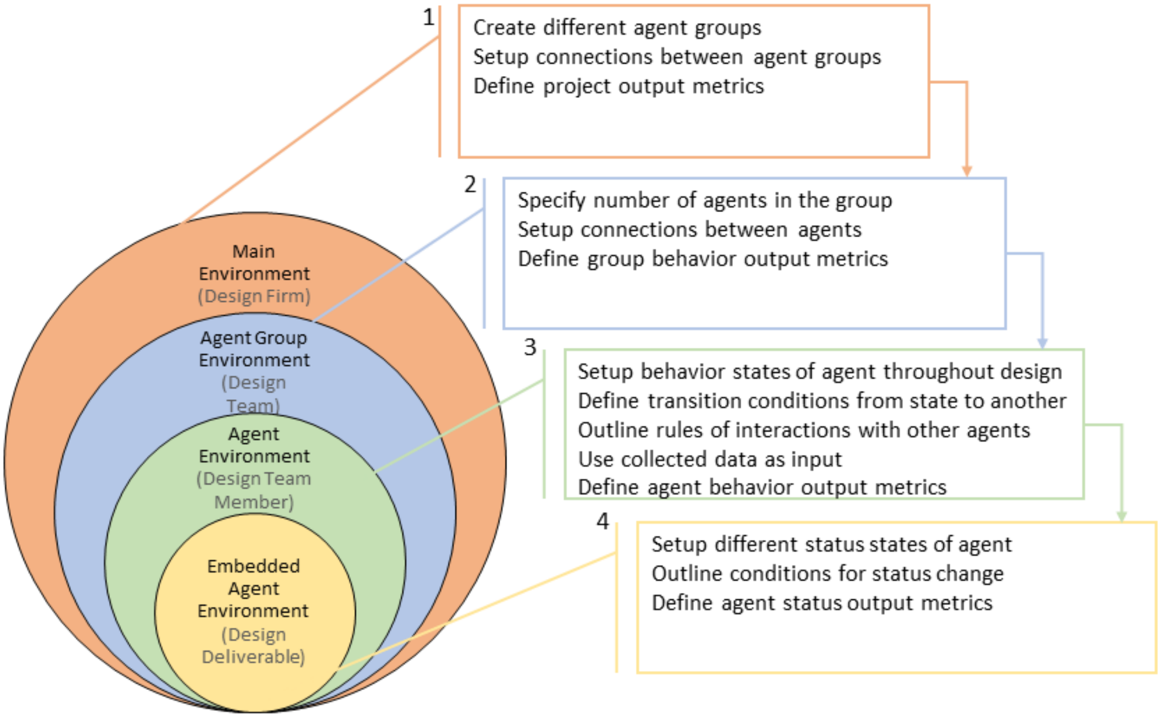

Figure 6.5 - ABM environment and process

6.4.2. AnyLogic ABM interface

- *Main and agent group environment setup*

The AnyLogic main environment is depicted in Figure 6.6. There are 10 agent groups as indicated in Figure 6.6 representing the 8 design teams (architecture, structure, transportation, etc.), the BIM design unit team, and the managerial board team. Variables are model elements used to keep track of project metrics of interest, such as the total number of design deliverables shared, produced, reworked, reviewed, etc. Moreover, for each agent group (design team), a similar set of variables is defined to collect agent group level metrics as discussed earlier. Other model elements depicted in Figure 6.6 such as Functions and Events are used to recurrently collect metric values in order to capture the workflow trends over the design period at every time interval. In the main environment, the connections between agent group members and the assigned reviewers of each member are also defined.

- *Agent (team member) environment setup*

Each agent group of the 10 groups has a defined number of agents (team members). For example, the agent group “archs” symbolizing architects is composed of 5 team members. For simplifying the explanation, an architect agent environment (a team member of the agent group “archs”, shown in Figure 6.7, will be examined. This agent is autonomous (runs without continuous user input), reactive (has a set of solution and decisions to take based on present conditions), info-gathering (it collects and classifies information), and adaptive (where it changes its behavior based on experiences, system behavior, and interactions). Moreover, it is important to note that each agent has a certain set of skills, work experience, competencies, and characteristics that can influence their behaviors. However, these factors are not explicitly considered in the simulation model for the purpose of maintaining a reasonable level of model control, but are qualitatively assessed through the questionnaire

The architect has a state chart that defines and controls the different behavioral “states” he/she typically goes through each day. Although each agent performs many other actions, only relevant and typical behaviors common to all members are presented for simplicity. An agent can have these interchanging states as shown: designing and modeling, sharing deliverables, reviewing design work, reworking or modifying deliverables that have errors or require changes, collaborating and communicating with other agents, and performing clash rework. The different states and transitions between the behavioral states are presented in Table 6.2 and Figure 6.7. For example, an architect produces one or several BIM models, “archModels”, or documents, “archDocs” that can be drawings, reports, calculations, etc. after several designing and modeling iterations.

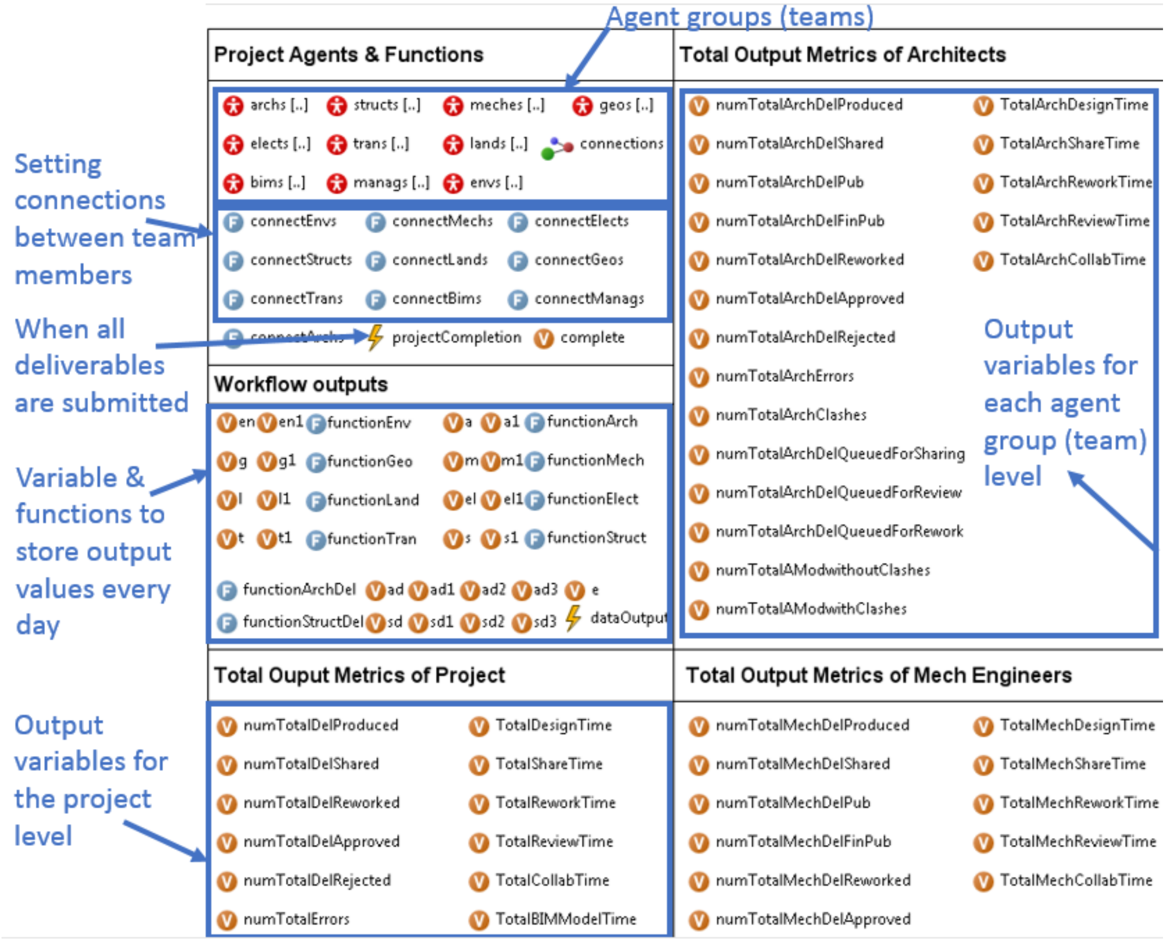

Figure 6.6 - Main environment (AnyLogic interface)

After generating design deliverables, the architect moves to the "Sharing" state in order to share the produced deliverables with other designers that are needed for their input. The produced deliverables that are shared are then queued for revision by those assigned as reviewers. The reviewers (which are also other agents) are notified that there are pending deliverables that need to be reviewed. When the agent needs to review a deliverable, a transition from the current state to the reviewing state occurs based on the received notifications. The same logic follows for the transitions between the different states. The interchanges or transitions from a state to another are dictated by interactions and "requests or messages" from other team members in the design process.

Table 6.2 - States and transitions of team member agent

State	Description	Transition process
Designing/ modeling	When a person is working on designing or modeling deliverables like BIMs, drawings, reports, etc.	When complete, the person is prompted to share the design work with others
Sharing	Upon designing, the person shares the design work through emails, logs, physically, etc.	When complete, the person moves to another state based on requests from others or work to be done
Reviewing	If there are deliverables that need revision, the person enters this state and reviews deliverables of other members	When complete, the person gives a decision: "errors" or "no errors" based on conformance, presence of errors, changes, etc.
Reworking/ modifying	When a deliverable requires modifications, the person enters this state and performs the needed changes	When complete, the person is again prompted to share the modified work for another cycle of revision and feedback from reviewers
Coordinating/ Collaborating	The person casually enters this state when he/she needs to collaborate with others and be involved in teamwork	When complete, the person goes back to other states in the state chart or based on requests from other team members
Clash rework	When rework is needed due to BIM clashes after clash detection	Exits the state when prompted to perform other actions

The time spent in each state is defined through the parameters indicated in Figure 6.7, such as "Tdesign" which is the time of each designing or modeling iteration and "Trework" which is the time spent amending errors or incorporating changes into deliverables. The inputs for these parameters are obtained through Section 4 of the questionnaires administered, where for each agent group, the provided values are averaged into stochastic ranges across its members and specified for each parameter. Moreover, the transitions between states and the behavioral state conditions are also based on the conducted interviews and observations from the work place.

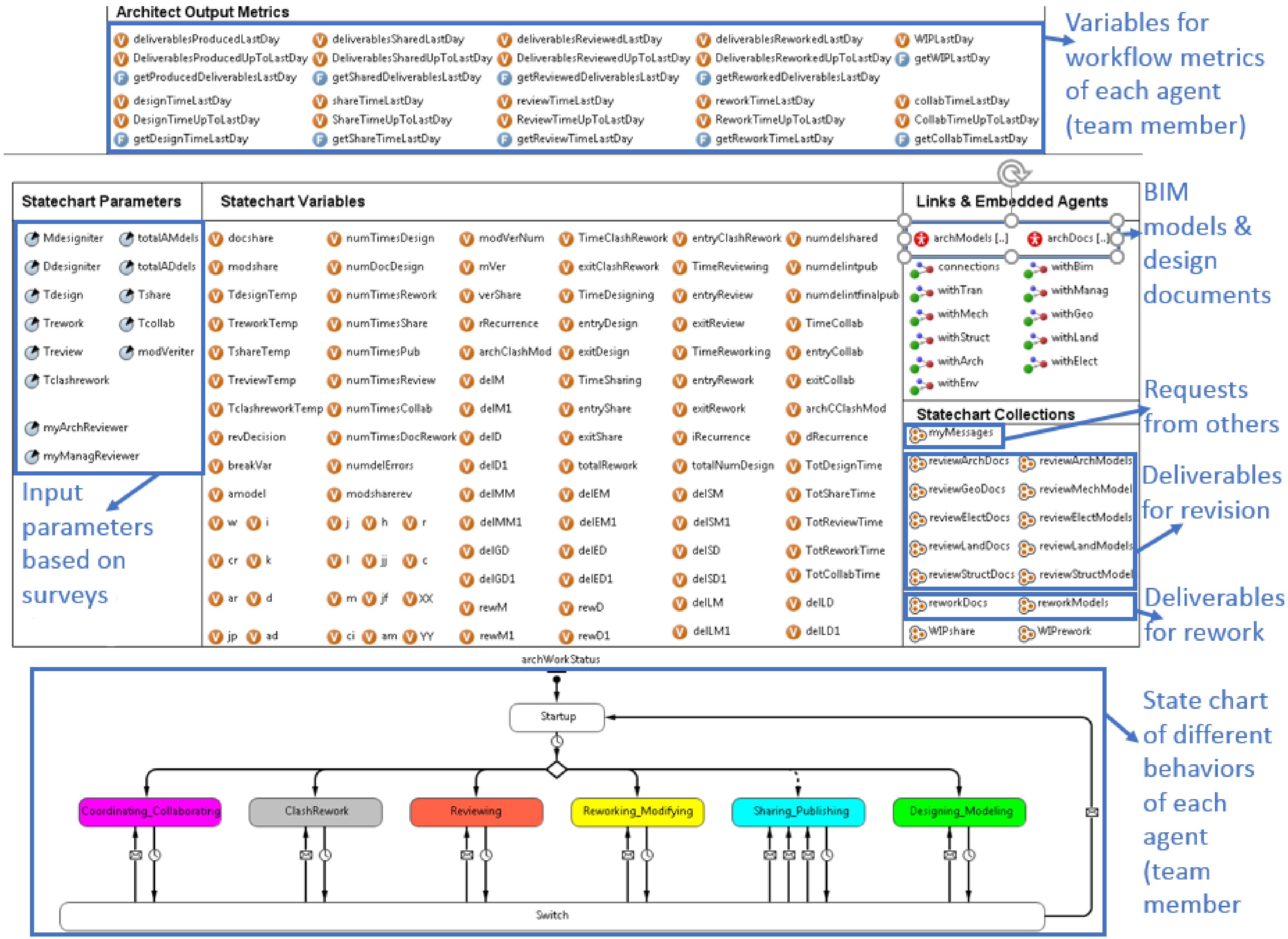

Figure 6.7 - Agent (team member) environment (AnyLogic interface)

- *Embedded agent (deliverable) environment setup*

Each team member produces different kinds of deliverables. For instance, an architect produces architectural BIM models referred to as “archModels” and/or other documents such as architectural drawings, reports, analysis referred to as “archDocs”. Similarly, a structural engineer produces structural BIM models “structModels” and other structural analysis, calculations, and reports referred to as “structDocs”. Each design deliverable produced, whether a BIM model or design document, has a similar state chart that reflects the different states a deliverable is in throughout design. These states are controlled by the behavior of the deliverable’s superior agent(s), the team members or the human agents.

A state chart of a typical architecture BIM model is selected for explanation and depicted in Figure 6.8. The different states it goes through are: “In progress” where the BIM model is still being modeled by the architect, then it is queued for sharing “Ready for sharing” on the system before completion for the use of other team members, then it undergoes other cycles of further modeling “Further progress” until it is complete for sharing on the system again “Ready for sharing1”. The model is then queued for revisions “Ready for review” before it is reviewed by the assigned reviewers where it enters the “Under Review” state. Since each designer has reviewers from within or outside the same discipline, the deliverable then enters different review decision states. For example, an architect has an assigned architect reviewer and the manager who checks the design as well. Therefore, the states “Okay by arch” and “Okay by manager” reflect if the design has passed the revisions conducted by the architect reviewers and manager, whereas “Errors_Changes by arch” and “Errors_Changes by manag” reflect the presence of errors or changes by the architect and manager. Moreover, if the deliverable is approved by the architect reviewer, the manager might detect certain errors or highlight changes needed. If there are errors or

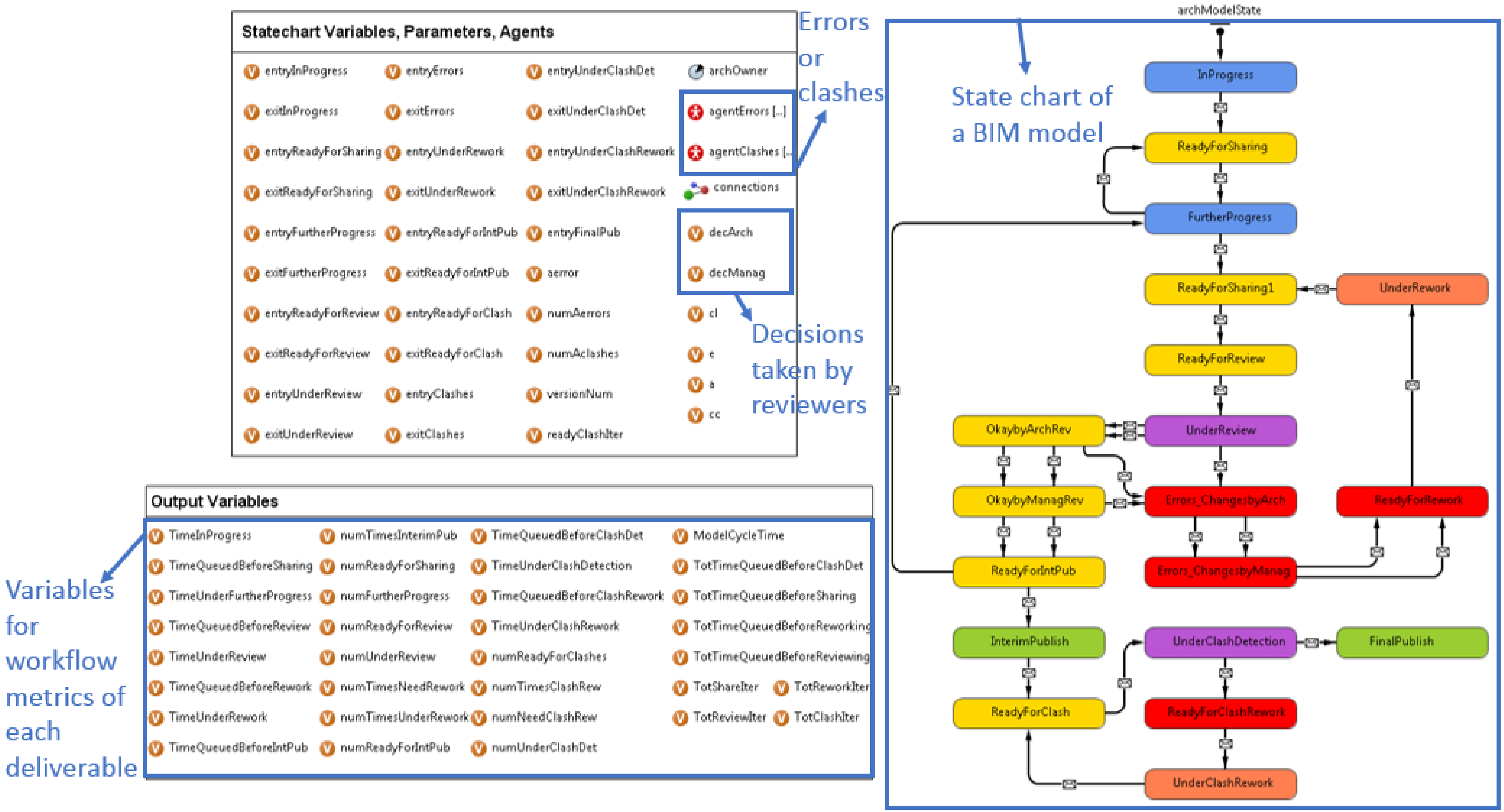

Figure 6.8 - Deliverable environment (AnyLogic interface)

changes, the deliverable is queued for rework “Ready for rework” before it undergoes rework “Under Rework” by the architect. The other states and transitions are explained in Table 6.3.

Table 6.3 - States and transitions of deliverable

State	Description	Transition process
In progress	When it is under modeling	Moves to ready for sharing when it needs to be shared for others’ use
Ready for sharing	When it is ready to be shared but queued before it is shared	Moves to further progress modeling when person shares it with others
Further progress	When it undergoes further modeling until it is complete	Moves to ready for sharing1 upon its completion
Ready for review	When it is ready for review but still queued for revision	Moves to under review when reviewers start reviewing
Under review	When it starts being reviewed by one of the assigned reviewers	When completed by first reviewer, it moves to a decision state by each reviewer “okay by reviewer” or “errors_changes by reviewer”
Okay by reviewer	If there are no errors or changes and conforms with requirements	Moves to second (third, etc) reviewer for his/her decision as well
Errors or changes by reviewer	If there are errors or changes needed or does not conform with requirements	Moves to second (third, etc) reviewer for his/her decision as well
Ready for rework	When it needs rework to amend errors or changes but queued for rework	Moves to under rework when designer starts reworking, and then moves to ready for sharing1 again
Ready for interim publication	When it is ready for interim publishing on the system	Moves to ready for clash detection when it is published on the system
Ready for clash detection	When it is ready for clash detection but awaiting all other models to be ready	Moves to under clash detection when the bim coordinator compiles all models
Under clash detection	When the bim coordinator compiles all models	Moves to ready for clash rework if errors are detected or published on system if there are no clashes
Ready for clash rework	When it is ready for clash rework but queued for rework	Moves to under clash rework when designer works on removing clashes and then to another cycle of clash detection
Published on system	When there are no clashes left in the model	This state marks the completion of the BIM model produced

The time spent in each state is controlled by the stochastic duration of each action performed by the designer and reviewers. The transitions are based on "messages" received from the designer or reviewers. For example, when a designer starts to rework the deliverable, the designer sends "Reworking" message to the state chart of the deliverable that moves it from "Ready for Rework" to "Under Rework" state. The duration spent in the "Under Rework" state depends on how long the designer spends reworking this deliverable. Moreover, the duration spent in each state and the number of times a state is triggered can also be collected for each deliverable. This gives insight into each deliverable for workflow analysis, which is discussed in the Workflow Metrics section.

In regards to the presence of errors or clashes in each deliverable, a certain probability is assigned to either create errors in the deliverable or not. Upon reworking, a certain probability is also assigned to fix these errors or clashes, which if not completely fixed, requires another cycle of revision and rework which is common in the design process.

The model setup is based on the questionnaires, informal discussions with project participants, and observations conducted by the author. The state charts of the team members as well as the deliverables were also checked with the BIM unit managers and coordinator to validate their logic.

6.4.3. Empirical data collection

In order to setup the ABM model, several inputs for the model and agents presented in Table 6.4 are required. The parameters for the agent (team member) discussed earlier such as "Tdesign" or "Trework" are needed as input for the behavioral state chart.

The input values are specified based on the questionnaires conducted with each member of the design team as well as data logs extracted from the project collaboration website (PCW) of the case-study project. The PCW is an online sharing portal where deliverables, files, and other documents are shared on so members can easily access the files. Specifically, Section 4 of the questionnaire asks the team member to provide the average time it takes him/her to complete a certain design deliverable such as a BIM model or design analysis report, the average time spent reviewing or modifying a design deliverable that has errors or requires changes, and the average time spent communicating and collaborating with others. When possible, the members were also asked to provide the number and type of deliverables they receive from and send to each other within a given day or week.

Table 6.4 - Inputs for model and agents

Inputs for model and agents	
Number of teams	Number of deliverables produced per agent
Number of members per team	Number of rework iterations per agent
Connections between members	Number of revisions done per agent
Time needed to design/model per agent	Frequency of collaboration per agent
Time needed to share/publish per agent	Frequency of sharing per agent
Time needed to collaborate per agent	Manner of sharing (batches or one at a time)
Time needed to review per agent	Manner of designing (one or several in parallel)
Time needed to rework per agent	Assigned reviewers of each agent

The project collaboration website is used to compile all data in one centralized online system for an automated management of project information and facilitating collaboration between teams. Some information from the data logs are used to validate or fill missing responses by the members, such as the time needed for rework (difference between the modification dates of different revisions of the same deliverable), number of rework and revision iterations (evident from the number of revisions for each document). The PCW logs the time each file is uploaded or modified, the original and modified size, creator, and modifier of each file, version number, as well as relevant comments provided by the users. The PCW provides a large coverage of file transaction processes during the project design phase and a reliable repository for easy access and perusal of users.

The two data sources are used to complement each other where certain exchanged information could not be tracked through one of them. On one hand, some team members could not recall detailed values they were asked to provide such as the number of deliverables they were exchanging per day or how many times they modified a certain information deliverable. On the other hand, some information deliverables are exchanged via emails or screen sharing phone calls, which are not formally logged to the PCW which, as a result, does not capture all actions and behaviors at every time interval. Therefore, by analyzing and merging two data sources, a more comprehensive and realistic modeling of design workflow is made possible. The results of the questionnaires from each member were aggregated and averaged. In order to adjust or validate some inputs provided by the members through the questionnaires, a sample of actions in the data logs extracted were filtered and analyzed for each member. Some results from the questionnaires and an analyzed sample of data logs are cross checked against each other and the validated adjusted outcomes are used as inputs in the ABM model.

Where certain data from the PCW were not available, the values provided by the members were cross checked against each other to ensure that there are no unjustified discrepancies in their results. In the case of outliers, the averaged values were used to replace these outliers. It is important to note that the purpose of simulation is not to replicate the exact design workflow process but to allow to measure and observe trends occurring in design processes. Therefore, the data used in the model from the case study serves to represent some reality and credibility of behavior of the system rather than using theoretical or hypothetical values.

6.4.4. Workflow output metrics

A set of output metrics are developed to measure workflow during the design phase. These metrics are calculated using the dependent output variables in the model. Workflow can be assessed by measuring the trends of design information sharing, the work-in-process (WIP), design production, amount of rework, amount of revisions, and how daily work is divided between the different tasks, which identifies value adding work from non-value adding work such as negative rework (non-value adding work that is repeated) and excessive revisions. These metrics allow to track workflow at the level of each agent (team member), agent group (team), and project level. Each metric is explained below and the respective equations at each level are presented in Table 6.6.

1. Design rate

This metric visualizes the designing and modeling trends of each team member, team, and project as a whole. It is calculated, for a single agent, as a percentage by determining the number of deliverables produced at a given time ($nDP_{i,t}$) out of the total number of deliverables produced by this member (TDP_i) and calculating the metric throughout the design phase duration. For the group, it is calculated by summing up the total number of deliverables produced by the team members at a given time ($\sum_{i=0}^{TMD} nDP_{i,t}$) and dividing it by the total deliverables produced by the team ($\sum_{i=0}^{TMD} TDP_i$) throughout design. The same applied to the project level. This metric allows to compare at each interval a member's rate to the average rate of the team and project to determine the member's design activity. Moreover, it allows to track whether design deliverables are designed concurrently or sequentially, which can reflect having more readily available design information for use or delays in acquiring the needed data by other members. The formula for each member, team, and project are shown in Table 6.6.

2. Share rate

The sharing rate metric visualizes the exchange patterns of design deliverables by each member, group, and the entire project. It is measured, for a single agent, as a percentage by determining the number of deliverables shared at a given time ($nDS_{i,t}$) out of the total number of deliverables shared (TDS_i). It is calculated at each time interval throughout the design phase duration. Similar to the design rate metric, this metric is calculated for the team level and project level. Sharing patterns can indicate interrupted flow if there are irregularities in the sharing levels across different time intervals. For example, there can be peaks of sharing (batches) before submission deadlines rather than a continuous sharing trend throughout design.

Table 6.5 - Definitions of acronyms used in Table 6.6

Acronym Definitions	
TDP_i: total number of deliverables produced by member i	**$nDP_{i,t}$**: number of deliverables produced by member i at time t
TDS_i: total number of deliverables shared by member i	**$nDS_{i,t}$**: number of deliverables shared by member i at time t
TDV_i: total number of deliverables reviewed by member i	**$nDV_{i,t}$**: number of deliverables reviewed by member i at time t
TDW_i: total number of deliverables reworked by member i	**$nDW_{i,t}$**: number of deliverables reworked by member i at time t
$TWIP_i$: total number of work-in-process for member i (queued for sharing, rework, review)	**$nDH_{i,t}$**: number of hours spent designing by member i at time t
TMD: total number of members in each design team	**$nSH_{i,t}$**: number of hours spent sharing by member i at time t
TM: total number of members working on the project	**$nVH_{i,t}$**: number of hours spent reviewing by member i at time t
TT: total number of working hours per working day	**$nWH_{i,t}$**: number of hours spent reworking by member i at time t
$nDQ_{i,t}$: number of deliverables queued (WIP) by member i at time t	**$nCH_{i,t}$**: number of hours spent communicating and collaborating by member i at time t

3. Review rate:

The review rate metric visualizes the revision patterns of design deliverables by each member, group, and the entire project. It is measured, for a single agent, as a percentage by determining the number of deliverables reviewed at a given time

($nDV_{i,t}$) out of the total number of deliverables reworked (TDV_i). It is calculated at each time interval throughout the design phase duration. Similar to the design and sharing rate metrics, this metric is calculated for the team level and project level. The revision trends allow to detect excessive revision cycles that indicate the presence and persistence of errors or changes. This in turn can reflect the need for rework, which is considered to be a major waste in design.

Table 6.6 - Design workflow metrics' formulas of members, teams, and project

Metric	Single Agent Level	Agent Group Level	Project Level
Design Rate	$DR_A = \frac{nDP_{i,t}}{TDP_i} x100$	$DR_G = \frac{\sum_{i=0}^{TMD} nDP_{i,t}}{\sum_{i=0}^{TMD} TDP_i} x100$	$DR_P = \frac{\sum_{i=0}^{TM} nDP_{i,t}}{\sum_{i=0}^{TM} TDP_i} x100$
Share Rate	$SR_A = \frac{nDS_{i,t}}{TDS_i} x100$	$SR_G = \frac{\sum_{i=0}^{TMD} nDS_{i,t}}{\sum_{i=0}^{TMD} TDS_i} x100$	$SR_P = \frac{\sum_{i=0}^{TM} nDS_{i,t}}{\sum_{i=0}^{TM} TDS_i} x100$
Review Rate	$VR_A = \frac{nDV_{i,t}}{TDV_i} x100$	$VR_G = \frac{\sum_{i=0}^{TMD} nDV_{i,t}}{\sum_{i=0}^{TMD} TDV_i} x100$	$VR_P = \frac{\sum_{i=0}^{TM} nDV_{i,t}}{\sum_{i=0}^{TM} TDV_i} x100$
Rework Rate	$WR_A = \frac{nDW_{i,t}}{TDW_i} x100$	$WR_G = \frac{\sum_{i=0}^{TMD} nDW_{i,t}}{\sum_{i=0}^{TMD} TDW_i} x100$	$WR_P = \frac{\sum_{i=0}^{TM} nDW_{i,t}}{\sum_{i=0}^{TM} TDW_i} x100$
WIP	$WIP_A = \frac{nDQ_{i,t}}{TWIP_i} x100$	$WIP_G = \frac{\sum_{i=0}^{TMD} nDQ_{i,t}}{\sum_{i=0}^{TMD} TWIP_i} x100$	$WIP_P = \frac{\sum_{i=0}^{TM} nDQ_{i,t}}{\sum_{i=0}^{TM} TWIP_i} x100$
Design Time	$DT_A = \frac{nDH_{i,t}}{TT} x100$	$DT_G = \frac{\sum_{i=0}^{TMD} nDH_{i,t}}{TMD * TT} x100$	$DT_P = \frac{\sum_{i=0}^{TM} nDH_{i,t}}{TM * TT} x100$
Share Time	$ST_A = \frac{nSH_{i,t}}{TT} x100$	$ST_G = \frac{\sum_{i=0}^{TMD} nSH_{i,t}}{TMD * TT} x100$	$ST_P = \frac{\sum_{i=0}^{TM} nSH_{i,t}}{TM * TT} x100$
Review Time	$VT_A = \frac{nVH_{i,t}}{TT} x100$	$VT_G = \frac{\sum_{i=0}^{TMD} nVH_{i,t}}{TMD * TT} x100$	$VT_P = \frac{\sum_{i=0}^{TM} nVH_{i,t}}{TM * TT} x100$
Rework Time	$WT_A = \frac{nWH_{i,t}}{TT} x100$	$WT_G = \frac{\sum_{i=0}^{TMD} nWH_{i,t}}{TMD * TT} x100$	$WT_P = \frac{\sum_{i=0}^{TM} nWH_{i,t}}{TM * TT} x100$
Collab. Time	$CT_A = \frac{nCH_{i,t}}{TT} x100$	$CT_G = \frac{\sum_{i=0}^{TMD} nCH_{i,t}}{TMD * TT} x100$	$CT_P = \frac{\sum_{i=0}^{TM} nCH_{i,t}}{TM * TT} x100$

4. Rework rate:

This metric visualizes the rework patterns of design deliverables by each member, group, and the entire project. It is measured, for a single agent, as a percentage by determining the number of deliverables reworked at a given time ($nDW_{i,t}$) out of the total number of deliverables reworked (TDW_i). It is calculated at each time interval throughout the design phase duration. Similar to the previous metrics, this metric is calculated for the team level and project level as well. The rework rate is a direct indicator of the presence of defective design deliverables or the introduction of changes that require several iterations considered as non-value adding time. While there can be positive iterations, having excessive rework over a short period is considered negative and wasteful.

5. Work-in-process (WIP)

WIP is the amount of work that has not been yet complete. In workflow terms, it reflects the number of deliverables that are queued for either sharing, reviewing, or reworking before any action is taken upon them. This is considered waste in design and can create bottlenecks that consequently disrupt workflow. It is measured for each member, team, and project as a whole. For a member, it is calculated as a percentage by dividing the total number of deliverables queued ($nDQ_{i,t}$) for sharing, reviewing, or reworking, at a given time by the total number of queued deliverables over the design phase duration ($TWIP_i$).

6. Design time

This metric measures the percentage of each day that is spent on designing and modeling. It is measured, similar to the other metrics, for each member, team, and project level. For a member, it is calculated by dividing the time spent designing ($nDH_{i,t}$) over the total number of working hours in a given day (TT). For a team, it is calculated by averaging the time spent designing for the team ($\frac{\sum_{i=0}^{TMD} nDH_{i,t}}{TMD}$) and dividing by the total number of working hours in a given day (TT). It reflects whether each day is majorly spent on value adding design or other wasteful non-value activities such as rework and excessive revisions.

7. Share time

This metric measures the percentage of each day that is spent on sharing design deliverables with others. It is measured, similar to the other metrics, for each member, team, and project level. For a member, it is calculated by dividing the time spent sharing ($nSH_{i,t}$) over the total number of working hours in a given day (TT). It reflects whether there are days where no sharing occurs at all as compared to other consecutive days that experience batch sharing. Such outcomes can indicate smooth versus irregular workflow trends.

8. Review time

This metric measures the percentage of each day that is spent reviewing design deliverables. It is measured, similar to the other metrics, for each member, team, and project level. For a member, it is calculated by dividing the time spent reviewing ($nVH_{i,t}$) over the total number of working hours in a given day (TT). This metric shows whether there is an excessive portion of the day spent on reviewing which indicates that more time is spent on non-value adding work and the presence of design errors and changes.

9. Rework time

The rework time metric measures the percentage of each day that is spent reworking design deliverables. It is measured, for each member, team, and project level. For a member, it is calculated by dividing time spent reworking ($nWH_{i,t}$) over the total number of working hours in a day (TT). Similar to the review time, this metric shows whether there is a lot of time spent on rework which reflects generation of wasteful time, presence of errors and changes, and interruptions to workflow.

10. Collaboration time

This metric shows the fraction of each day a member or team spends coordinating with others and collaborating with the teams. The metric is measured in a similar fashion as the previous metrics. It allows to indicate whether there is proper coordination and collaboration between the team members, which in turn can reflect, along with the other metrics, smooth or interrupted workflow.

- *Deliverable output metrics*

Aside from measuring workflow metrics for each member, team, and the project, the simulation model allows to track workflow attributes related to each design deliverable as well. Table 6.7 outlines the different workflow metrics for a deliverable with their respective descriptions.

Table 6.7 - Workflow metrics for design deliverable

Metric	Acr.	Description	Metric	Acr.	Description
Rework Iterations	WI	Number of times a deliverable is reworked throughout design	**% Review Queue Time**	VQT	Percentage of design lead time a deliverable spends in queue before it is reviewed
Review Iterations	VI	Number of times a deliverable is reviewed throughout design	**% Sharing Queue Time**	SQT	Percentage of design lead time a deliverable spends in queue before it is shared
Sharing Iterations	SI	Number of times a deliverable is shared throughout design	**% Non-Value Adding Time**	NVT	Percentage of design lead time that is non-value adding (sum of WQT, VQT, and SQT)
Design Lead Time	DLT	Time between deliverable start and completion	**% Processing Time**	PT	Percentage of design lead time a deliverable is designed, reviewed, and reworked
% Rework Queue Time	WQT	Percentage of design lead time a deliverable spends in queue before it is reworked			

The Rework Iterations metric measures the number of rework cycles a deliverable goes through throughout the design phase. It is measured daily not only to show the number of rework cycles, but also to show the rework trends over time. This metric helps identify deliverables with errors, non-conformance, and changes needed to be implemented. The Review Iterations metric, similar to the Rework Iterations metric, measures the number of revision cycles needed for a deliverable. A large number of revision cycles reflects the presence of persistent errors due to a lack of attention from the designer or design requirements that are not clear, or excessive changes to the design. In all cases, the excessive revisions and reworks reflect problems with workflow and communication as well as conflicts due to a lack of coordination and collaboration between disciplines. The Sharing Iterations metric measures how many times a deliverable is shared throughout the design phase as well as the trends of sharing, whether continuously or with large discrepancies between each sharing cycle. This allows, in parallel with the sharing rate of each team member, to check if the workflow is smooth or irregular.

The Design Lead Time is the duration between the creation of the deliverable and its final completion. An increase in the number of rework and revision cycles for each deliverable makes its Design Lead Time excessively longer than the average lead time of other deliverables. In order to measure idle time of a deliverable, the time a deliverable is held in queue before any action is taken upon it, a set of metrics are used: (1) % Rework Queue Time which is the percentage of time a deliverable is queued before it is shared out of its Design Lead Time, (2) % Review Queue Time which is the percentage of time a deliverable is queued before it is reviewed out of its Design Lead Time, (3) % Sharing Queue Time which is the percentage of time a deliverable is queued before it is shared out of its Design Lead Time, (4) % Non-Value Adding Time which is the total percentage of the Design Lead Time a deliverable is queued (sum of

WQT, VQT, SQT) and considered as non-value adding (waste) time, and (5) %Processing Time which is the total percentage of the Design Lead Time a deliverable is actually being designed, reviewed, or reworked, which is 100% - NVT . These 5 metrics allows to detect deliverables causing bottlenecks in the design and disrupting workflow. Deliverables with excessively longer queue times than the average queuing times are considered to be bottlenecks in the system. Bottlenecks are likely to disrupt workflow, resulting in undesired errors, extra fees, and longer cycle times. Team members causing these excessive queue times for the deliverable can be detected and the proper corrective measures can be performed to enhance the workflow.

The results of Sections 1 and 2 of the questionnaire, the resulting Gephi map and metrics, collaboration metrics, BIM maturity score, as well as the agent-based workflow simulation output metrics results are presented and discussed in Chapter 7.

6.4.5. Model verification and validation

In order to verify if the developed model correctly delivers the intended concept, several procedures were performed based on Bennett et al. (2013) to answer the question "Did we build the model right?": (a) evaluate the alignment of the model's scope and aims with the research intentions, (b) check validity of model input data and output consistency, (c) track performance through the model's visual interface where the different states and transitions are monitored throughout the design process while cross checking the values of the variables with the input data used, (d) monitor model logical performance through basic indicators such as the summing the lower level agents outputs and checking for equality with simulation output of higher level agents, and (e) perform necessary adjustments for a correct simulation of the research purpose.

After verifying that the model correctly implements the intended concept, a validation of the model's accuracy and credibility in representing the real system is required to answer the question “Did we build the right model”? (Law, 2014). Some techniques outlined by Sargent (2011) are used to validate the model, mainly: (a) face validation, where experts (the BIM manager and coordinator) in the field of BIM and design processes provided feedback regarding the credibility of the member’s and deliverable’s state charts and the model’s logic overall, (b) output validation, where some output from the model such as sharing trends are checked with sharing trends extracted from the project data log, and (c) triangulation of results (performed in Chapter 7), where results from different sources of evidence are cross-analyzed to check for convergence of results and conclusions which serve as a validation of the model’s setup.

The verification and validation steps performed for the model are explained in detail in the results chapter. Although the validation processes used do not cover all aspects of the model due to their complexity, they still provide a reasonable assessment of the model’s correctness and credibility in representing the BIM’s design process. Moreover, different project setups and contracts can yield a different model, therefore the model is case specific and represents a simplified version of the real system.

6.4.6. Model strengths and limitations

The model simulates the behavior of agents, their interactions, and the resulting workflows throughout the design phase. The developed model, like any simulation model, cannot fully capture the global system or replicate the same behavior and results. However, the actual purpose of the agent-based simulation is not to make decisions or predict future outcomes at this stage; instead, it is developed as an exploratory and experimental tool to explore different scenarios and understand underlying dynamics and mechanisms that lead to the observed outcomes. Moreover, the obtained results are not meant to mirror precisely what goes on between teams and members, yet these results serve to provide an in depth understanding of workflows occurring during design and highlight hidden trends that are hard to capture through usual observations or data log analysis. In fact, regular data log analysis conceals a lot of dynamics and human interactions that are at the core of how workflow is shaped.

Besides showing information flow trends such as sharing patterns of design deliverables, the model allows to show the distribution of daily member and team efforts between, for example, value added design and negative rework iterations. This enables researchers and practitioners to further understand the relationships between the achieved workflow trends and the underlying behaviors and interactions between teams. Going into a more detailed level, this approach allows to track and understand the process every deliverable goes through in the design phase from initiation to completion, to better detect and understand how and where bottlenecks are occurring. A deliverable can be tracked for time it spends being queued for revision, rework, or sharing, reflecting the amount of work-in-process in the system. Work-in-process in turn can help warn for upcoming bottlenecks that are likely to disrupt workflow, resulting in undesired errors, extra fees, and longer cycle times. The concept of the approach that integrates the social network topology along with modeling the dynamics of information exchange is applicable to any contractual and project setup. While the simulation model developed is specific to the case study, the model can be tailored to reflect the ongoing processes for any case study. This allows the concept to be usable and applicable to a wide range of design and construction projects.

The model includes potential limitations in the setup, data collection process and results' analysis. The model is a simplified representation of the real system, so some attributes of the agents are not explicitly modeled. Data and required input are subject to the respondents' personal knowledge and estimated values for certain answers of the questionnaire, whereas the data logs do not present a complete view of transactions performed where users do not log everything all the time. Moreover, questionnaire responses are subject to the respondents' bias and subjective feedback even though they are asked to be fully objective and honest. Consequently, the data used does not reflect the characteristics of all project types and conditions, but only reflects an estimated representation of the case study. Similarly, case study analysis is project specific where results might not be generalizable to the entire industry, even though they can provide important insights and inferences.

CHAPTER 7

ANALYSIS AND DISCUSSIONS OF RESULTS

7.1. Data triangulation of results

To achieve triangulation, different sources of evidence used in this research are used for the validation of the achieved results. Results from the surveys conducted, the social network analysis, the collaboration metrics, the BIM maturity score, the agent-based modeling, and the project database information are cross-verified and analyzed in light of each other to reach consenting conclusions and results. Figure 7.1 shows the different sources and the cross-analysis process for achieving triangulation.

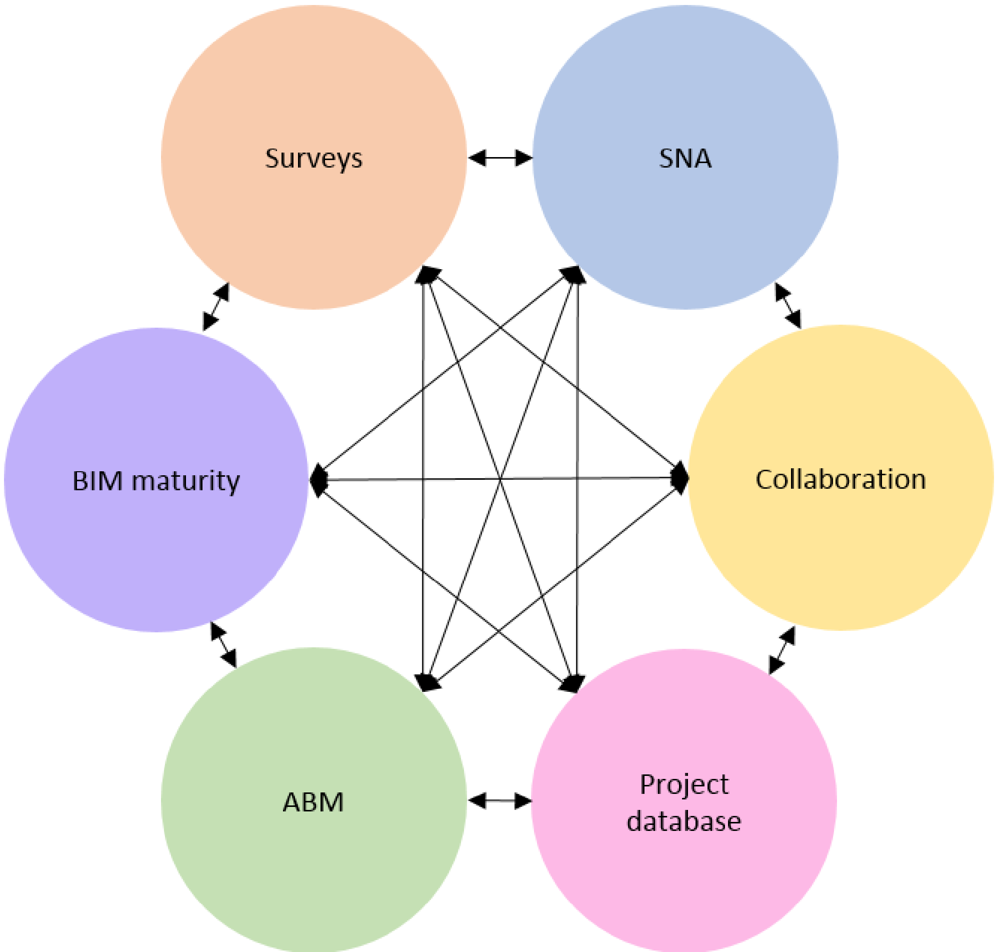

Figure 7.1 - Data triangulation from different sources of evidence

7.2. Demographic and BIM design process results

In order to set the ground for later analysis and discussion, the results of the demographic and BIM design process sections (Section 1 and 2) of the questionnaire are presented. The responses of the 38 design members were aggregated. Figure 7.2 shows the different percentage distributions of the professions involved in the design of the case study project, where about 20% of the respondents have an architectural background and profession, 15% work as structural engineers, 10% work in the mechanical department, about 39% of respondents are divided equally into 13% as electrical engineers, landscape and signage designers, and transportation engineers, whereas 8% are geotechnical engineers and the remaining 5% are resources and environmental engineers.

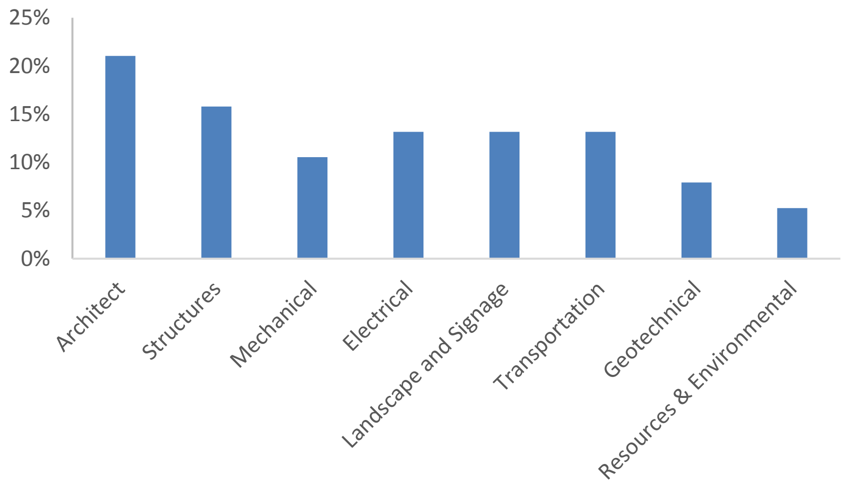

Figure 7.2 - Professions of participants

When analyzing workflow results, it is important to keep in mind that the designers are also involved on other projects, where the questionnaire results show that the majority of participants are involved in at least 2 projects at the time, where 18% of the respondents were working in 6 projects in parallel as shown in Figure 7.3. The BIM unit members are not involved in designing any specific project, but assist designers with their BIM modeling inquiries alongside their other duties.

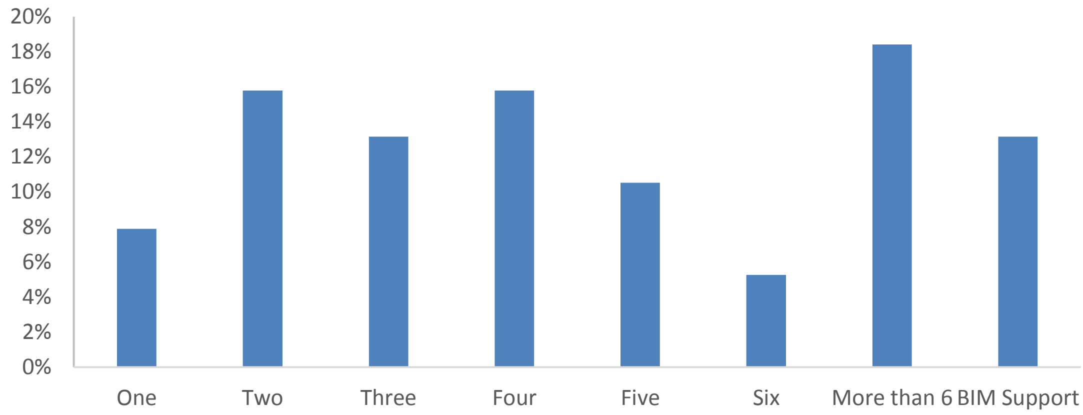

Figure 7.3 - Number of projects participants are involved in

The respondents were asked to indicate the number of years they have worked at the firm, in the industry overall, and the amount of BIM use experience. There is a wide diversity in the experience of team members, where 39% have less than 5 years of experience and 61% have more than 5 years of experience as Figure 7.4 shows.

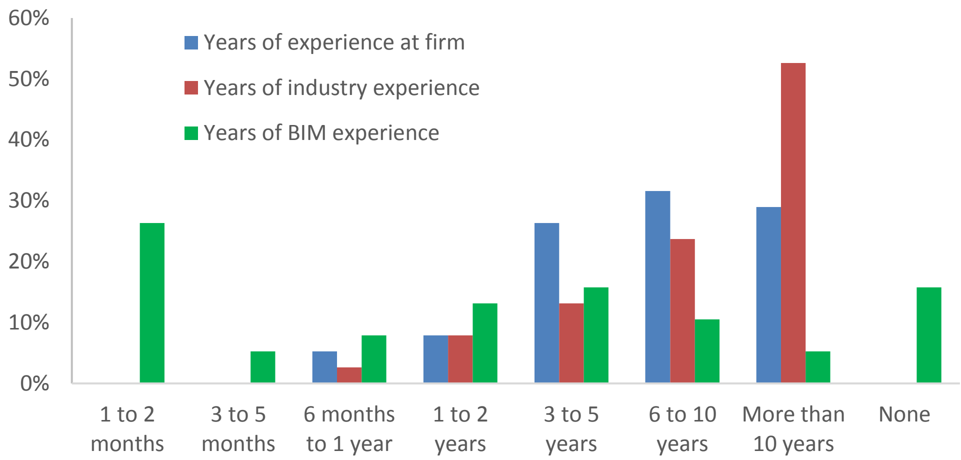

Figure 7.4 – Years of experience at firm, industry, and BIM

Regarding BIM use, the majority of the respondents (53%) have less than 2 years of experience using BIM, whereas 16% have no BIM experience at all. This is one of the reasons that a BIM support team is present to assist the designers in their BIM use, since many of them are new to BIM and have little industry experience overall, but have received the necessary training.

Section 2 of the questionnaire asked the respondents to answer questions about their BIM design process, such as their design and modeling environment, the deliverables along the BIM models they use to communicate and share their design, the BIM coordination process, as well as the reasons for which they use BIM (or think it should be used for). Results are shown in Figure 7.5.

Regarding the design and modeling environment, 61% of the responses indicates that BIM is used as the main design environment. Another 10% of the responses shows that BIM is used first for modeling then the needed information is extracted from it, whereas a contrasting 16% of responses reflects that first design is performed in other software, drawn in AutoCAD, and then modeled in a BIM tool. The remaining 13% of respondents do not use BIM.

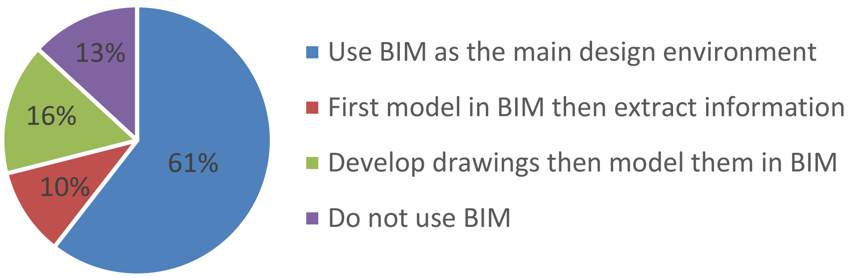

Figure 7.5 - Design and modeling environment

When asked why BIM is not used as the main environment, some respondents indicated that the used BIM tool becomes less efficient and too burdensome when using it for drawing design details, hence preferring to use basic AutoCAD for the parts of the model that require fine detailing. Moreover, some engineers perform design analysis and calculations in separate tools they are used to and believe are a lot more advanced than BIM-based tools. They then model the resulting design in BIM as requested by the design requirements.

Since BIM is not solely used as the design and modeling environment, the respondents were asked to state the different deliverables they use in order to exchange and coordinate their design information alongside the BIM models. 33% of these deliverables are design drawings extracted from the BIM models with an equivalent of 31% of drawings prepared in other tools such as AutoCAD. The other deliverables, as shown in Figure 7.6, are 12% calculations and analysis performed in other non-BIM tools. Only 12% of responses indicate the use of only BIM models as the main deliverables used for information exchange and coordination.

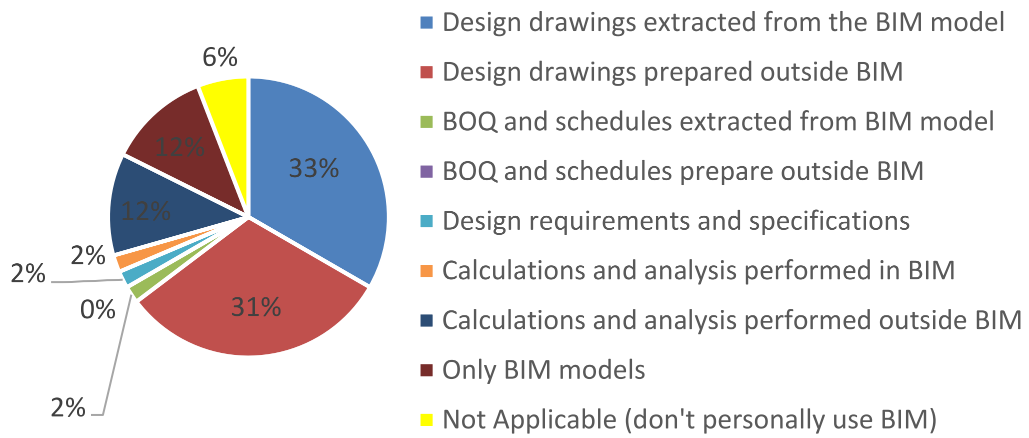

Figure 7.6 - Design deliverables used in addition to BIMs

Regarding the BIM modeling process, each designer has separate models for different parts of the project so that the BIM tool used does not get overloaded and prevent slowing down of the BIM tool's processing capability Only 20% of the responses indicates that the models are updated continuously on the system and merged into the central file for the team's use (within the same team). When the others were asked about the reason they do not update their models continuously for use by the project members, they mentioned that they avoid overwhelming their team members with constant updates and only share them when others ask them to or when they believe the model is ready to be shared.

The respondents were asked to identify the ways in which they use BIM and results are presented in Figure 7.7. 18% of the total responses for the choices indicates that BIM is used as a 3D model for representation and visualization purposes, and another 18% of responses shows that designers using BIM also use it or are aware that it is used mainly for clash detection. The third BIM use, with 16% of total responses, is for the coordination and sharing information between different disciplines. Although BIM is not yet used for facility operations and management at the firm, 11% of the responses indicate that the respondents are aware that is it an open database for the facility's lifecycle information.

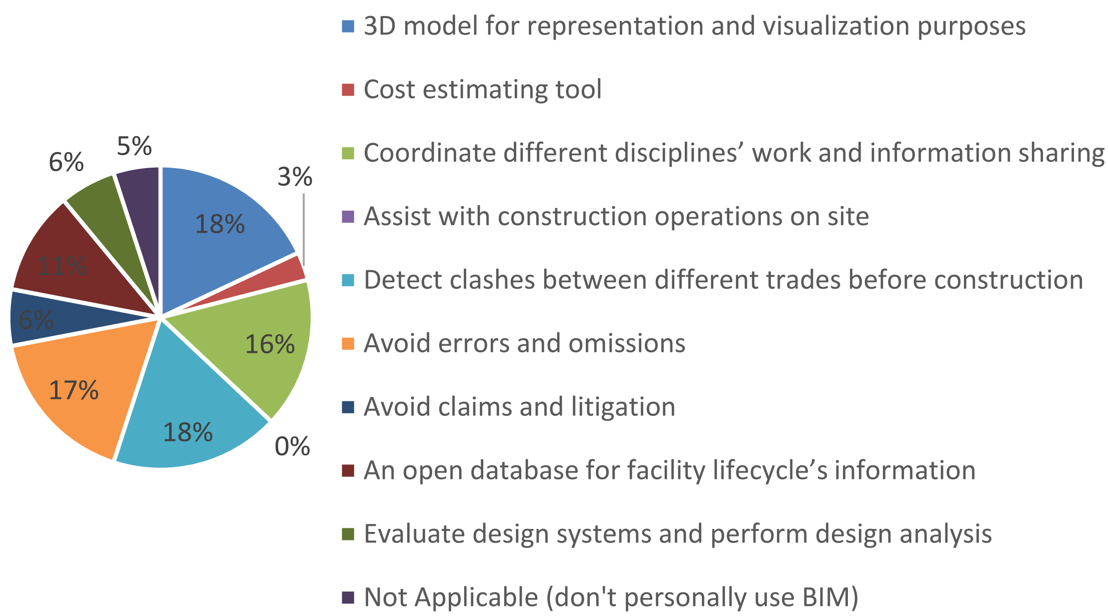

Figure 7.7 - BIM uses

When asked about the BIM design coordination process, most of the respondents indicated that they sometimes meet up with members from within and outside their team to coordinate their design models and deliverables. They also agreed that the BIM coordinator is responsible for collecting the BIM models and performing clash detection to highlight conflicts between different trades. When asked how frequently clash detection was performed, most respondents mentioned that it occurred before the submission to the client for the sake of merging all parts of the project into one whole project. Clash detection was not requested at this stage and was thus not performed for detecting conflicts at this design level.

7.3. Network topology results

Mapping the communication network between project participants serves as a preliminary tool to gain some insight into the interaction processes during the design phase. The topology of the design social network is mapped in Gephi based on the questionnaire results of Section 3. To build the topology map, results from each participant pertaining to the individuals he/she interacts with and the frequency of these interactions were used from the questionnaires. Figure 7.8 shows the resulting Gephi map with the alphanumeric codes defined in Table 7.1.

The spatial configuration of the network resulted from the application of the Force Atlas 2 algorithm in Gephi. This algorithm allows nodes to repel like charged particles while connections are attracted like springs to eventually converge to a state of balance (Jacomy et al., 2014). The resulting topology can help with the visual interpretation of the data by showing proximity and remoteness of communities of nodes. The resulting network consists of 38 nodes representing the different design participants such as the architects, electrical engineers, BIM support team members, managers, etc. The links shown in Figure 7.8 represent the communication paths existing between the different nodes within the same department and across different disciplines. The nodes form 223 links within the network with different weights (link thickness) reflecting the frequency of communication between two nodes.

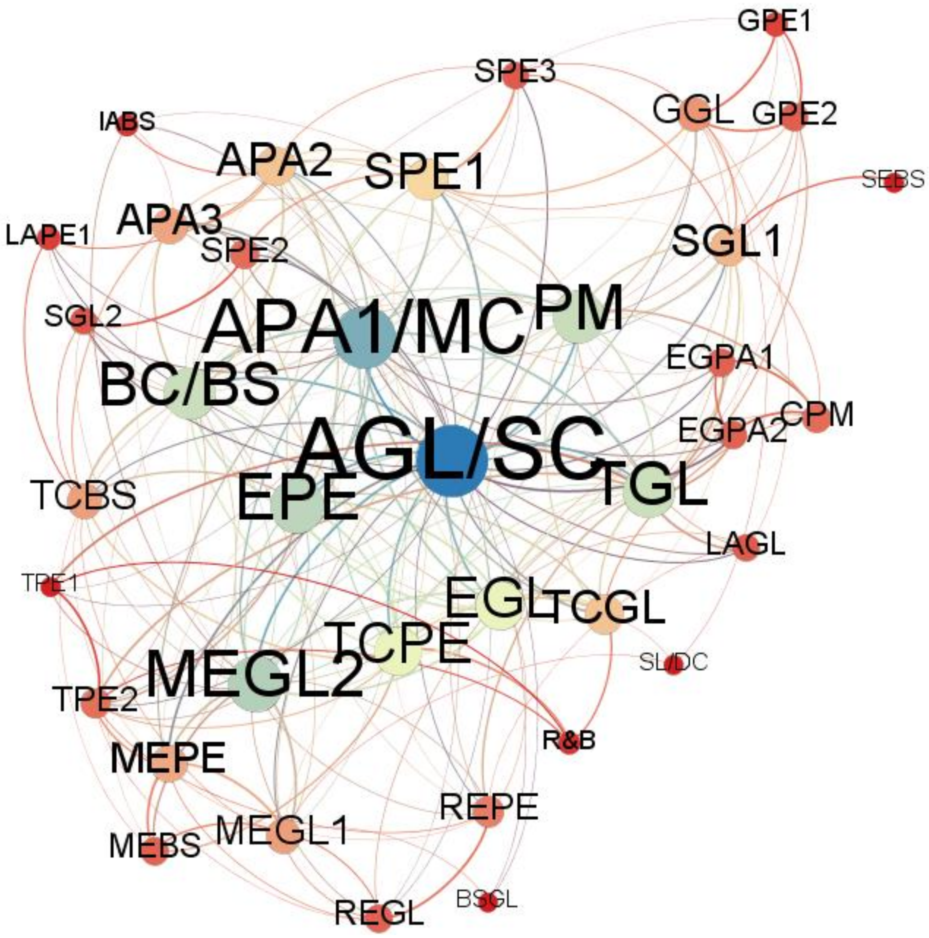

Figure 7.8 - Design social network topology (Gephi, Force Atlas 2 algorithm)

Table 7.1 - Definitions of codes in topology map

Code	Definition	Code	Definition
PM	Project manager 1	**GCL**	Geotechnical group leader
CPM	Project manager 2	**GPE1**	Geotechnical engineer
SL/DC	Sustainability leader	**GEP2**	Geotechnical engineer
BC/BS	BIM coordinator and support	**LAGL**	Landscape architecture group leader
MEBS	Mechanical BIM support	**LAPE1**	Landscape architect
SEBS	Structural BIM support	**EGPA1**	Signage graphic designer
TCBS	Electrical/telecom BIM support	**EGPA2**	Signage graphic designer
IABS	Interior/architect. BIM support	**MEGL1**	Mechanical group leader
AGL/SC	Architecture group leader	**MEGL2**	Mechanical group leader
APA1/MC	Architect & model coordinator	**MEPE**	Mechanical engineer
APA2	Architect	**SGL1**	Structural group leader
APA3	Architect	**SGL2**	Structural group leader
BSGL	Building safety group leader	**SPE1**	Structural engineer
EGL	Electrical group leader	**SPE2**	Structural engineer
TCGL	Telecom group leader	**SPE3**	Structural engineer
EPE	Electrical engineer	**TGL**	Transportation group leader
TCPE	Telecom engineer	**TPE1**	Transportation engineer
REGL	Resources & environ. leader	**TPE2**	Transportation engineer
REPE	Environmental engineer	**R&B**	Transportation sub-consultant

An initial observation of the topology map shows a clustered network without the presence of separate communities. Communities are formed when there are only in-between connections among nodes of the same discipline and low or absent interactions between a node and nodes from other design teams. The absence of major notable isolated community structures upon the application of the Force Atlas 2 indicates that the design discipline type does not really affect how nodes connect with other nodes in their network. However, the links are thicker between nodes of the same design discipline than the links between a node and nodes of other design teams. This reflects that communication is more frequent between similar design team members than with members of other teams.

When analyzing the extent of communication, the density of links is considered to determine how much connections exists between the nodes out of the maximum possible number of connections in the network. The maximum number of links in an undirected (two-way communication) network is N*(N-1)/2 where N is the number of nodes. For 38 nodes, the maximum number of possible links is 703 links. However, with only 223 existing links in the resulting map, the density of the network is only 0.32 as shown in the metrics calculated in Table 7.2. A 32% density is considered as a sparsely connected network with sporadic connection trends observed in the map where it is relatively denser in the middle and sparser at the peripheries.

Table 7.2 - Values of SNA metrics

Metric	Average Value	Standard Deviation
Number of nodes	38	-
Number of links	223	-
Graph density	0.32	-
Average degree centrality	11.74	7.55
Average closeness centrality	0.58	0.09
Average path length	1.78	-
Average betweenness centrality	14.42	22.67
Average clustering coefficient	0.63	0.22
Network modularity	0	-

To further evaluate this matter, the degree centrality of the nodes is considered. The average degree centrality for a node in the network depicted is 11.74, which means that on average an individual is connected to about 12 other nodes out of a maximum of 37 possible nodes (32%) in an ideally connected network, reflecting the sparse density value obtained. Moreover, the standard deviation of degree centrality between the different design members is 7.55 showing discrepancies between individuals. In fact, when observing the map, it is evident that some nodes are more prominent (larger node size) than other nodes in the network (smaller node size).

Referring to the expanded table of the social network and collaboration metrics, which is provided in Appendix C, as well as to the network topology map, 6 main nodes can be highlighted in the network with the highest degree centralities: the AGL/SC (30), the APA1/MC (27), the MEGL2 (27), the BC/BS (26), and the PM (25). These results are not surprising due to the roles played by these members, where the architecture group leader (AGL/SC) and model coordinator (APA1/MC) are responsible for coordinating, reviewing, instructing, and facilitating the design with the rest of the members. Their vast experience in architectural design and coordination with other design disciplines makes them central to the flow of information in the network. Similarly, the mechanical group leader (MEGL2) is a prominent member in the network where mechanical works require a high level of coordination and management with the rest of the design teams. The BIM coordinator (BC/BS) is also dominant in the network as he is responsible for the support and coordination of all BIM related matters with the teams as well as the management members due his high level of BIM competency and know-how. The project manager (PM) is responsible for managing the project overall, providing instructions, dealing with any arising problems, and supervising the design works, and coordinating matters with the Client. In contrast, other members of the network play less prominent roles and are less connected to the rest of the nodes such as some project engineers with degree centralities as low as 1 and 3.

If the hubs of the network are to be removed, the network becomes less cohesive, the density will further decrease, and the remaining members will need to go through other more nodes to reach the desired node. The number of steps needed to reach a desired node in the network is known as the path length. In this network, the average path length is 1.78 (about 2 steps), meaning that it takes one additional intermediate member to reach the desired node. The inverse of the average path length is the closeness centrality measure that measures how near a node is to others. The average value calculated is 0.58 reflecting that an average node is about 58% close to the rest of its connected nodes, which is around half of the network members. The value is neither low nor high, but it would be preferable if members were connected to a much larger portion of the network. If the hubs are removed, members will need more intermediate nodes to reach each other. In fact, prominent nodes or hubs play a brokerage role in connecting others, like a bridge. This notion is reflected by the betweenness centrality metric shown in Table 7.2 with an average value of 14.42. This value means that on average, a node lies on 14 communication paths, i.e., it amounts up to 14 bridges in the network for other nodes to connect to each other. Due to the uneven distribution of roles of the nodes, the resulting standard deviation of this metric is 22.67 reflecting a wide discrepancy in the prominence and influence of certain members over others. For example, the AGL/SC has a betweenness of centrality of approximately 90 where as a structural project engineer (SPE3) has an approximate value of 1. This reinforces the presence of a centralized system where information flow is majorly controlled by the hubs of the network, whom if removed, will disrupt vital communications that other less connected nodes depend on for acquiring information.

Additionally, when these hubs become too busy, they will form bottlenecks and hinder information sharing, decision making, and design aspects depending on these hubs.

Modularity and clustering coefficient metrics allow to detect the prevailing presence of communities and closed triads in the network. The earlier observation of the map with the Force Atlas 2 configuration does not reveal the presence of multiple separate communities. This observation is in line with the modularity metrics where its value is zero, confirming the absence of multiple distinct communities. Yet, the average clustering coefficient value of 0.63 indicates that the network forms a clustered system to some extent but with isolated member pairs that, if connected with other isolate member pairs, could have resulted in distinct communities. These measures support the initial observations that the design discipline type does not directly affect how nodes connect with other nodes in their network, and nodes form connections regardless of their design background.

When examining the links between nodes, it is important to look into the type of these interactions. Results from the surveys regarding the modes of communication between design participants reveal further insights into the nature of the existing links and node-to-node interactions. Each participant was asked to specify, for each person he/she interacts with, the modes of communication used with their respective percentage use. Figure 7.9 shows that, on average, only 16% of communication modes are performed through informal face-to-face discussions and only 12% of interactions occur through official project meetings. On the other hand, the rest of these connections occur through phone calls (supported with screen sharing) and emails, with 31% and 41% of the time respectively. The relevant design data (drawings, models, calculations, specifications, etc.) discussed in these interactions are also placed in the project's database repository for relevant members to access. Moreover, discussions with the members revealed that the main mode of communication between members of the same team is informal face-to-face discussions, whereas the majority of interactions between a member and members of other disciplines occurs through phone calls, emails, and formal meetings. Therefore, although the design discipline does not influence how members connect with each other, the mode of communication differs if it is within the same team or across different teams. The solid line in Figure 7.9 represents a trend of how the quality of information exchanged changes under different communication modes. The solid line represented is based on translating descriptions of communication modes studied by El-Tayeh and Gil (2007) into a graphical trend line. The percentages of communication quality are only approximations to qualitatively show the changes between different modes.

If not understood or interpreted properly, design will be plagued with errors, some of which can be detected through the conflicting design documentation and analysis. However, other errors will pass unnoticed and manifest during the construction period. With engineering design being a highly visual process, the mode of communicating design is crucial in avoiding the misunderstanding and misinterpretation of the design intent. In this regard, face-to-face interactions and meetings provide synchronous social communication that has rich content in terms of the underlying knowledge and experiences of the members being exchanged (El-Tayeh & Gil, 2007). Moreover, it enables real-time visual analysis of the design where informed decisions can better be supported. As a result, the quality of communication enabled through informal face-to-face interactions as well as formal meetings is higher due to the more effective and information rich exchanges. Although some participants noted in the survey that they consider meetings and face-to-face teamwork to be time consuming, they were content with the outcomes of such interactions. As mentioned earlier, most of the communication occurring between members within the same design discipline occurs through informal face-to-face interactions due to the physical proximity of their members. Formal meetings are set up for members of different disciplines to meet and discuss design and progress related issues as stipulated by the contractual agreements.

On the other hand, phone calls and emails constitute the largest portion of the communication modes, and are most dominant between interactions of members of different disciplines. However, the quality of information exchange decreases with such means where a lot of information and design intent gets misinterpreted and misunderstood due to the ambiguity and limited problem solving capabilities (El-Tayeh & Gil, 2007). During phone calls, even those supported with screen sharing options, the social interaction and common knowledge and experience shared between members is hindered and reduced over such calls. Similarly, emails do not provide real-time problem solving and still maintain a high level of ambiguity and unclear intents. User perceive that phone calls and emails are most useful for confirming or clarifying issues, but fail to support the deep exchange of ideas, solutions, and information (El-Tayeh & Gil, 2007).

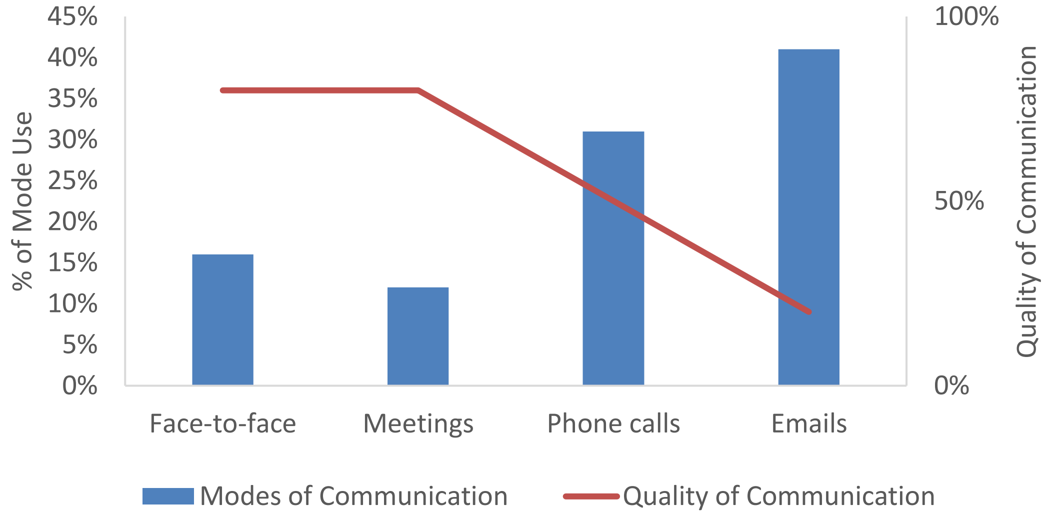

Figure 7.9 - Modes and quality of communication
(solid line represented is based on translating descriptions of communication modes studied by El-Tayeh and Gil (2007))

Therefore, observing the links as they exist in a social network map is not sufficient to understand the underlying types of communication. For example, there are no detectable communities in the network. This implies that members were connecting with other members regardless of their design discipline background. At first, this observation reflects a well clustered network. However, a more in depth analysis of the type of communication revealed that the quality of in-team communication occurring through physical face-to-face meetings is higher than between-team communication happening over phone calls or via emails. Therefore, it is not only important to consider the number of existing links or how they form, but also the quality of such interactions controlled by the means of communication is also critical in understanding the social mechanisms occurring during the design phase.

When considering a network topology under an ideal BIM-based environment, the expected structure would have a much higher density where most of the nodes are connected with each other. Moreover, there will be less prominent hubs that control the flow of information and more of a de-centralized structure instead. Under the decentralized structure, all nodes have the same influence more or less and the network becomes more fertile for more accessible flow of information. In addition, a utopian BIM environment would foster more collaboration where it supports an integrated project delivery environment. Under an IPD environment, more players from the construction phase will be present early on in design to provide construction know-how for more informed decision making (Hickethier et al., 2013). Such IPD projects that use colocation may have better communication. In contrast, traditional design environments exhibit a more centralized structure with dominant hubs that majorly influence the flow of information. This renders the network prone to communication challenges if the hubs are removed. Moreover, traditional networks following the classic design project hierarchy exhibit the formation of small communities where members only communicate with members within their design team and are thus isolated from the rest of the network (Al Hattab & Hamzeh, 2015; Chinowsky et al., 2008). Compared to the ideal BIM environment on one hand and the traditional design delivery topology on the other, the existing BIM-based design process of the case study falls in between both structures, where it exhibits minor aspects of BIM such as the absence of community formations where members communicate with other network members, as well as other aspects of centralization and hubs formation characterizing traditional network structures.

7.4. Collaboration metrics results

Collaboration can take on different levels (Maier et al., 2008): (1) level one is the lowest collaboration level where individuals solely look after their own tasks, do not know or think of common goals, and do not identify with teams; (2) level two of collaboration is where collaboration happens only if it is asked for to fulfil certain tasks but members still follow their own goals in small groups that form to achieve these tasks; (3) the third level of collaboration occurs proactively for members to learn and improve their experiences and approaches, members start considering ways to achieve the common goals through more team work; and (4) level four is the highest level of collaboration where it happens continuously and constructively; members clearly understand the common goals and continuously improve and assess them, and team identity is reflected upon, maintained, and strengthened. In order to quantitatively assess the collaboration level on the network considered in this study, the different collaboration indices introduced earlier in Table 6.1 are calculated for each member as well as the network. The values of teamwork, decision-making, and coordination constants and their resulting indices for each member are presented in Appendix C.

Based on qualitative responses to survey questions regarding members' perceptions about collaboration and frequency of teamwork, the constant values were assumed to range between 0.3 to 0.5 for members who do not play central roles in the network, and values of 0.7 for the hubs. The average network collaboration indices, standard deviations, and respective percentages out of the maximum possible values are presented in Table 7.3.

To better analyze the results shown in Table 7.3, an understanding of the team work scales, decision making scales, and coordination scales is required. A) The teamwork scale assesses the activity and interconnectedness of a member within a network and his/her tendency to identify with teams towards common goals (Durugbo et al., 2011; Maier et al., 2008). This scale is a function of the clustering coefficient and degree centrality. The more central the person is in the network and interconnected within a team, the more likely he/she is to support teamwork and understand the value of common goals. The more isolated a member is, he/she is less able to be engaged in teamwork and reflect on the purpose of collaboration. The case study results show that the average teamwork scale for the network is 7.47 representing only 19.70% of a maximum value of 38. This low value shows that teamwork is not a leading feature in the existing network. This is primarily due to the sparsely connected members as well as the overall attitude towards teamwork during design. By examining individual teamwork values, the resulting standard deviation is 5.57, which is a wide discrepancy between different individuals. For example, the AGL/SC and APA1/MC rank 21.24 (55.90%) and 19.15 (50.40%) respectively due to their high degree centralities and natural roles played as teamwork facilitators. In contrast, LAPE1 (a landscape engineer) and EGPA1 (an environmental engineer) rank 2.90 (7.6%) and 3.86 (10.1%) respectively due to their minor positions in the network topology and their less involvement in teamwork efforts. Note that all of these results are project specific, i.e., these will be different on a different type of project.

Table 7.3 - Average values of collaboration metrics

Metric	**Average Value**	**Standard Deviation**	**Maximum Value**	**Respective Percentage**
Average teamwork scale	7.47	5.57	38.00	19.70%
Average decision-making scale	0.68	0.19	2.00	34.00%
Average coordination scale	7.45	5.69	38.00	19.60%

B) The decision-making scale assesses the ease with which a member can make decisions based on its closeness (reach) to the rest of the members in the network and its interconnectedness within the network cluster (Durugbo et al., 2011). Decision-making depends on acquiring the needed timely information easily and the consensus from the network members. Therefore, this scale is a function of the closeness centrality and clustering coefficient. The result of the network decision-making scale is 0.68 representing only 34.00% of a maximum value of 2. This indicates that on average the members have less than half the possible decision-making ease. This is mostly a result of the fact that the members are only half close to the rest of the network members and are not clustered with the entire network. The standard deviation does not vary greatly between different members because the closeness centrality and clustering coefficient metrics are similar for most of the members. This result means that the members cannot easily retrieve timely information since they are not very close to all the required members and are not clustered with the majority of the network to acquire consensus on their decisions.

C) The coordination scale assesses the ability of members to organize interactions in order to maintain and update the flow of information and other resources (Stempfle & Badke-Schaub, 2002). It is therefore a function of both the degree and closeness centrality. It is not only important to be directly connected to people in order to coordinate work and maintain good information flow, but also the degree of closeness to the indirect members can determine how easily this information can flow between members in order to harmonize tasks. The resulting network coordination scale is 7.45 representing only 19.60% of a maximum value of 38. This value reflects the low presence of proper coordination in the network which can further be justified by examining member coordination indices. The differences between member's values from the overall network average are large as indicated by a standard deviation value of 5.69. The AGL/SC and APA1/MC both have the highest values of coordination due to their integral position and role in the design phase. Their values of 21.59 (56.81%) and 19.45 (51.18%), respectively, are much higher than other isolated and less connected members such as EGPA2 with 2.76 (7.26%) and LAPE1 with 2.75 (7.23%) values. Similar to the teamwork scale values, the wide differences in the degree centralities make the more prominent members more capable of coordinating work, whereas the isolated and farther members are less capable of harmonizing interactions with others.

Under a utopic BIM environment, the collaboration metric results are expected to be much higher due to the collaborative interactions that BIM processes advocate. Under highly collaborative environments, members are continuously involved in team work and have strong sense of belonging to the project team as a whole (Maier et al., 2008). Moreover, goals and objectives of the project are clearly identified and understood by the members. This is expressed by proper and continuous communication and harmonized interactions to reach them (Durugbo et al., 2011; Maier et al., 2008). On the other hand, traditional project environments have transactional contracts and punitive approaches that does not encourage collaboration. Team work only happens occasionally when called for by the contract agreement, and members seek their own benefit and do not relate to a project level team identity (Chinowsky et al., 2008). Due to having highly centralized and controlled decision-making, only a few players steer the project towards the desired objectives. The case under study exhibits more characteristics from traditional project based collaboration. This is due its relatively low values of the collaboration scales where the resulting values show that coordination, teamwork, and decision making are relatively low with major discrepancies between different members in the network. Moreover, the prevailing network structure of the case study is centralized with the presence of hubs and other loosely connected members. Therefore, the design network in this study is more similar to traditional design networks although it utilizes the BIM technology.

7.5. BIM maturity score result

To have an informal assessment and gain some insights into the BIM maturity and practices of the organization where the case study took place, a BIM Maturity Discovery Score, developed by Succar (2009a), is measured. Twelve scores are measured individually where ten of them represent competency areas, one represents capability stage, and one represents the organizational scale. For each area, different maturity levels exist from which one level is selected for each stage: (*initial "a", defined "b", managed "c", integrated "d", or optimized "e"*). Each level is given a score (specified in Table 7.4) based on the implementation range. These are then summed up and averaged to give the average BIM maturity score.

Table 7.4 shows the values for each score and the final average score. Each area and stage is ranked based on discussions and interviews held with different members of the project teams, author's observations of the work place dynamics, as well as general discussions related to the organization's practices held with the BIM managers and coordinators of the BIM department regarding technology, policies, and involved processes. Each of these levels and the criteria for ranking the scores are explained in the tables presented in Appendix B.

Table 7.4 – Summary BIM maturity discovery score

BIM Maturity Matrix *Assessment at Granularity Level 1*		**a** **10 pts**	**b** **20 pts**	**c** **30 pts**	**d** **40 pts**	**e** **50 pts**
(1) Technology	**(i) Software**		x			
	(ii) Hardware		x			
	(iii) Network			x		
(2) Process	**(i) Leadership**			x		
	(ii) Human Resources		x			
	(iii) Infrastructure		x			
	(iv) Products & Services			x		
(3) Policy	**(i) Contractual**			x		
	(ii) Regulatory		x			
	(iii) Preparatory			x		
(4) Stage	**Collaboration [2]**		x			
(5) Scale	**Organization [9]**		x			
Total Points						**290**
Maturity Score						**24.17**

(1) Regarding the technology set at the organization, (i) the software area related to the applications used, deliverables and data required, is considered as a Defined area and scored a “b (20 pts)”. Under defined software, its usage is considered to be unified across the organization and project teams. Moreover, the project teams mostly rely on the BIM models to generate 2D drawings and 3D deliverables as indicated by the responses to the surveys (Figures 7.5 and 7.6). In addition, teams and the organization prioritize interoperability of exchanged data as well as define data usage and storage. Similarly, (ii) the hardware used in the organization is scored a “b (20 pts)” where equipment specifications needed for the delivery of BIM products and services are defined and standardized across the firm and teams (Succar, 2009a). Additionally, the equipment used are upgraded and maintained properly to effectively meet the needs. The (iii) network aspect of the technology area is ranked a “c (30 pts)” indicating a managed process of harvesting, storing, and sharing knowledge within the firm and other firms. An internal database platform is used for information sharing and

exchange, and an online project collaboration website (PCW) is also used to share deliverables and provide access to external firms such as the Client and other sub-consultants. The content of these platforms are properly managed and regulated for data sharing.

(2) The process competency level includes four areas (Succar, 2009a): (i) the leadership area which reflects the innovative, strategic, organizational, communicative, and managerial aspects of the organization, (ii) the human resources area which is related to the roles, competencies, experience, and dynamics of the members of the teams. (iii) infrastructure which is related to the workplace environment and knowledge, and the (iv) products and services which relate to the specifications used, project delivery approach as well as research and development efforts.

For (i) the leadership area, a Managed score of "c (30 pts)" is assigned where the common goal and vision of BIM implementation in the organization and project use is properly understood and communicated across the members. The BIM strategy is founded on action plans and acknowledged as a combination of technologies, processes, and policies that need to be managed to support innovations (Succar, 2009a). However, although acknowledged, BIM is used more popularly in this organization as a production tool and technology rather than as a collaborative process, which prevents this area from scoring higher. The (ii) human resources area is considered as defined and scored a "b (20 pts)". In this organization, BIM roles are informally defined and teams are accordingly formed. Each project is planned separately where an execution plan is developed to specifically meet each project. Moreover, as indicated by the results of the surveys, most users are relatively inexperienced in BIM use which requires the support of the BIM unit and renders productivity relatively unpredictable. Regarding (iii) the infrastructure area, the work environment of the firm and the tools used are recognized as factors that affect the motivation and productivity of the employees. Knowledge and information sharing are also recognized as assets and are therefore harvested and documented in the systems and databases. Accordingly, this area is considered as defined and scored a “b (20 pts)”. The final area regarding (iv) the products and services is ranked as Managed “c (30 pts)” where international standards are enforced and implemented for the deployment of BIM services.

(3) The third competency set pertains to the policy aspect and consists of three areas (Succar, 2009a): (i) the contractual area relating to the responsibilities, rewards, and risks, (ii) the regulatory area relating to the standards, guidelines, and regulation implemented at the organization, and (iii) the preparatory area relating to the research efforts and educational and training programs employed.

The (i) contractual area is managed and scored “c (30 pts)” where the contracts spell out BIM related intellectual properties, liabilities, and conflict resolution strategies. The (ii) regulatory area is defined and scored “b (20 pts)” where guidelines regarding training, standards, quality, and performance benchmarks are available and well-defined. The third area regarding (iii) preparatory efforts is managed and scored “c (30 pts)”, where trainings at the organization are well-managed and customized to meet specific needs of the members in line with the competency and performance objectives.

(4) The BIM capability stage is selected to be at Stage 2 “modeling-based collaboration” and ranked as defined “b (20 pts)”. Although the collaboration metrics calculated earlier indicate a low level of collaboration and team work on the project, there is still some level of well-defined but reactive collaboration with identifiable signs of respect and trust among project members (Succar, 2009a).

(5) The organizational scale selected is at the micro level, i.e., the organization level. This level is ranked as defined “b (20 pts)” where different roles in the BIM implementation process are defined and BIM leadership roles are formalized. However, leadership is not fully integrated into the organization’s leadership structure.

The resulting scores of each area, scale, and stage are summed up and averaged. The resulting BIM discovery maturity score for this organization is 24.17. The maximum score achievable is 50. Although certain project teams within the organization might have a higher maturity level than others, the resulting organizational maturity level represents a global assessment for the entire organization. Therefore, the organization studied has an average BIM maturity where focus is placed mostly on the technology and standards. The full potential of BIM use as a collaborative and integrative process, however, is not fully harnessed and implemented in the organization. These results are supported by the findings of the social network analysis where the topology reflects a centralized system with information hubs rather than equally involved members in the information and knowledge sharing processes. In addition, the low density reflects that there are not as many connections and interactions as there can be under highly collaborative BIM environments where BIM is understood as a collaborative process. Similarly, the results of the BIM maturity score are in line with the results of the collaboration scales of teamwork and coordination that reflect a low tendency for harmonizing interactions and working collaboratively towards achieving the BIM vision of the organization.

An ideal BIM organization harnesses BIM as a decentralized process fostering collaborative design that is facilitated through the use of BIM (Azouz et al., 2014). The BIM technology can facilitate the integration of information and knowledge sharing. When the process is understood and implemented, this integration and knowledge sharing becomes explicit for all the members when they collaborate to achieve project goals as well as the organizations vision. Risks and rewards then become better accepted and shared when a solid ground for trust is achieved. However, in organizations or projects that use BIM as a modeling tool rather than a process for improvement, collaboration, and innovation, information sharing and knowledge creation will still come short, and the quality of design and workflow will still suffer. The organization assessed in this study shows a less than average BIM maturity far from a utopic BIM state, where collaboration is not embedded in its culture. This organization also uses BIM as a software and not a life-cycle management process, which reflects the low values of collaborative metrics and centralized network structure.

7.6. Agent-based design workflow results

The dynamics of information exchange occurring within the design social network were simulated using agent-based modeling. The different outcome aspects of workflow measured for the members are (refer to Table 6.6): design rate, share rate, review rate, rework rate, WIP, design time, share time, review time, rework time, and collaboration time. These outcomes are outputs from the simulation model. Each of these metrics are measured at agent (individual level), team (department level), and project level. Moreover, the number of rework, review, and share iterations are measured for each deliverable in addition to the percentage of the deliverable design lead time spent in queue for rework, review, and sharing (refer to Table 6.7). Since the input parameters for the model are stochastic such as the duration needed for designing, reviewing, and reworking (refer to Table 6.4), multiple iterations are performed to account for variability and account for a large number of scenarios. To specify the number of iterations sufficient for covering a reasonable number of scenarios, automatic runs were performed for 10, 40, 100, and 500 iterations. For these options, one output aspect pertaining to the project sharing trend was selected as a reference for comparison. The obtained values over the simulation duration were averaged and plotted for each of the 10, 40, 100, and 500 iterations. The average trend plots for each number of iterations were graphed against each other in order to determine if the accuracy of the results varies across the number of iterations chosen. If they varied, the number of iteration offering the smallest standard error will be selected and manual iterations will then be performed to calculate the standard errors for each output metric. If the trend plots are converging and consistent with the each other, then it is sufficient to perform a smaller number of manual iterations to save time and calculate the standard errors for each output metric. The output plot trends for each number of iterations regarding the project sharing metric are presented in Figure 7.10.

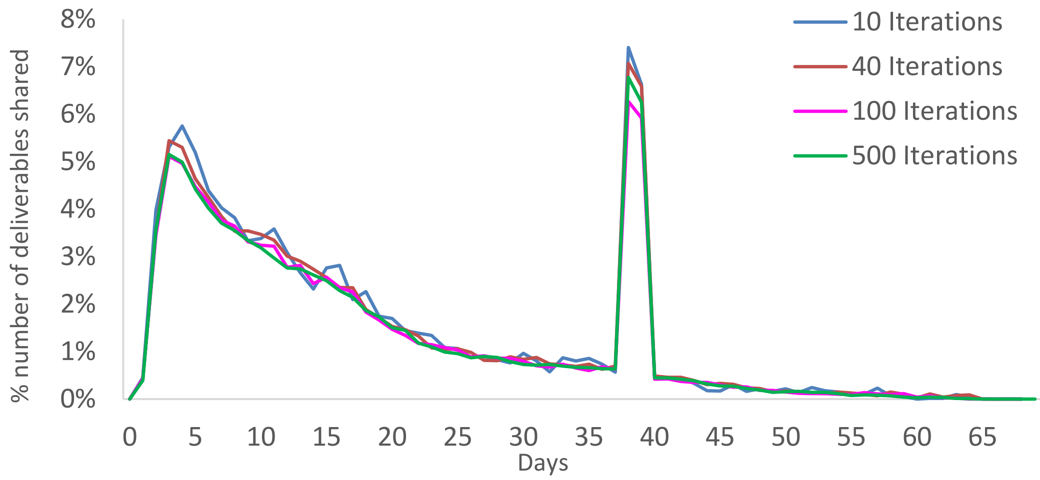

Figure 7.10 - Number of iterations for project sharing trend output

The resulting plot trends for each of the 10, 40, 100, and 500 iterations shows that there are subtle differences in the trends between smaller number and larger number of iterations. Therefore, in order to save time when calculating standard errors for each output metric, 40 manual iterations were deemed sufficient and representative of multiple scenarios to account for variability. Moreover, the results show that the simulation model is behaving consistently with the stochastic inputs, and there are no notable deviations from the set of rules specified for the agents and system modeled.

7.6.1. Model Verification

In order to verify the output of the model, several steps are taken as explained earlier in Section 6.4.5. (a) The scope of the model and its output is aligned with the research objectives. (b) To check for consistency and robustness of the output, the values of the stochastic input parameters were changed by running multiple scenarios (iterations). The resulting output trends converged to similar patterns and there were no notable discrepancies between them. This verifies that the model rules are consistent and agents are behaving according to these rules. (c) During the runs, the behaviors of the agents were constantly monitored through the visual simulation software interface to identify any problems during the course of simulation. Some problems in the model's algorithm were visually detected and corrected accordingly. (d) The model's logical performance and internal execution of the defined rules and algorithms were checked for by monitoring the output. As shown in Figure 7.11, the output metrics of each individual, team, and project are cross-checked with each other. The individuals were checked for behavior and major discrepancies among the agents were not present. For example, the design peak values and peak times vary slightly with justified reasons, but no major unjustified variations were present. There was consistency between the different agent behaviors, implying that the rules are executed similarly for each agent. Then, the simulated team metric output values were compared to the sum of the individual team member metric output values. The results were identical and further verify that the model is behaving correctly and executing the algorithms properly. The final step was to check that the entire system simulation performance is consistent with the lower level agents' behavior where the simulated project metrics output values were cross-checked with the sum of the output metric values of the teams. The results were identical thus verifying that the model functions correctly. Finally, (e) the model was adjusted to more closely represent the real behaviors of the agents and system.

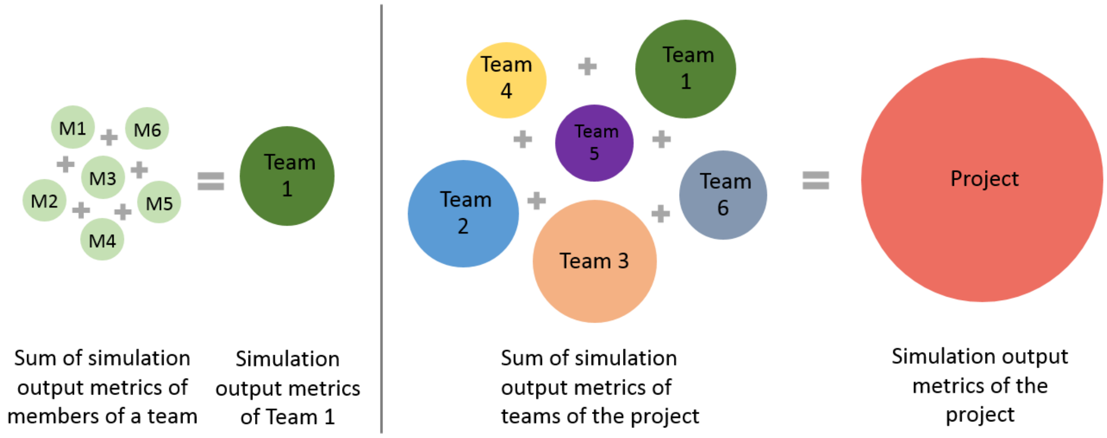

Figure 7.11 - Verification of model's logic and algorithms

7.6.2. Model validation

Validating the model requires that it represents a realistic depiction of the real system. Face validation with experts and output validation with actual project data were performed. A preliminary approach is to perform (a) face validation, where experts in BIM and design processes were asked to provide their feedback about the developed model. In this regard, the BIM manager and coordinator provided their feedback and input regarding the credibility of each agent's behavioral state charts (designers and deliverables) as well as the model's logic overall. The model was adjusted based on their feedback and suggestions. Moreover, the surveys were used as input for the model whereas the output was verified using project data logs.

After running the model for multiple iterations, (b) the output was validated by cross-checking the resulting trends at the project level for one output metric, the sharing rate trend, with actual data collected from the project's database. First of all, choosing the project level is considered representative of the entire model since it was verified that the simulation output of the project metrics is identical to the sum of the simulation outputs of the teams and members. Second of all, choosing the sharing rate metric is representative of the underlying behaviors as it emerges from (and contributes to) the trends of reworking, reviewing, and designing. Finally, the actual data collected from the databases were examined. There were discrepancies in the data logging dates into the systems were some files showed dates of storage, updates, and transfers that were inconsistent with the actual dates they were created, stored, updates, and transferred. This inconsistency was a result of how the computer logs the dates depending on when, where from, where to, and who created, modified, and acted upon the files. Thus, the inconsistent logs were not used in the validation process. However, the only correct logs were the file drives pertaining to the shared folders of the entire project which logs the date files were moved into the shared folders for access by team members.

Accordingly, the average simulation output sharing rate trend from 40 iterations is cross-checked with the actual project sharing trend. The empirical cumulative distribution functions (ECDF) of each is plotted against time percentages as shown in Figure 7.12. In order to statistically test if these two ECDFs are statistically similar or different, a Kolmogorov-Smirnov test (K-S test) is used. The K-S test is used to compare the two ECDFs. The K-S test is a non-parametric test to check if a sample comes for a specific ECDF.

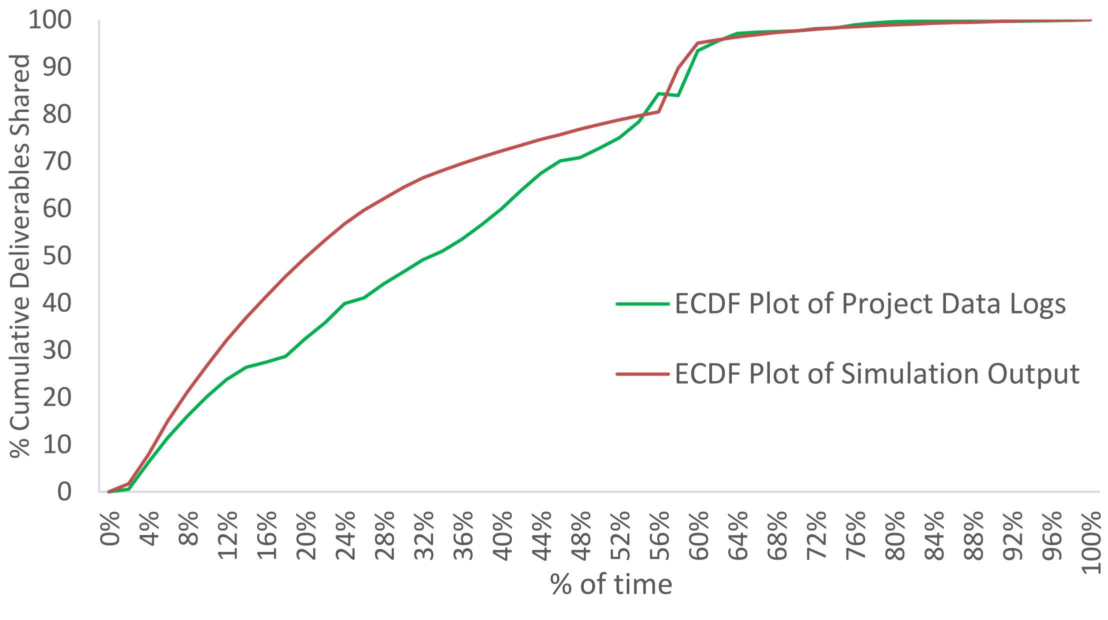

Figure 7.12 - Validation of simulation output with actual data logs

The results of the K-S test at a significance value α=0.05 show a KS statistic of D=0.1569 and a p-value=0.557. With p-value much greater than α and a D value not significantly greater than zero, the two ECDFs are statistically similar, meaning that one sample is drawn from the other distribution. Therefore, the simulation results are validated and similar to the actual data logs sharing trends where the mode captures a realistic representation of the real-life system under study.

Finally, (c) the comparison of the results from the different sources of evidence, which is performed through the rest of this chapter, shows the convergence of these results and conclusions thus validating the model's logic and outputs.

7.6.3. Individual designer level

Design workflow dynamics are captured by simulating the behavior of the agents in the system. Dynamics pertaining to designing, sharing, reworking, reviewing, the work-in-process, and how time spent each day is divided between these different activities are a reflection of design workflow characteristics of the design phase. Observing the design workflow trends of each member in the network helps understand his/her ongoing dynamics in relation to his/her respective role in the design process. In order to examine how different roles and positions in the social network can impact design workflow, selected members with different roles will be examined to explain the relationship between design workflow and social influence.

- *AGL/SC design workflow rate trends*

Figure 7.13 illustrates the output metric trends for the percentage of the number of deliverables produced, shared between members of the same team, reviewed, reworked, in-process, and shared on the common system each day. The deliverables can be BIM models and other documents such as drawings, analysis calculations, reports, etc. The methods of sharing these documents that the respondents were able to approximately quantify were through emails and files exchange on the folders and PCW. Phone calls were hard to quantify and no records were available for reference. Other general non-documentable information such as informal face-to-face discussions were approximately assessed by the time spent collaborating each day.

Figure 7.13 shows design workflow trends of the AGL/SC, which are also similar to the APA1/MC but are not shown here to avoid redundancy. The design rate metric depicted as the percent average number of deliverables produced each day is represented by the blue solid trend line. Each trend line value has a standard error (%) value indicated in the legend with +/-; meaning, the values plotted can vary with an additional increase of the provided standard error value or a reduction of that standard error value. Design rate shows an early peak of deliverables production since the AGL/SC is responsible for setting up the design requirements, instructions, and common models based on which the other disciplines will develop their design on.

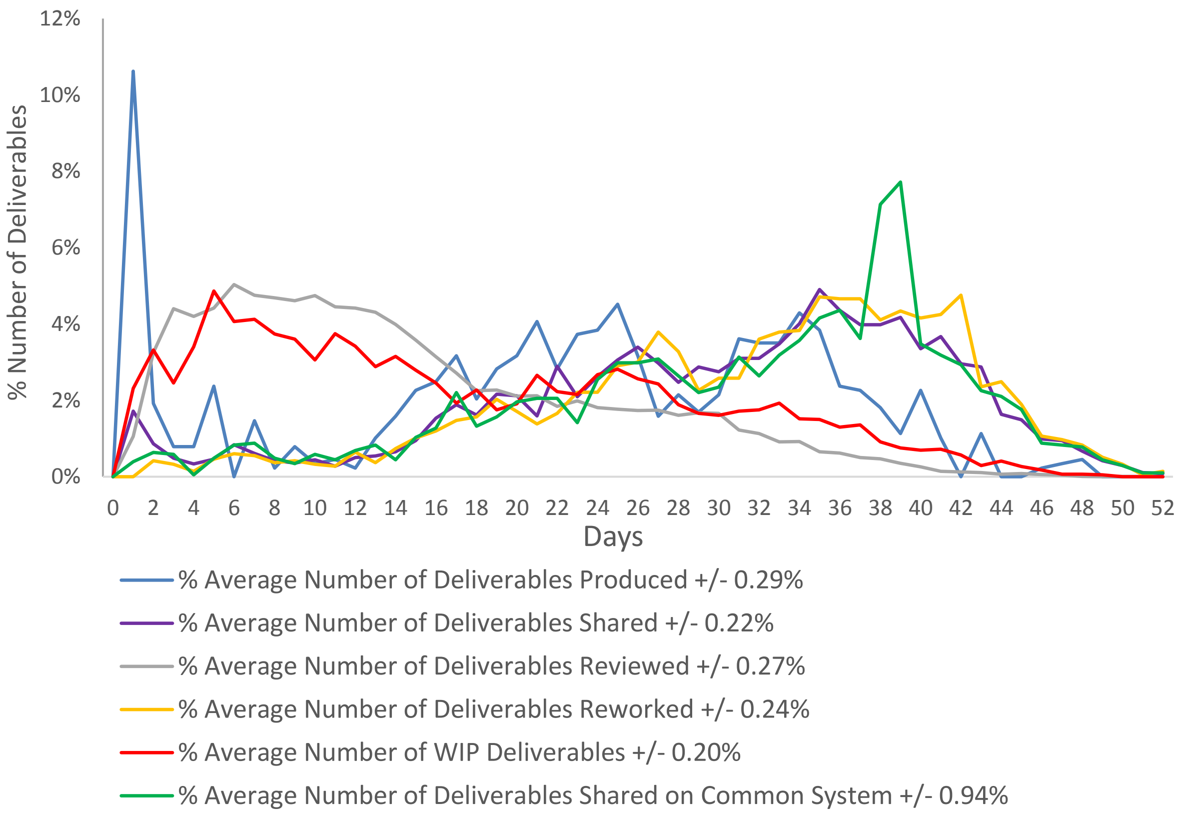

Figure 7.13 – AGL/SC design workflow rate trends

Some of these models are still incomplete but are shared early on with the team and project members so they can proceed with their designing activities. Accordingly, the team sharing and common sharing trend lines (purple and green) also begin early-on in the design phase. Since the AGL/SC and APA1/MC are responsible majorly for coordinating and reviewing the works of the project members as they noted in their survey responses, a lot of deliverables are channeled to them for revision. This is reflected by the quick increase in the review rate that diminishes the person's ability to design further deliverables. In addition, the work-in-process (WIP) trend line shows heightened levels early-on given that some of these deliverables produced are under progress. This is also due to the presence of queued deliverables from other members that need to be reviewed by the AGL/SC and APA1/MC. This notable increase in WIP means that the AGL/SC and APA1/MC have a lot of tasks to complete which are not occurring at a fast enough rate. This makes the AGL/SC and APA1/MC bottlenecks when handling most of the responsibility of revisions, designing, and instructions on their own.

As examined earlier, the AGL/SC and APA1/MC are network hubs and central to the flow of information between the different members. Therefore, with the large WIP occurring, it is likely that the flow of information will suffer and members will experience delays while they wait for feedback and information. This matter prolongs to the middle of the project, after which the reviewing process subsides and the AGL/SC and APA1/MC can resume work on designing and sharing those designs with the rest of the members. While changes are inevitable during design, the rework trend line increases while designing as iterations under the conceptual and schematic design phases are very common. However, iterations can result from interrupted work as experienced by the AGL/SC and APA1/MC as well as the lack of proper communication that results in a misunderstanding and misinterpretation of design requirements and intent. The peak in the sharing rate to the common system peaks towards the end of the project as there was a milestone for submitting the design deliverables to the Client. Examining the sharing trend lines, there is variability in the sharing trends where the patterns are not smooth and constant throughout the project duration. The major peak occurred before the submission so that all deliverables can be integrated and checked for before submission rather than being checked and integrated throughout the design process.

- *AGL/SC daily time division*

Figure 7.14 shows, on a daily basis, how time is divided between the different activities of the AGL/SC. Similar to the observed trends in Figure 7.13, the beginning of the project exhibits a surge in designing time spent and collaboration. During the beginning of the project, more collaboration occurs during the briefing period and the kick-off meetings spelled out in the contract to discuss the design requirements and provide the instructions and roles to the different members. Throughout the project, much of the AGL/SC's time is dedicated to the revision of others' work and maintains some level of collaboration at the beginning.

When starting to work on design again, rework increases and continues towards the end of the project due to the delay in the production of design and the errors resulting from continuous switching between different activities each day as seen in the graph. Collaboration and coordination are maintained as a natural part of their role for coordinating the works of others and collaborating for design fulfilment with team leaders and the PM. As the design activity picks up in the middle towards the end of the design phase, so does the activity of rework to amend and modify their resulting design. Sharing time increases notably towards the submission to the client. Overall, the daily time divisions show the effort invested for each activity and the continuous switching between them which can negatively affect the design process and cause unnecessary rework. Moreover, uneven workflow among team members exasperates the situation and creates bottlenecks in the system.

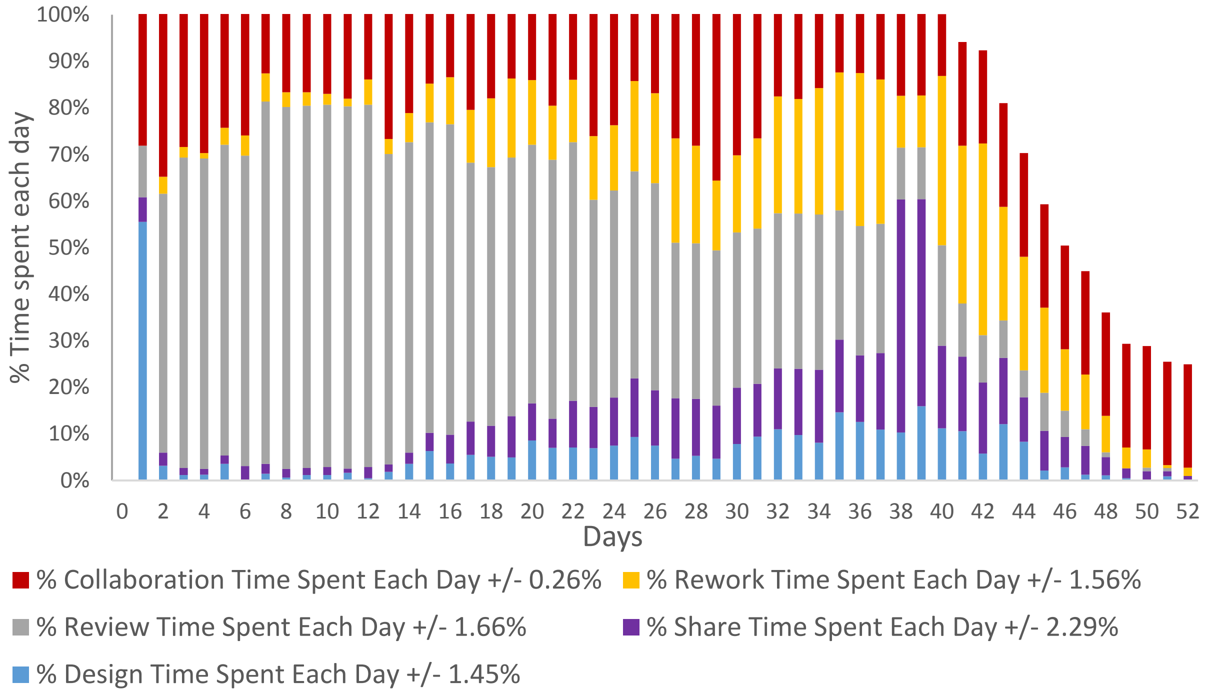

Figure 7.14 - AGL/SC time division each day

- *MEPE design workflow rate trends*

To examine how design workflow differs with the role and position in the network, a less central member, the MEPE (mechanical project engineer) is selected. Note that similar trends are observed for such less central nodes, but to avoid redundancy, only the MEPE member will be examined as a reference for the rest. Compared to the AGL/SC, the MEPE design production starts a few days after the project initiation as seen in Figure 7.15. This is a result of waiting for the architectural deliverables to be partially ready and the instructions to be delivered so that the mechanical engineers as well as other discipline members can start designing. Due to his/her less central role and lower design scopes in the schematic and conceptual design phases, the design is completed within a few weeks accompanied by a notable volume of rework. When asked about reasons for rework, the respondents mentioned that the design requirements are not always clear or understood, resulting in constant changes to their design that prolongs for a good portion of the design phase duration as evident in Figure 7.15.

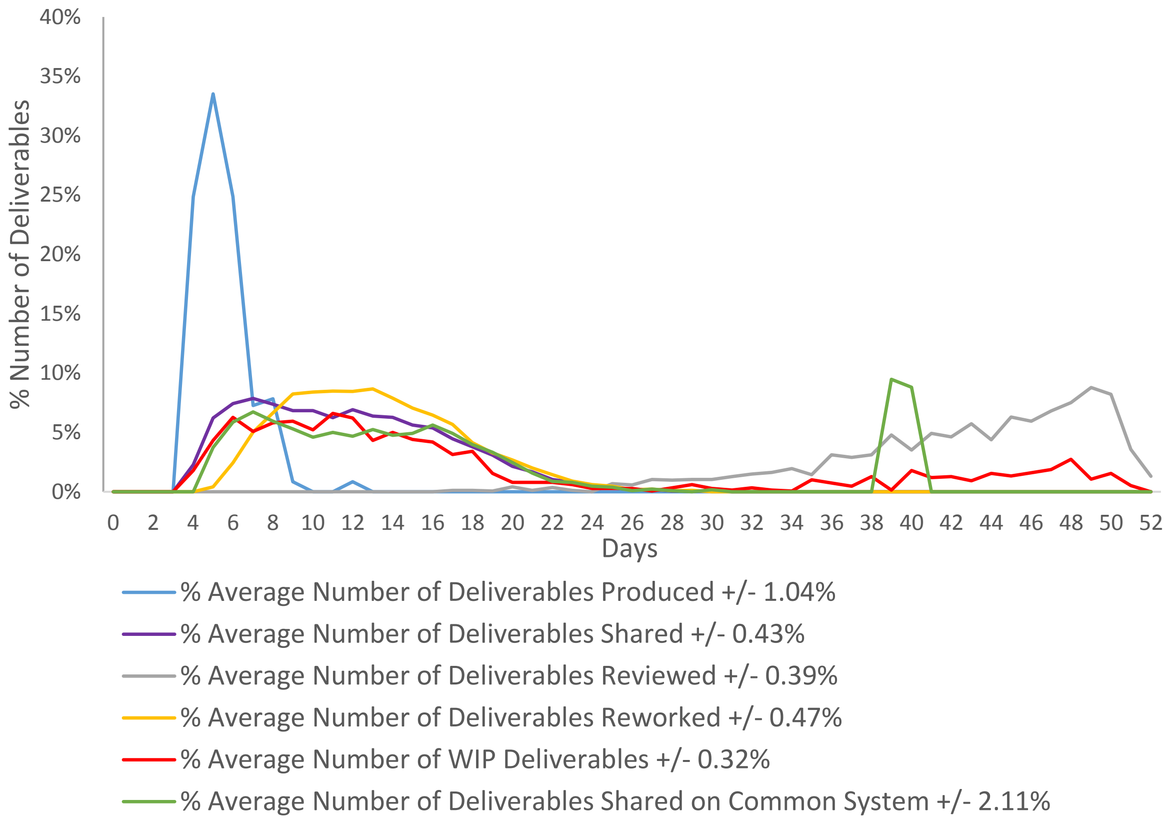

Figure 7.15 - MEPE design workflow rate trends

Sharing deliverables and information with the members of the same team and the project happens a few days after designing where the design becomes ready for exchange even when not complete. This reflects early sharing necessary for sharing incomplete information needed by others. However, sharing then subsides as design progresses towards completion of rework and designing, only to peak during the submission to the client. It is therefore not very continuous throughout the design phase. Since the MEPE's approach is to prioritize his/her design work before reviewing deliverables assigned to him/her, reviewing is pushed towards the middle and end of the design phase. This means that members waiting for the feedback of the MEPE's reviews will have to perform their rework at a delayed time. The WIP volume increases where multiple deliverables are being queued for rework and revision and then subsides when the MEPE is done with rework and starts the revision process.

- *MEPE daily time division*

The first few days of the design involve collaboration with other teams' members during the kick-off design meetings for briefing the requirements and assignments as shown in Figure 7.16. Afterwards, the designing begins followed by reworking and sharing of the deliverables generated. Collaboration starts to decrease in comparison to the beginning of the project where members become occupied with production rather than collaboration. Similar to what was observed for the AGL/SC daily activities, there is a surge in sharing and collaboration when client submissions are due. Based on these trends, information sharing and collaboration are not steadily sustained throughout the design phase. They only occur when asked for at the beginning of the project and before submission deadlines.

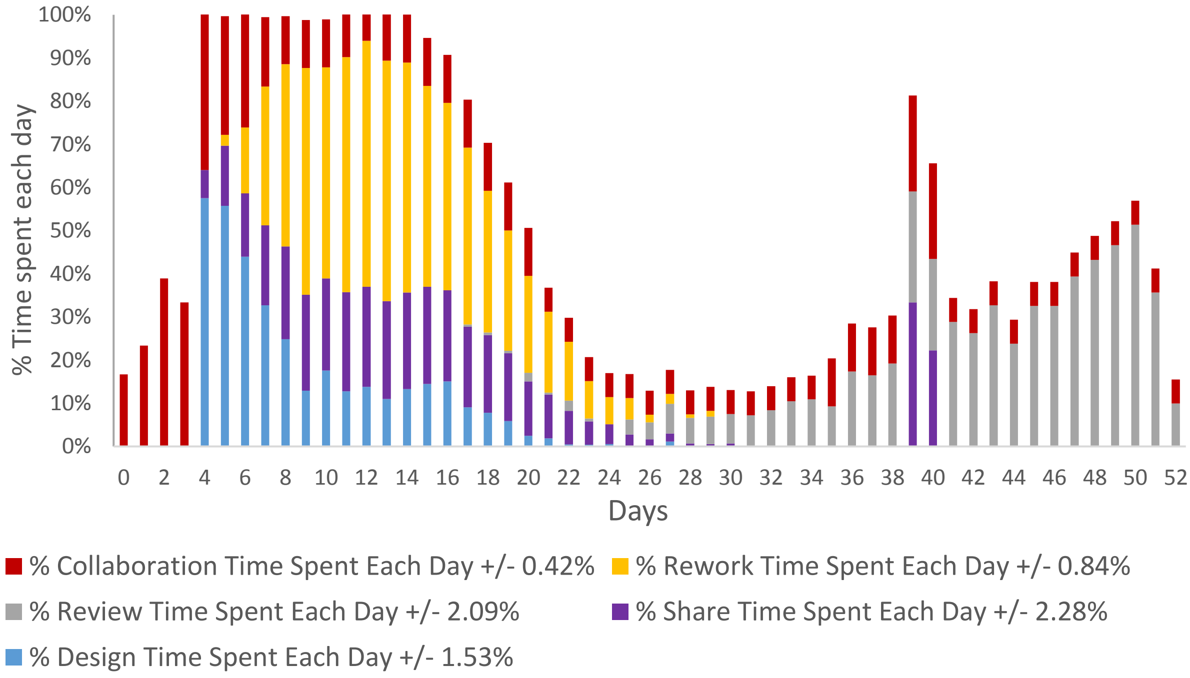

Figure 7.16 - MEPE time division each day

By examining members with different positions and roles in the design social network, it is evident that their resulting individual workflows show discrepancies. On one hand, the AGL/SC and APA1/MC being the central hubs of the network, are majorly occupied and overloaded with revisions and coordinating works of others where as their design efforts are shifted towards the middle and end of the project. On the other hand, the MEPE and other less central members of the network have less crowded daily activities, experience delays at the beginning of the project waiting on design input from the architectural team, and spend more time performing rework. Rework, as these respondents indicated, is a result of the requirements not always clear, changes that are constantly requested, and discrepancies between different design disciplines that are constantly arising. These factors combined result in several cycles of rework which count as negative iterations. Collaboration is more present in the daily activities of the AGL/SC and APA1/MC due to their central coordination roles, which is also supported by the findings of the collaboration scales measured earlier. In contrast, collaboration decreases notably throughout the design efforts of the less central members, which is also supported by the collaboration scales measured earlier where they are far less than those values of hubs. Therefore, design workflow of each individual is impacted by their role in the design process as well as their interconnectedness and position in the network which impacts their ability to coordinate, collaborate, and be involved in teamwork.

7.6.4. Team level

The resulting team level design workflow trends emerge from the underlying direct interactions of the team members as well as their indirect interactions with other team members during the design phase.

- *Architecture team design workflow trends*

Figure 7.17 illustrates the design workflow trends of the architecture design team. Although the AGL/SC had more uneven trend lines resulting from their roles in the design process, the emerging architectural team workflow trends are toned down with other less central architects present in the team. Design peaks early to set up the architectural models and specifications needed by the rest of the disciplines and design work continues throughout the project at a decreasing rate towards the end of the design process.

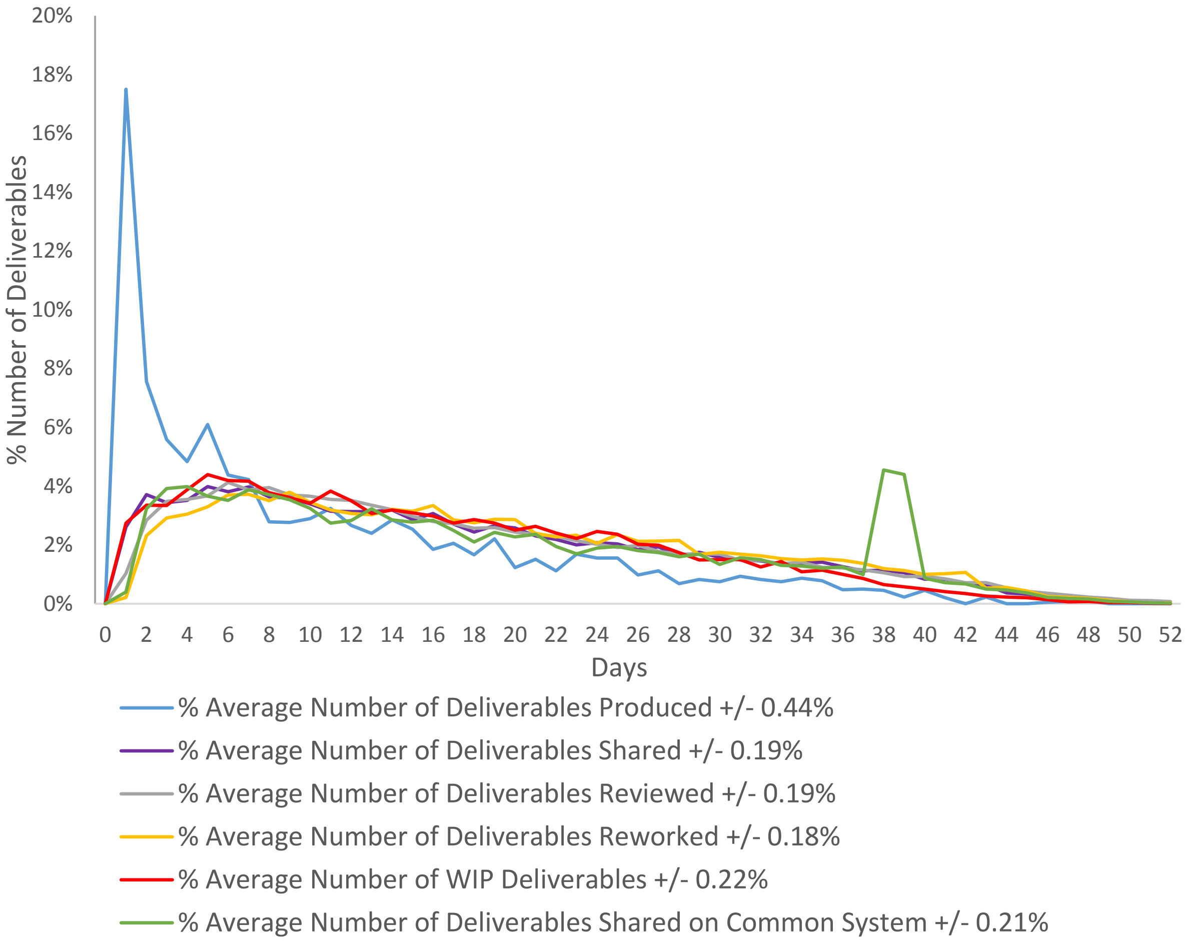

Figure 7.17 - Architecture team design workflow rate trends

The trends lines are similar for rework which is accompanied by the following design efforts due to the changes requested and conflicts between the disciplines. Sharing design deliverables between the architectural team members is continuous as similar team members have access to the work folders of each other. Similarly, sharing deliverables on the common system for members of other disciplines to access continues throughout because architectural drawings are always needed as reference for other disciplines to base their designs upon. Yet, sharing peaks before submission to the client on the common system as observed earlier in the individual trend plots. WIP persists throughout the design process for the entire team where members are involved in different simultaneous tasks such as reviewing, reworking, and designing.

- *Architecture team daily time division*

The daily time division of the architectural team throughout the design phase, as depicted in Figure 7.18, shows a majorly higher time spent on reviewing deliverables of other team and non-team members. Moreover, rework, as observed in Figure 7.17, seems to persist throughout the project due to the changes and conflicts with other design disciplines especially under conceptual and schematic designs. Although collaboration is present throughout the design process within the architectural team, more time invested in collaboration at the early weeks of the design phase can likely yield less rework time and revision time spent. On the other hand, sharing time does not constitute a large daily portion due to the close physical proximity of the architectural team member which requires less time to physically or virtually share information and documents. However, the ease of exchanging information is not related to the "quality" of sharing information as discussed earlier. Having shared goals and aligned vision of the design needs of each other is what matters during collaboration and information exchange. Considering the design time spent, it is evidently much less than time spent on revision and rework. Most of the design deliverables in progress are undergoing several cycles of rework rather than generating new design deliverables.

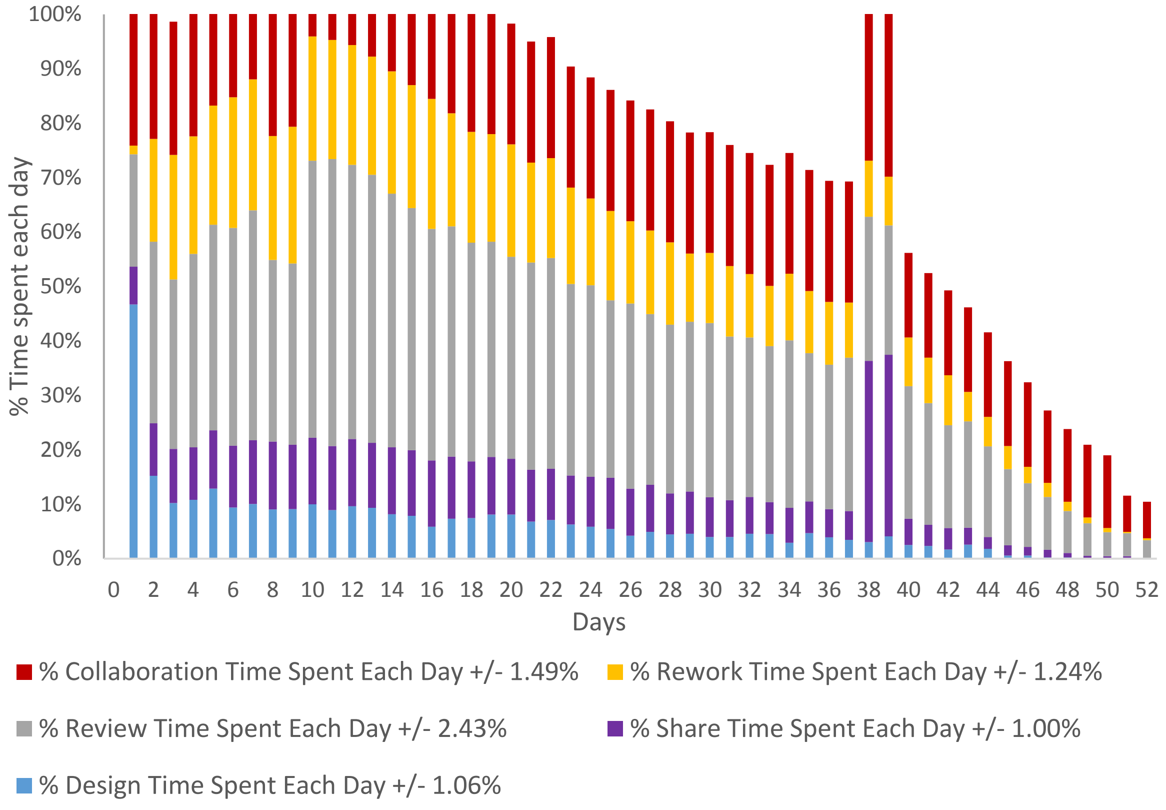

Figure 7.18 - Architecture team time division each day

<u>Structural engineering team design workflow trends</u>

Taking another design team for examination, the design workflow trends of the structural design team are depicted in Figure 7.19. The design workflow trends exhibit similar attributes to those of the architectural team, with a few days' delay in the design production process initiation, where the design team members of the structural design team, and other disciplines alike, wait on initial input from the architectural team to base their design on. In comparison to the percentage number of deliverables reworked and shared, the structural design team deliverables undergo more cycles of rework by its members that are shared back and forth for revision.

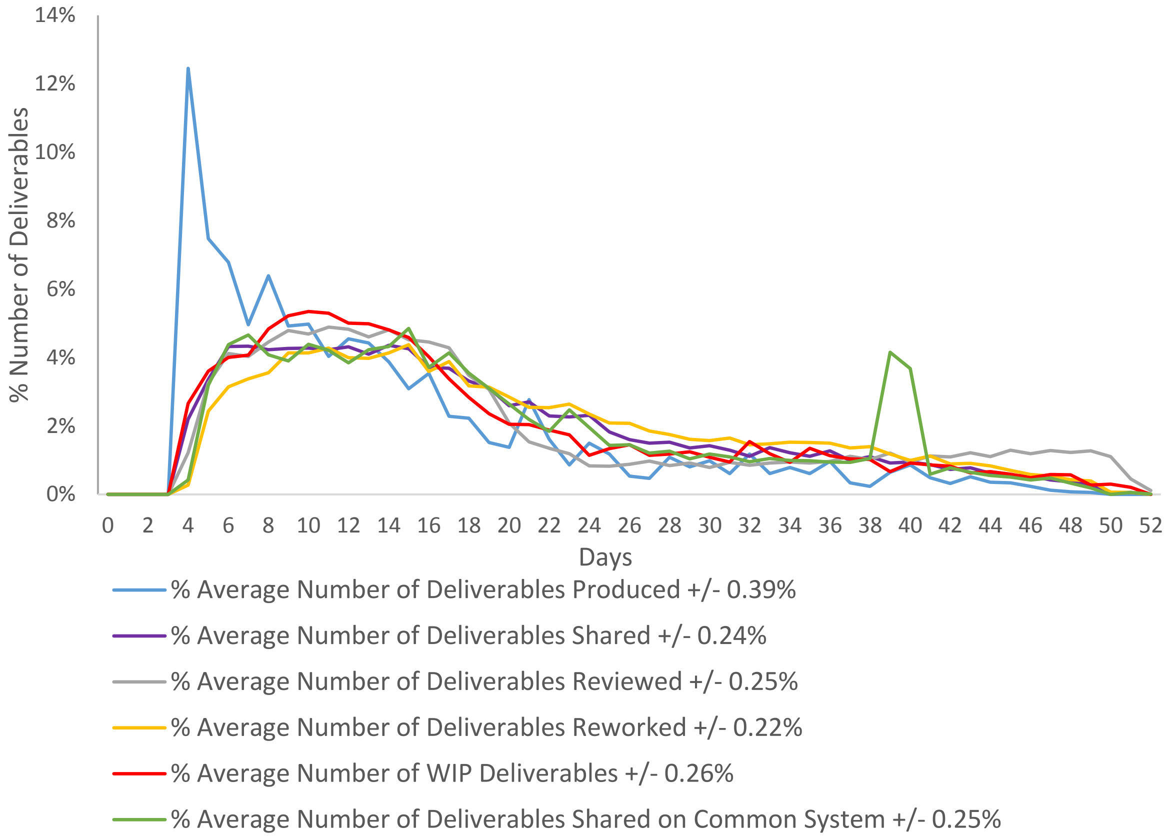

Figure 7.19 - Structural engineering team design workflow rate trends

- *Structural engineering team daily time division*

When comparing the amount of team collaboration time invested to the amount of time spent on rework shown in Figure 7.20, it seems that low collaboration might be linked to the resulting rework amount. Rework can either be positive (value adding) or negative (non-value adding and wasteful). Although it is not differentiated in this study (further research is required to cover this aspect), preliminary responses by the members regarding clarity of requirements and changes indicate that most of the rework performed is a result of incomplete understanding of requirements and insufficient daily teamwork with other design teams. In the absence of collaboration and team work, design intent and requirements are not clearly understood, which is reflected by the produced design deliverables that contain misalignments with the specifications.

This misalignment results in errors and design conflicts which then perpetuate into rework for the team and other disciplines as well.

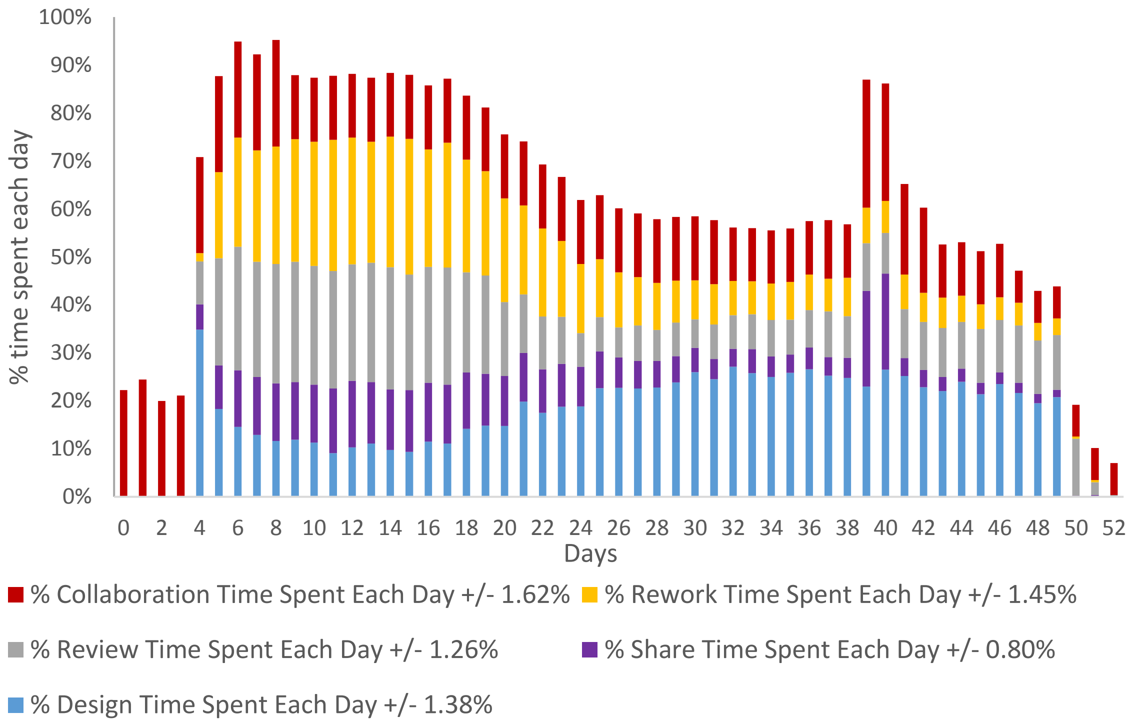

Figure 7.20 - Structural engineering team time division each day

Observing the design workflow trends of the team level can provide further insights into the emerging trends than individual levels. Different teams with different roles in the design process can have differing design workflow trends depending on the amount of collaboration invested, the level of team work and interactions present between teams, the quality of such information exchanges and communication, and the presence or absence of shared understanding and common aligned goals. These factors in turn will shape workflow aspects such as the amount and trend of rework, revisions, and design. It is important to highlight that the relationship between workflow trends and their influencing factors is interdependent, where such factors can become results of what they caused, and vice versa.

7.6.5. Project level

The resulting emergent behavior captured by the agent-based modeling of the entire system is depicted by the project level design workflow trends shown in Figure 7.21. With each individual and each team having a unique design workflow “blueprint”, the project level trends can capture emergent behavior that cannot be seen by simply isolating each member or team and summing them up.

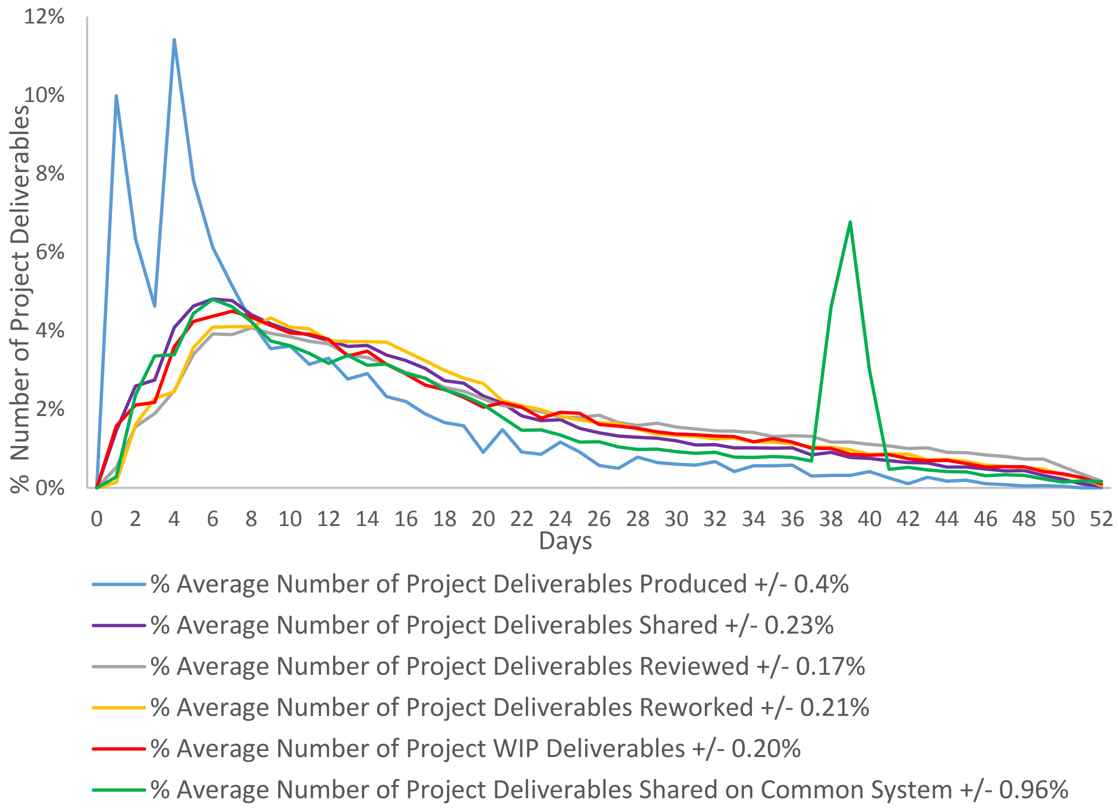

Figure 7.21 - Project level design workflow rate trends

There are two design production peaks resulting from those of the architectural design production and the design production of other delayed design teams. Revision efforts are constantly occurring at a decreasing rate resulting from the rework cycles taking place for the previously mentioned reasons. The WIP levels are also maintained throughout due to the overall amount of work handled by the design members and teams that exceeds their daily capacity to manage multiple activities with several rework and revision cycles. In-team sharing is slightly higher than team-to-team sharing where team-to-team sharing occurs after members feel their design is ready to be shared on common folders with the rest of the project members. This can be an indicator of lower trust with other teams where they cannot access folders of deliverables of other non-team members due to the traditional approach of secrecy and protecting each team's knowledge. However, before submission to the client, a surge in sharing on the common system appears so deliverables can be integrated and finalized for submission.

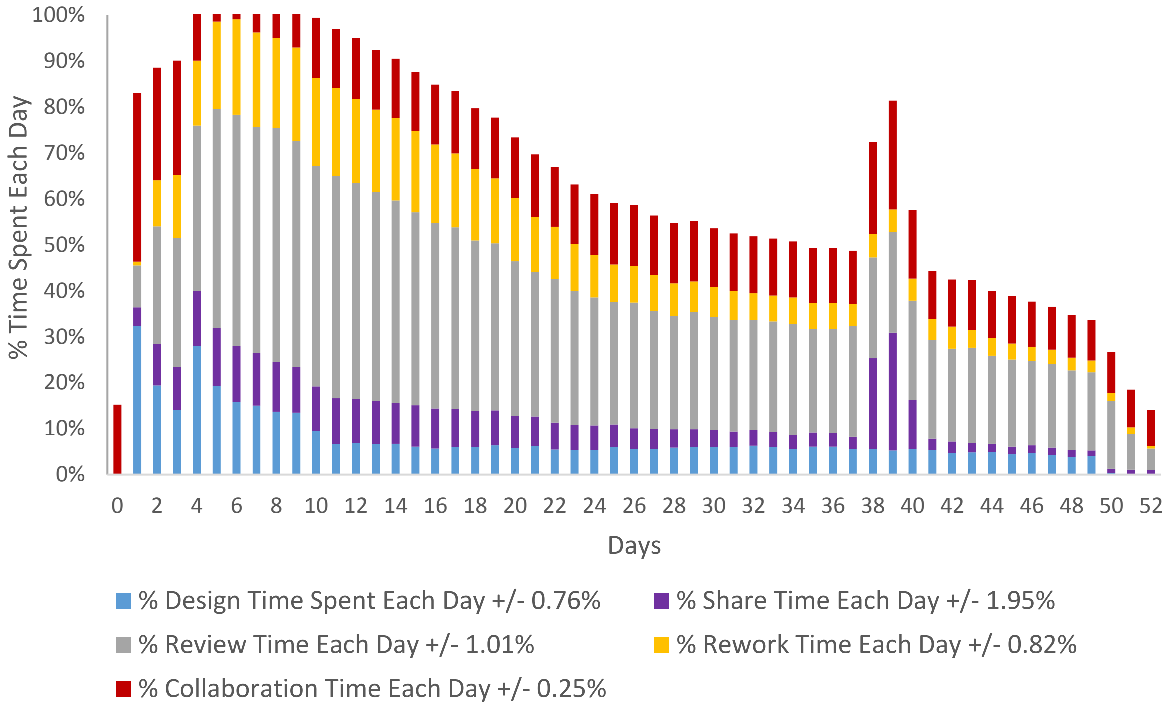

Figure 7.22 - Project level time division each day

The resulting daily time division between different activities for the entire design social network is illustrated in Figure 7.22. Similar to the observed individual and team level trends, rework and revision efforts constitute the largest portion of the daily time invested, which comes at the expense of less time spent performing value adding design (design that adds value at each step of the process) and effective sharing. This can be linked to the low levels of collaboration at the beginning of design when collaboration is especially necessary. It is believed that if more time is spent collaborating and performing value adding design in a teamwork environment where tacit knowledge can be transformed into explicit and shared understanding, rework and revision amounts can be reduced and prevented from dragging towards the end of the design phase (Koskela et al., 2016). However, the respondents indicated that collaborative meetings occurred as stipulated in the contract, and other informal teamwork occurred between members of their own team when a problem arises. The culture of continuous collaboration and founding common knowledge was less evident during the observations of the workplace and interactions between members.

Sharing time constitutes a smaller part of each day where project level sharing mode is performed mainly through virtual means such as folder access, emails, and phone calls. Although these means save time and simplify the data exchange processes, the quality of such interactions are diminished to virtual transactions that lack in-depth understanding and formation of shared knowledge necessary to bring about the client's design intent.

7.6.6. Design deliverable attributes

The attributes pertaining to design deliverables such as models and drawings can also be tracked and examined through the agent-based modeling approach. Table 7.5 shows average attributes of 30 BIM models produced by different disciplines. On average, a BIM model undergoes 7 cycles of revision which require 5 cycles of rework, indicating 71% of the times a model is reviewed, it requires rework as a result of errors or changes needed. Moreover, on average, the model is shared 10 times throughout its 18 days of design lead time (from initiation to completion), indicating that there might be days where it is not shared at all. That happens when it is being developed or reworked. In fact, the average sharing queue time constitutes 17% of the total design lead time, the average review queue time is 7%, and the average rework time is 13% of the total design lead time. Combined, these queue times sum up to 37% of the design lead time being non-productive and non-value adding to the design process which is considered waste. Put in actual days, an alarming 6.5 days of the 18 days are non-productive whereas a deliverable only undergoes processing for 11.5 days.

Table 7.5 - Deliverable workflow values

Metric	Acr.	Average Value	Metric	Acr.	Average Value
Rework Iterations	WI	5 times	**% Review Queue Time**	VQT	7%
Review Iterations	VI	7 times	**% Sharing Queue Time**	SQT	17%
Sharing Iterations	SI	10 times	**% Non-Value Adding Time**	NVT	37%
Design Lead Time	DLT	18 days	**% Processing Time**	PT	63%
% Rework Queue Time	WQT	13%			

These values, in line with findings in other studies such as Ballard (2000b), are not surprising given the multiple revision and rework cycles they undergo which were also seen in the individual level, team level, and project level design workflow trends and daily time division charts. The system overall suffers from inefficiencies, that if targeted, can be improved to reduce wastes and improve the flow of information so that the correct and right information can be timely obtained. This in turn would help reduce the generation of design errors, reduce rework and revision cycles, and provide more time for value adding design processing and value creation.

7.7. Discussion of the study's outcomes

The studied design stages are at the conceptual and schematic levels. At these levels, timely and continuous sharing of information between members and teams is highly critical to avoid errors and excessive negative rework. Errors that are created and pass undetected into later documentation and construction stages resulting in time and cost overruns, and worst of all, fatal failures. Information flow failures are tightly linked to direct errors (mistakes appearing directly in design) and latent failures (hidden errors that propagate and result in failures). Such failures are manifested, for instance, when designers are not being aware of the needs of other project participants or all the requirements of design. The lack of proper information exchange and shared cognition creates a medium for the incidence of failures. Module 1 of this study presented a qualitative understanding of information flow under traditional and BIM-based design phases, the underlying relations between information flow and error generation, and the mechanisms of such error diffusions under traditional and ideal BIM-based networks. Module 2 then expanded this understanding into a measurable framework to analyze the design workflow dynamics in a BIM-based case study project. An integrated social-process perspective combined social network topologies and characteristics with workflow dynamics occurring in these previously "hidden" interaction links. This novel integrative approach revealed relationships between the composition of social and collaborative interactions of members and teams on one hand, and their resulting individual, team, and project level design workflow trends on the other.

The cross-analysis of the different sources of evidence (surveys, social network topology and metrics, collaboration scales, simulation design workflow trends, project data logs, and BIM maturity score), shown in Figure 7.1, reveals several insights and relationships. The BIM maturity score revealed that the organization of the case-study scores an average maturity where it exhibits only some "managed" BIM levels regarding technology and standards used whereas the rest of the aspects related to the process and collaboration are still at a "defined" level. This indicates that the real potential of BIM as a collaborative and integrative process is not truly and fully harnessed and implemented at the organization. The survey results show that 53% of the respondents have less than 2 years of BIM use experience, and answers regarding teamwork and collaboration indicate that one meeting was held at the beginning of the design phase that all members attended. Informal face-to-face meetings were common between members of the same discipline; however, the majority of interactions and communication were conducted virtually across members of different disciplines. Given that the quality of communication decreases notably with virtual communication methods, there should be more focus on and embedment of effective collaboration in the organization's culture. This matter is also supported by the observations noted by the author where each member worked solely on their computer most of the time and conducted/ received phone calls when certain conflicts were detected. However, only some members, such as the project manager and the architecture group leaders, who are the hubs of the social network, played more dominant roles in collaborating with others as they are responsible for coordination and revision of design of different disciplines.

The findings of the BIM maturity score are also supported by the findings of the social network analysis where the topology reflects a centralized system with information hubs rather than equally involved members in the information and knowledge sharing processes. In addition, the low density reflects that there are not as many connections and interactions as there can be under highly collaborative BIM environments where BIM is understood as a collaborative process. Similarly, the results of the BIM maturity score as well as the social network composition are in line with the resulting low values of the collaboration scales of teamwork and coordination that reflect a low tendency for harmonizing interactions and working collaboratively towards achieving the organizations' BIM vision.

In order to visualize and analyze how a company's BIM maturity and social collaborative interactions impact design workflow, the results of the agent-based simulation model show trends of the design workflow metrics introduced earlier. Trends of designing, sharing, reviewing, reworking, and WIP rates for each member reveal discrepancies in workflow dynamics between members based on the roles played by each and their respective position in the social network, impacting their behavior and tendency to collaborate and exchange information. Team and project level workflow trends show that rework, revision, and WIP amounts dominate the trends and constitute a major amount of daily time spent on activities. On the other hand, little time is invested in collaborating as the indicated in the respondents' answers when asked to estimate the daily amount of time they spend collaborating with others. This low amount of time spent collaborating and the virtual mode of communication can be linked to the persistent rework and revision cycles observed leading to continuous WIP levels throughout the design phase. Analyzing metrics of deliverables produced also reveal multiple revision and rework cycles with an alarming value of non-value adding time of deliverables being queued in WIP before being processed.

Therefore, solely using BIM as production tool rather than a whole integrative process does not reap the anticipated benefits that the BIM industry aspires. If collaboration was a common practice throughout the design phase, design requirements can become clearly understood where ideas, thoughts, and concerns of the members can be stated to each other and a common vision and shared understanding can be formed. Conflicts and errors rising from the misunderstanding or misinterpretations of other's ideas and designs can be lessened and more readily resolved when the technical capabilities of BIM use are merged with its collaboration-enabling abilities.

The results of integrating both the analysis of the involved design social network analysis and the simulated workflow dynamics occurring in the vague social interaction links revealed the presence and potential reasons for inefficiencies in the studied design workflow system. Problems with the centralized communication and collaboration social structure and quality, the partial harnessing of the full potential of the BIM process, and the absence of an integrated collaborative culture of shared knowledge and aligned visions lead to an inefficient design workflow. These matters result in a workflow that is plagued with wastes such as excessive rework and revision cycles resulting from changes and errors, poor flow of information, and a relatively high amount of non-value adding time.

When isolating the social perspective and the workflow dynamics perspective, the potential links revealed could not be detected where observed workflow dynamics cannot be understood in the light of the underlying communication and social interactions. Additionally, the sole analysis of the network topology and collaboration scales cannot expose characteristics and trends of design workflow. Therefore, combining these two perspectives and integrating multiple sources of evidence provide a more constructive analysis and informed understanding of the observed patterns.

7.7.1. Comparison to traditional and other BIM cases

To benchmark where the resulting information flow of the studied BIM-based design project stands in comparison to traditional design delivery and advanced BIM-based design delivery, two research studies conducted on information flow are selected. The first study is based on the detailed design stage of 14 traditional 2D design projects of a major airport facility (Tribelsky & Sacks, 2010). The second study replicated the methodology of the first but is applied on 4 BIM-based projects (Demian & Walters, 2013). These studies do not consider the social aspects involved and study information flow by measuring information flow trends from actions performed on detailed data logs of project extranet services. However, a rough qualitative comparison of the outcomes of those studies with the outcomes of this study is performed to benchmark the results. The results of the information flow on the traditional project delivery projects showed that about half of the projects exhibited strong presence of bottlenecks in the system, medium to large scales of rework, medium to large batch sizes of information deliverables that were shared indicated that information were stored in silos and not shared continuously, as well as medium to large WIP inventories of more than half of the projects (Tribelsky & Sacks, 2010). Results from case studies of BIM-based design projects which used a BIM-based workflow system to support collaboration indicated several benefits reaped from the use of this system (Demian & Walters, 2013): (1) more accurate, appropriate, and on-time exchange of information between participants was achieved, (2) earlier creation of critical information related to design and coordination generating significant value for later production stages was promoted through the use of the BIM-workflow system, and (3) the exploitation of BIM's visual and collaborative capabilities by its users is significant for timely flow of information.

Based on the discussed results of this study and the presented outcomes of the two research studies of traditional and collaborative BIM-based workflow systems, this case study fits more into the characteristics of traditional design delivery workflow. Although this study exhibits more continuous but low levels of information sharing during the design phase as compared to the high batch sizes of stored silos, its workflow trends are still plagued with multiple rework cycles and persistent WIP levels. Moreover, these sharing trends are based on virtual communication modes with lower information exchange quality and low collaborative efforts that can be attributed to the resulting problems of excessive rework and non-value adding wastes. To schematically summarize where this study stands in comparison to ideal BIM workflow and the typical traditional 2D CAD flow, Figure 7.23 illustrates its position.

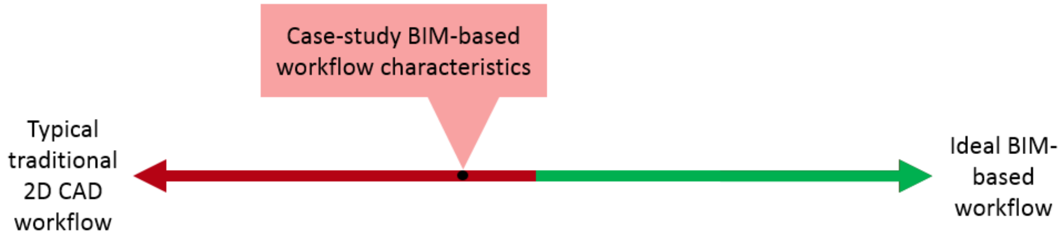

Figure 7.23 - Comparison of case-study to traditional and BIM-based workflows

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

Design processes and invested efforts have become increasingly complex with the advancement in required design specifications, end-user needs and preferences, involved systems and programs of the planned facility, as well as the pursuit for more sustainable and adaptable building designs. These factors, along with the technological advances making information generation and storage easier, result in the rapid proliferation of information and data. With such fast and large production of information quantities and the constraints placed on deadlines and budgets, errors and conflicts are very likely to arise. As a result, workflow of design information is likely to suffer yielding wastes such as excessive rework and revision cycles, faulty design and thus jeopardized quality, and cost overruns and schedule delays, all of which prevent the generation of value for the client and end-users.

Research efforts have been addressing these matters by developing methodologies and frameworks in order to improve the status of design workflow in the construction industry. Some studies focused on the social interactions of the design process members, while other studies explored the flow of design information. Under these efforts, some studies focused on the structuring of design tasks to achieve a proper sequence to meet budget and deadline requirements. Yet, these approaches ignored the complex nature of design, which is ill-defined, iterative, and highly dependent on human and social interactions as well as the intensive dependencies of design tasks.

Given the complex nature of design resulting from the interdependencies of the people involved as well as the information needed and generated, a new perspective is presented in this study that considers this complexity and integrates the social aspects of people's interactions with the exchanged information. In this regard, this research uses social network theory and agent-based simulation in order to analyze and better understand the underlying dynamics and factors impacting design workflow resulting from the use of BIM.

This chapter summarizes the research methodology developed and highlights the key findings of this study. Recommendations and suggestions for practice and research based on the resulting outcomes of this study are also presented in this chapter, and the contributions are also highlighted. Finally, further plans and ideas for to extend this research are suggested for future research.

8.1. Summary and conclusions

8.1.1. Summary of the study

- *Summary of methodology*

The aim of this study is to understand, measure, and analyze design workflow and assess the impact of BIM on workflow. The methodology used included two modules. The first module aimed at providing a preliminary insight into information flow attributes and the existing problems with traditional flow. Process flow diagrams were then developed in order to qualitatively represent and compare these information flows between different disciplines under traditional and BIM-based environments. Then, the relationship between poor information flow and design errors was presented to highlight the importance of proper flow in avoiding faulty designs and the resulting undesired wastes. An agent-based modeling of error diffusion under traditional and BIM-based designs was performed to study the behavior of error diffusions and prevention under different environments.

The second module further expands the first by implementing a measurement framework to quantify and analyze design workflow trends. The approach used integrates the social and process aspects of design by incorporating social network analysis for analyzing the design communication topology of its members as well as agent-based modeling for simulating interaction dynamics occurring between these members. Metrics are then developed to analyze the trends of design workflow characteristics such as rework, revision, designing, collaborating, and sharing. A BIM-based design case study is used for assessing the impact of BIM use on design workflow using the integrated social-process approach. The obtained results were then compared to cases from literature exploring information flow on traditional and BIM projects.

- *Summary of results*

Simulation results from the first Module show that the ideal hypothetical use of BIM can result in a reduction in the diffusion of errors within the social network. This is achieved by better communication of involved parties, the automated clash detection and code checking enabled through BIM which detects errors more effectively and timely, and a better learning and prevention mechanisms enabled by a proactive approach and mentality.

Cross-analysis and validation was performed on the results from various sources of evidence including: administered surveys, social network analysis, collaboration scales, BIM maturity score of the organization, the agent-based simulation, and project data logs. The analysis of these results shows that the social network is centralized with some design members as hubs while others are less connected to the network. This means that members acting as hubs have more access to information and are in control of decision making, whereas less connected members might not have timely access to information. This discrepancy in node prominence and centralization are likely to disrupt the flow of design information in the network. Moreover, the network is not densely connected indicating insufficient communication and interaction in the network. As indicated in the survey results, these existing interactions are majorly based on virtual communication methods such as emails and phone calls which degrade the quality of interactions and can result in misunderstanding and misinterpretation given that design is a highly visual process. On the other hand, collaboration scales show that there are low levels of teamwork and coordination between members due to the poorly connected network and the wide discrepancies in the roles and positions of members in the network. A rough analysis of the organization's BIM maturity level further reveals that BIM implementation is still at a low average level and not mature enough to be implemented and utilized as a collaborative process.

This lack of collaboration and interconnectivity resulted in simulation workflow trends that show excessive rework and revision iterations as well as persistent levels of WIP in the system. In addition, resulting sharing trends occur virtually, peak before a certain submission deadline, and are not sustained at high levels throughout the design process. These workflow trends vary from member to member depending on their roles and respective positions in the network, however, they still exhibit these fundamental problems. Further examination of the workflow attributes pertaining to the generated deliverables revealed design lead time that is non-productive. These non-value adding portions of the design lead time are due to deliverables being queued for long durations before they are designed, reworked, or reviewed. This is considered major waste in design and disrupts the flow of information in timely and efficiently.

8.1.2. Key findings of the study

- *BIM implementation and collaboration*

The key findings of this study indicate that the use of BIM does not explicitly result in improved design quality and reduced wastes. In fact, the success of BIM in achieving the desired outcomes of its use highly depends on the ways in which BIM is incorporated into an organization and project. The sole use of BIM as a software or drafting tool under a traditional design mind-set does not necessarily improve the design process. In the absence of collaboration and a true spirit of teamwork, BIM’s full potential is not achieved. While BIM supports and encourages the collaboration of teams through its power of integrating building information through its smart visual and analytical capabilities, failing to form a collaborative and integrated design environment renders BIM a mere 3D drafting tool. Therefore, a change in traditional mind sets and the poorly connected social environment is necessary to reap the benefits of BIM’s use.

Establishing a shared understanding and common vision between all members is important so that each member is aware of the needs of other members. This allows to have more design input and output consideration of the members so that the timely and correct exchange of information can occur. Moreover, collaboration can increase the understanding of the design requirements and prevent the misinterpretation of design intent among teams. It can also reveal misconceptions and provide timely clarifications that can in turn prevent or reduce the generation and diffusion of design errors. Such errors and changes are a major cause for multiple iterations of revisions and rework, waste of design effort into unproductive energy and time, as well as delays in schedules and increase in set budgets. These errors and resulting wastes are a cause of and result of poor flow of information. Therefore, BIM use should be implemented fully as a process and not just a tool so that design workflow can be improved.

- *Design workflow patterns*

The study also shows that design workflow can be measured and visualized during the design phase, and such patterns can be tracked for each member, team, and the emerging system behavior resulting from the social interactions of the participants. The data collected can be used to calculate design workflow attributes such as the designing rate, sharing rate, reworking rate, revision rate, the amount of WIP in the system, as well as the daily time division between design, rework, revision, collaboration, and sharing efforts. Moreover, the study shows that it is possible to collect workflow data pertaining to the deliverables generated such as the number of rework, revision, and share iterations, the queueing duration before a deliverable is reworked, shared, or reviewed. Such data can highlight unproductive and non-value adding times in the design workflow systems and can indicate the presence of high WIP levels which cause bottlenecks and interruptions in the flow of design information.

- *Answers to research questions*

The study aims at addressing the research questions that were defined for this research. The following summarizes these questions and how the study answered them:

Q1: What are the main attributes and leading interrupters of design workflow? Chapter 4 described the attributes of design workflow such as being chaotic, having interdependent tasks, needing to be measured in terms of information flow, etc. Moreover, the interrupters that disrupt the workflow were also identified. Accumulating design information in inventories and withholding information, generating design errors and requesting changes, acquiring new information, as well as improperly communication and not collaborating are key interrupters of the smooth flow.

Q2: How do teams interact and what deliverables are generated at each design stage? Chapter 5 presented process-flow diagrams that were developed to present three things simultaneously: (1) information flow, (2) clear information exchange between the different disciplines, and (3) data deliverables resulting from each design process. Process flow diagrams for traditional and BIM-based design environments were compared to highlight the resulting changes from BIM use on the flow of information.

Q3: How do design errors diffuse within traditional and BIM-based social networks? Chapter 5 also addressed how design errors diffuse under different social networks. Agent-based models simulated the dispersion of errors under traditional and BIM-based design environments. Results showed that under favorable BIM use, errors diffuse more rapidly, however, they are detected and resolved faster. This is due to the advantages of automated clash detection and design checking enable through BIM, as well as the proper communication between the involved members.

Q4: What metrics can be used to measure workflow?

Chapter 6 developed workflow output metrics to measure the patterns of design workflow. The metrics developed were: designing rate, sharing rate, reviewing rate, reworking rate, WIP rates, time spent designing, reviewing, reworking, collaborating, and sharing. Metrics pertaining to the deliverables were also developed and measured, namely: number of rework, revision, and sharing iterations, as well as the time queued for rework, revision, and sharing. These metrics together help understand and assess workflow trends resulting from BIM use.

Q5: How do the network topology and collaboration impact workflow dynamics?

Chapter 6 presented the setup for mapping the network topology and the collaboration scaled used to assess the interaction and collaboration patters within the social network. Chapter 7 presented the results of the mapped network topology and collaboration metrics of a BIM-based design case study. Results show that centralized and loosely connected networks can result in persistent reworks and revision cycles, high WIP levels, and unsmooth sharing trends. Moreover, collaboration scales pertaining to teamwork, coordination, and decision making ranked low values. This can also be linked to the resulting workflow trends due to low level of collaboration and shared understanding between the project participants.

Q6: What is the impact of BIM use and maturity on the flow of design information?

Chapter 6 presented a matrix for measuring the BIM maturity level of the organization studied. The matrix assesses different areas of BIM maturity such as the process, policy, technology, competency, and organizational level. Chapter 7 revealed that the organization scores a less than average maturity level, where BIM is used majorly as a tool rather than a collaborative process. This is linked to the improper design workflow trends. The results reveal that the use of BIM does not necessarily result in improved design workflow processes. In fact, proper workflow is contingent upon adopting a BIM-based collaborative process, embedding shared knowledges and common goals between members, and fostering a decentralized and well-connected social network.

8.2. Contributions and recommendations

The design workflow patterns and metrics developed are value adding for research efforts on construction design because they provide a visual and measurable method to analyze and observe design dynamics occurring during any phase of design. This can help detect workflow problems and explore potential relationships between the success or failure of design and the observed workflow trends. However, this requires a further study to link design workflow trends with indicators of a project's performance.

Moreover, this study contributes to science by introducing a new perspective that changes the way design workflow has been previously analyzed, whether on BIM-based or traditional 2D CAD designs. By integrating social mechanisms and workflow dynamics, the resulting trends can be better understood and linked to the underlying social and collaborative interactions of the involved participants. This can then enable decision makers and managers to take the right actions to enhance workflow by targeting the root causes of the observed trends. While these root causes such as social interactions, BIM maturity, and the levels of collaboration were previously concealed, this study paves the way to link these underlying factors to the resulting workflow patterns and detected problems. The integrated perspective thus provides deeper insights so that problems with design workflow can be better tackled and addressed.

In relation to BIM research and practice, this study contributes to the knowledge on BIM design implications. Results highlight the need for implementing a BIM-based design "process" rather than only a BIM-based design "tool" so that collaboration and shared understanding can be an integral part of the design process. A shift from traditional design mind sets into integrated collaborative environments is necessary to realize the benefits widely known from BIM use. The lack of BIM maturity and poorly connected social ties lacking coordination and teamwork cannot change traditional design workflow. Therefore, the findings and approach of this study can contribute to research and practice by paving the way for a proactive design management approach where root causes of poor workflow become clear and the necessary steps to counteract them can be planned and implemented. Based on the findings, several recommendations for research and practice can be put forth:

(1) BIM needs to be first envisioned as a collaborative process and its capabilities for improving design and a facility's lifecycle need to be clearly delineated and understood.

(2) A change in traditional mindset needs to occur so that true collaboration and teamwork can be a natural part of the design environment.

(3) BIM use should be an enabler for integrating building information by pooling knowledge and shared understanding from all involved members.

(4) Organizations or project parties should adopt a proactive approach when improving their design by investigating root causes, visualizing and measuring on going workflow patterns, and implementing changes by counteracting underlying root causes.

(5) Research efforts need to have a more comprehensive and integrative perspective of all contributing aspects involved in shaping design workflow and avoid the split of social and technical aspects.

(6) More research focus should be placed to highlight the importance of achieving flow and value generation as well as to address the impacts of improper design workflow on the quality of design processes.

8.3. Future research

This research can be extended to be applied on more case studies to experiment with different environments to examine and analyze the changes in workflow patterns so that more generalizable outcomes can be achieved. Moreover, future research will focus on sharing the findings with the involved organization/ project teams so that the needed actions can be implemented towards the desired outputs. Changes in workflow resulting from the implemented corrective actions can be tracked to assess the effectiveness of the adopted steps. The method can also be applied to other design phases to detect changes in workflow and provide new insights into factors involved in workflow shaping. To understand how workflow can impact a project's performance, future efforts are needed to link design workflow trends with indicators or predictors of a project's performance through measuring Key Performance Indicators (KPI's).

This research can be expanded to newer dimensions where the developed methodology can be customized and implemented on other phases of a construction project such as on site construction where errors and rework can be highly costly and detrimental to the project's success. Following a similar integration of social and process perspectives, the interactions of teams and members involved in performing construction tasks can be analyzed in relation to the workflow of construction operations. Research in this area can help link underlying factors previously ignored to resulting construction workflow trends so that this phase, in turn, can be improved.

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1. SURVEY

Preamble:

❖ **Introduction**

I am humbly asking you to complete this survey, which is estimated to take about 15-20 minutes of your valuable time.

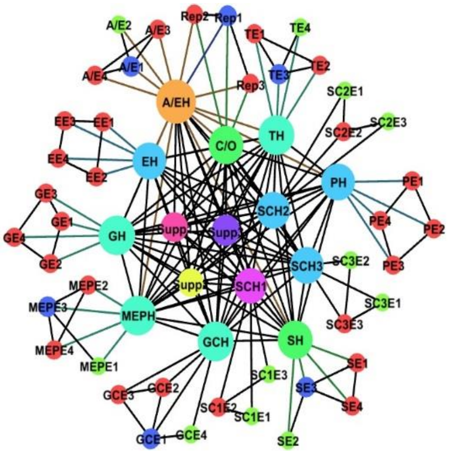
The purpose of my research is to understand how information flows between project participants within an organization, so that a theory, a model, and means of measurement can be developed.

Your valuable survey input will allow me to map out the communication network of your organization through Social Network Analysis (SNA). SNA is a very effective means as it provides both visual and mathematical analysis and interpretation of human relationships. Your input will also allow me to model (simulate) the dynamics of design information exchange and measure valuable metrics.

❖ **Survey Sections**

The survey consists of 3 sections.

- Section 1: includes seven questions about your demographical information.
- Section 2: includes general questions about the BIM-based design process you undergo
- Section 3: asks you to list the people with whom you interact (from within or outside your organization) within the scope of your profession. For each person, a set of information is required regarding the interaction and information exchange occurring with this person. The names of the people, including yours, are confidential and will not be disclosed in any private or public analyses, and instead will be given alphanumeric codes (i.e., Name = A1 or B9…) for the mapping of the social network. The result is a map similar to the image on the right:



- Section 4: aims to help gather information about your design process: types of deliverables you produce, time to design, reviewing deliverables, and other information. The information provided is also anonymous and will not be disclosed to any individual. The data gathered will be used as input for the simulation that will model how individual and network characteristics affect design workflow under different environments.

Section 1: Demographical Information

Q1. Name & Contact No.: ____________________

Department's Name: ____________________

Q2. What is your profession?

- ☐ BIM support
- ☐ Architect
- ☐ Project manager
- ☐ Design/ Construction Manager
- ☐ Facility/Operations Manager
- ☐ Planning Engineer
- ☐ Structural Engineer
- ☐ Geotechnical Engineer
- ☐ Transportation Engineer
- ☐ Telecom Engineer
- ☐ Landscape
- ☐ Environmental Engineer
- ☐ Mechanical Engineer
- ☐ Electrical Engineer
- ☐ Manufacturing Engineer
- ☐ Industrial Engineer
- ☐ Other, please specify: ____________________

Q3. What is the highest educational qualification you have completed?

- ☐ High School Certificate
- ☐ Bachelor's Degree
- ☐ Master's Degree
- ☐ Doctorate
- ☐ Other, please specify: ____________________

Q4. How long have you worked for this firm?

- ☐ Less than 6 months
- ☐ 6 months to 1 year
- ☐ 2 to 3 years
- ☐ 4 to 5 years
- ☐ 6 to 10 years
- ☐ More than 10 years
- ☐ Other, please specify: ____________________

Q6. Your overall experience in the building industry is:

- ☐ Less than 6 months
- ☐ 6 months to 1 year
- ☐ 2 to 3 years
- ☐ 4 to 5 years
- ☐ 6 to 10 years
- ☐ More than 10 years
- ☐ Other, please specify: ____________________

Section 2: Building Information Modeling Design Process

This set of questions aims to help us understand the process of designing through Building Information Modeling in order to better simulate and understand the design information flow under BIM-based design phases.

1. **How many months or years of experience do you have with BIM? __________** (months or years)

2. **How do you perform design and modeling using BIM? Please choose all the options that apply.**

- ☐ We first perform design using tools like AutoCAD, Etabs, etc., then model them through BIM (Revit, Bentley, etc.)
- ☐ We first design and model in BIM, then extract drawings, schedules, and other information and exchange them for further design, revisions, and coordination
- ☐ We design and model everything in the BIM environment without requiring other non-BIM software
- ☐ We design and model in BIM and non-BIM software as an iterative process (both ways)
- ☐ We do not use BIM at all
- ☐ Other, please explain: ____

3. **What deliverables do you use to coordinate and exchange design information? Please choose all the options that apply.**

- ☐ BIM model + design drawings extracted from the BIM model
- ☐ BIM model + design drawings prepared separately
- ☐ BIM model + BOQ and schedules extracted from BIM model
- ☐ BIM model + BOQ and schedules prepared separately
- ☐ BIM model + design requirements and specifications
- ☐ BIM model + design calculations and analysis performed through BIM model
- ☐ BIM model + design calculations and analysis performed outside BIM
- ☐ Only BIM models
- ☐ Only non-BIM documents (AutoCAD drawings, design analysis, schedules, etc.

4. **How do you coordinate BIM design models?**

- ☐ Before performing clash detection or coordinating your work with others, you continue developing your model and updating it on the system until others are ready to integrate their models with yours
- ☐ You meet with people from your team and other teams to perform design coordination together
- ☐ You, or someone from your team, collect(s) models of your team and perform clash detection

- ☐ Each person within your team models a zone or an issue on the project
- ☐ Someone integrates all models of disciplines into a central model and clash detection
- ☐ When performing clash detection, you only use the BIM models for automating the process
- ☐ When performing clash detection, you only use non-BIM documents to check for conflicts
- ☐ When performing clash detection, you use the BIM model and supporting documents extracted from BIM and other non-BIM related documents
- ☐ How frequently do you coordinate and perform clash detection?

____

5. Please choose the ways in which you use BIM. Please choose all options that apply

- ☐ as a 3D model for representation and visualization purposes
- ☐ as a cost estimating tool
- ☐ to coordinate different disciplines'/ trades' work and information sharing
- ☐ to assist with construction operations on site
- ☐ to detect clashes between different disciplines/ trades before construction
- ☐ to avoid errors and omissions
- ☐ to avoid claims and litigation
- ☐ as an open database for the project/facility lifecycle's information
- ☐ to evaluate design systems and perform design analysis

Other: ____

Section 3: Information Exchange and Communication

Please specify all the names of all people you interact with, the organization they work for, means of design information exchange and respective percentage, and direction and its percentage of design information exchange. Please choose all the options that apply.

	Person's Name	Means and respective percentages of design information exchange
1		☐Face-to-face ☐Emails ☐Meetings ☐Other: ☐Telephone + screen sharing
2		☐Face-to-face ☐Emails ☐Meetings ☐Other: ☐Telephone + screen sharing
3		☐Face-to-face ☐Emails ☐Meetings ☐Other: ☐Telephone + screen sharing
4		☐Face-to-face ☐Emails ☐Meetings ☐Other: ☐Telephone + screen sharing
5		☐Face-to-face ☐Emails ☐Meetings ☐Other: ☐Telephone + screen sharing
6		☐Face-to-face ☐Emails ☐Meetings ☐Other: ☐Telephone + screen sharing
7		☐Face-to-face ☐Emails ☐Meetings ☐Other: ☐Telephone + screen sharing
8		☐Face-to-face ☐Emails ☐Meetings ☐Other: ☐Telephone + screen sharing
9		☐Face-to-face ☐Emails ☐Meetings ☐Other: ☐Telephone + screen sharing
10		☐Face-to-face ☐Emails ☐Meetings ☐Other: ☐Telephone + screen sharing

Please specify the types of design models or deliverables (information) that you SEND TO each person. Also specify the average number of each type.

	Design deliverables you <u>SEND TO</u> each person
1	□BIM models _____ (per Day/Week) □BOQ, schedules, etc. _____ (per Day/Week) □Design drawings _____ (per Day/Week) □Task assignments _____ (per Day/Week) □Design calculations _____ (per Day/Week) □Instructions _____ (per Day/Week) □Design Specs _____ (per Day/Week) □Emails (general inquiries): ____ (per Day/Week)
2	□BIM models _____ (per Day/Week) □BOQ, schedules, etc. _____ (per Day/Week) □Design drawings _____ (per Day/Week) □Task assignments _____ (per Day/Week) □Design calculations _____ (per Day/Week) □Instructions _____ (per Day/Week) □Design Specs _____ (per Day/Week) □Emails (general inquiries): ____ (per Day/Week)
3	□BIM models _____ (per Day/Week) □BOQ, schedules, etc. _____ (per Day/Week) □Design drawings _____ (per Day/Week) □Task assignments _____ (per Day/Week) □Design calculations _____ (per Day/Week) □Instructions _____ (per Day/Week) □Design Specs _____ (per Day/Week) □Emails (general inquiries): ____ (per Day/Week)
4	□BIM models _____ (per Day/Week) □BOQ, schedules, etc. _____ (per Day/Week) □Design drawings _____ (per Day/Week) □Task assignments _____ (per Day/Week) □Design calculations _____ (per Day/Week) □Instructions _____ (per Day/Week) □Design Specs _____ (per Day/Week) □Emails (general inquiries): ____ (per Day/Week)
5	□BIM models _____ (per Day/Week) □BOQ, schedules, etc. _____ (per Day/Week) □Design drawings _____ (per Day/Week) □Task assignments _____ (per Day/Week) □Design calculations _____ (per Day/Week) □Instructions _____ (per Day/Week) □Design Specs _____ (per Day/Week) □Emails (general inquiries): ____ (per Day/Week)
6	□BIM models _____ (per Day/Week) □BOQ, schedules, etc. _____ (per Day/Week) □Design drawings _____ (per Day/Week) □Task assignments _____ (per Day/Week) □Design calculations _____ (per Day/Week) □Instructions _____ (per Day/Week) □Design Specs _____ (per Day/Week) □Emails (general inquiries): ____ (per Day/Week)
7	□BIM models _____ (per Day/Week) □BOQ, schedules, etc. _____ (per Day/Week) □Design drawings _____ (per Day/Week) □Task assignments _____ (per Day/Week) □Design calculations _____ (per Day/Week) □Instructions _____ (per Day/Week) □Design Specs _____ (per Day/Week) □Emails (general inquiries): ____ (per Day/Week)
8	□BIM models _____ (per Day or Week) □BOQ, schedules, etc. _____ (per Day or Week) □Design drawings _____ (per Day or Week) □Task assignments _____ (per Day or Week) □Design calculations _____ (per Day or Week) □Instructions _____ (per Day or Week) □Design Specs _____ (per Day or Week) □Emails (general inquiries): ____ (per Day or Week
9	□BIM models _____ (per Day/Week) □BOQ, schedules, etc. _____ (per Day/Week) □Design drawings _____ (per Day/Week) □Task assignments _____ (per Day/Week) □Design calculations _____ (per Day/Week) □Instructions _____ (per Day/Week) □Design Specs _____ (per Day/Week) □Emails (general inquiries): ____ (per Day/Week)
10	□BIM models _____ (per Day/Week) □BOQ, schedules, etc. _____ (per Day/Week) □Design drawings _____ (per Day/Week) □Task assignments _____ (per Day/Week) □Design calculations _____ (per Day/Week) □Instructions _____ (per Day/Week) □Design Specs _____ (per Day/Week) □Emails (general inquiries): ____ (per Day/Week)

Please specify the types of design models or deliverables (information) that you RECEIVE FROM each person. Also specify the average number of each type.

	Design deliverables you RECEIVE FROM each person	
1	□BIM models _____ (per Day/Week) □Design drawings _____ (per Day/Week) □Design calculations _____ (per Day/Week) □Design Specs _____ (per Day/Week)	□BOQ, schedules, etc. _____ (per Day/Week) □Task assignments _____ (per Day/Week) □Instructions _____ (per Day/Week) □Emails (general inquiries): ____ (per Day/Week)
2	□BIM models _____ (per Day/Week) □Design drawings _____ (per Day/Week) □Design calculations _____ (per Day/Week) □Design Specs _____ (per Day/Week)	□BOQ, schedules, etc. _____ (per Day/Week) □Task assignments _____ (per Day/Week) □Instructions _____ (per Day/Week) □Emails (general inquiries): ____ (per Day/Week)
3	□BIM models _____ (per Day/Week) □Design drawings _____ (per Day/Week) □Design calculations _____ (per Day/Week) □Design Specs _____ (per Day/Week)	□BOQ, schedules, etc. _____ (per Day/Week) □Task assignments _____ (per Day/Week) □Instructions _____ (per Day/Week) □Emails (general inquiries): ____ (per Day/Week)
4	□BIM models _____ (per Day/Week) □Design drawings _____ (per Day/Week) □Design calculations _____ (per Day/Week) □Design Specs _____ (per Day/Week)	□BOQ, schedules, etc. _____ (per Day/Week) □Task assignments _____ (per Day/Week) □Instructions _____ (per Day/Week) □Emails (general inquiries): ____ (per Day/Week)
5	□BIM models _____ (per Day/Week) □Design drawings _____ (per Day/Week) □Design calculations _____ (per Day/Week) □Design Specs _____ (per Day/Week)	□BOQ, schedules, etc. _____ (per Day/Week) □Task assignments _____ (per Day/Week) □Instructions _____ (per Day/Week) □Emails (general inquiries): ____ (per Day/Week)
6	□BIM models _____ (per Day/Week) □Design drawings _____ (per Day/Week) □Design calculations _____ (per Day/Week) □Design Specs _____ (per Day/Week)	□BOQ, schedules, etc. _____ (per Day/Week) □Task assignments _____ (per Day/Week) □Instructions _____ (per Day/Week) □Emails (general inquiries): ____ (per Day/Week)
7	□BIM models _____ (per Day/Week) □Design drawings _____ (per Day/Week) □Design calculations _____ (per Day/Week) □Design Specs _____ (per Day/Week)	□BOQ, schedules, etc. _____ (per Day/Week) □Task assignments _____ (per Day/Week) □Instructions _____ (per Day/Week) □Emails (general inquiries): ____ (per Day/Week)
8	□BIM models _____ (per Day or Week) □Design drawings _____ (per Day or Week) □Design calculations _____ (per Day or Week) □Design Specs _____ (per Day or Week)	□BOQ, schedules, etc. _____ (per Day or Week) □Task assignments _____ (per Day or Week) □Instructions _____ (per Day or Week) □Emails (general inquiries): ____ (per Day or Week
9	□BIM models _____ (per Day/Week) □Design drawings _____ (per Day/Week) □Design calculations _____ (per Day/Week) □Design Specs _____ (per Day/Week)	□BOQ, schedules, etc. _____ (per Day/Week) □Task assignments _____ (per Day/Week) □Instructions _____ (per Day/Week) □Emails (general inquiries): ____ (per Day/Week)
10	□BIM models _____ (per Day/Week) □Design drawings _____ (per Day/Week) □Design calculations _____ (per Day/Week) □Design Specs _____ (per Day/Week)	□BOQ, schedules, etc. _____ (per Day/Week) □Task assignments _____ (per Day/Week) □Instructions _____ (per Day/Week) □Emails (general inquiries): ____ (per Day/Week)

Please specify the relation of roles between you and each person, the use of information exchanged. Please choose all the options that apply.

	Role of person or use of the information exchanged	
1	□He/she reviews and coordinates your design □You review and coordinate his/her design □His/her design provides input for your design □Your design provides input for his/her design □His/her design helps you solve a problem, correct errors, or make a decision □Your design helps him/her solve a problem, correct errors, or make a decision	□He/she provides instructions □You provide instructions to him/her □Other, please specify: ______________
2	□He/she reviews and coordinates your design □You review and coordinate his/her design □His/her design provides input for your design □Your design provides input for his/her design □His/her design helps you solve a problem, correct errors, or make a decision □Your design helps him/her solve a problem, correct errors, or make a decision	□He/she provides instructions □You provide instructions to him/her □Other, please specify: ______________
3	□He/she reviews and coordinates your design □You review and coordinate his/her design □His/her design provides input for your design □Your design provides input for his/her design □His/her design helps you solve a problem, correct errors, or make a decision □Your design helps him/her solve a problem, correct errors, or make a decision	□He/she provides instructions □You provide instructions to him/her □Other, please specify: ______________
4	□He/she reviews and coordinates your design □You review and coordinate his/her design □His/her design provides input for your design □Your design provides input for his/her design □His/her design helps you solve a problem, correct errors, or make a decision □Your design helps him/her solve a problem, correct errors, or make a decision	□He/she provides instructions □You provide instructions to him/her □Other, please specify: ______________
5	□He/she reviews and coordinates your design □You review and coordinate his/her design □His/her design provides input for your design □Your design provides input for his/her design □His/her design helps you solve a problem, correct errors, or make a decision □Your design helps him/her solve a problem, correct errors, or make a decision	□He/she provides instructions □You provide instructions to him/her □Other, please specify: ______________
6	□He/she reviews and coordinates your design □You review and coordinate his/her design □His/her design provides input for your design □Your design provides input for his/her design □His/her design helps you solve a problem, correct errors, or make a decision □Your design helps him/her solve a problem, correct errors, or make a decision	□He/she provides instructions □You provide instructions to him/her □Other, please specify: ______________

7	□He/she reviews and coordinates your design □You review and coordinate his/her design □His/her design provides input for your design □Your design provides input for his/her design □His/her design helps you solve a problem, correct errors, or make a decision □Your design helps him/her solve a problem, correct errors, or make a decision	□He/she provides instructions □You provide instructions to him/her □Other, please specify: _____________
8	□He/she reviews and coordinates your design □You review and coordinate his/her design □His/her design provides input for your design □Your design provides input for his/her design □His/her design helps you solve a problem, correct errors, or make a decision □Your design helps him/her solve a problem, correct errors, or make a decision	□He/she provides instructions □You provide instructions to him/her □Other, please specify: _____________
9	□He/she reviews and coordinates your design □You review and coordinate his/her design □His/her design provides input for your design □Your design provides input for his/her design □His/her design helps you solve a problem, correct errors, or make a decision □Your design helps him/her solve a problem, correct errors, or make a decision	□He/she provides instructions □You provide instructions to him/her □Other, please specify: _____________
10	□He/she reviews and coordinates your design □You review and coordinate his/her design □His/her design provides input for your design □Your design provides input for his/her design □His/her design helps you solve a problem, correct errors, or make a decision □Your design helps him/her solve a problem, correct errors, or make a decision	□He/she provides instructions □You provide instructions to him/her □Other, please specify: _____________

Please specify the frequency and time of information exchange with each person.

	Frequency of exchange	Time at which you exchange information		Time interval between each exchange of design information	
1	1 2 3 4 5	☐ Every day casually ☐When there is a meeting ☐When deliverables are due	☐ When there is a problem ☐When requested by the other ☐When you request it	☐1-2 days ☐3-4 days ☐1 week	☐>1 week ☐<1 month ☐Other:
2	1 2 3 4 5	☐ Every day casually ☐When there is a meeting ☐When deliverables are due	☐ When there is a problem ☐When requested by the other ☐When you request it	☐1-2 days ☐3-4 days ☐1 week	☐>1 week ☐<1 month ☐Other:
3	1 2 3 4 5	☐ Every day casually ☐When there is a meeting ☐When deliverables are due	☐ When there is a problem ☐When requested by the other ☐When you request it	☐1-2 days ☐3-4 days ☐1 week	☐>1 week ☐<1 month ☐Other:
4	1 2 3 4 5	☐ Every day casually ☐When there is a meeting ☐When deliverables are due	☐ When there is a problem ☐When requested by the other ☐When you request it	☐1-2 days ☐3-4 days ☐1 week	☐>1 week ☐<1 month ☐Other:
5	1 2 3 4 5	☐ Every day casually ☐When there is a meeting ☐When deliverables are due	☐ When there is a problem ☐When requested by the other ☐When you request it	☐1-2 days ☐3-4 days ☐1 week	☐>1 week ☐<1 month ☐Other:
6	1 2 3 4 5	☐ Every day casually ☐When there is a meeting ☐When deliverables are due	☐ When there is a problem ☐When requested by the other ☐When you request it	☐1-2 days ☐3-4 days ☐1 week	☐>1 week ☐<1 month ☐Other:
7	1 2 3 4 5	☐ Every day casually ☐When there is a meeting ☐When deliverables are due	☐ When there is a problem ☐When requested by the other ☐When you request it	☐1-2 days ☐3-4 days ☐1 week	☐>1 week ☐<1 month ☐Other:
8	1 2 3 4 5	☐ Every day casually ☐When there is a meeting ☐When deliverables are due	☐ When there is a problem ☐When requested by the other ☐When you request it	☐1-2 days ☐3-4 days ☐1 week	☐>1 week ☐<1 month ☐Other:
9	1 2 3 4 5	☐ Every day casually ☐When there is a meeting ☐When deliverables are due	☐ When there is a problem ☐When requested by the other ☐When you request it	☐1-2 days ☐3-4 days ☐1 week	☐>1 week ☐<1 month ☐Other:
10	1 2 3 4 5	☐ Every day casually ☐When there is a meeting ☐When deliverables are due	☐ When there is a problem ☐When requested by the other ☐When you request it	☐1-2 days ☐3-4 days ☐1 week	☐>1 week ☐<1 month ☐Other:

Section 4: Information about the Design Process

1. **What are the different types and numbers of models and deliverables you PRODUCE per day (or week)?**
   Please tick the types and specify the respective number in the blanks where applicable, and circle if it is per Day or Per Week:

☐ BIM models _____ (Per Day or Week)

☐ CAD design drawings _____ (Per Day or Week)

☐ Design calculations _____ (Per Day or Week)

☐ Specs _____ (Per Day or Week)

☐ BOQ and schedules _____ (Per Day or Week)

☐ Reports _____ (Per Day or Week)

☐ Other: ___________________________________ (Per Day or Week)

2. **How many hours or days, on average, does it require you to COMPLETE a design model or deliverable?**
   Please tick the types and specify the respective number in the blanks where applicable, and circle if it is Hours or Days:

☐ BIM models _____

☐ CAD design drawing _____

☐ Design calculations _____

☐ Specs _____

☐ BOQ and schedules _____

☐ Reports _____

☐ Other: ___________________________________

3. **How many hours or days, on average, do you spend REVIEWING/ COORDINATING someone else's models or deliverables?**

   ___________________________________ (Hours or Days)

4. **How many hours or days, on average, does it require you to AMEND/ MODIFY your models or deliverables that need revisions?**

   ___________________________________ (Hours or Days)

5. **What is the average "acceptance/ revisions needed/ rejection/" ratio per your model or deliverable?**

Acceptance: _____% *Revisions needed:* _____% *Rejection:* _____%

6. When you receive a revisions needed or rejection on your model or deliverable, what are the reasons?

☐ Calculation mistake

☐ Omissions (missing information)

☐ Deviation from design requirements

☐ Using wrong information supplied though someone else's design deliverables

☐ Unclear design requirements

☐ Coordination problems with other designs (clashes, conflicts…)

☐ Other, please specify:

____

7. How many meetings are held per day or week, and what is the average duration of each meeting?

Number of Meeting(s): _______ (per day or week)

Meeting tyoes:

____

____

____

Average Duration of One Meeting: _______

8. Please choose all options that are TRUE:

☐ Do not stop until your design deliverable is complete
☐ Perform other tasks requested by others and then resume working on your design model or deliverable
☐ Work on several models or deliverables in parallel (concurrent designing)
☐ Create some errors, detect them, and correct them before sharing the model or deliverable with others
☐ Create some errors without noticing and correct them after others review your model or deliverable
☐ Share one model or deliverable immediately after its completion
☐ Wait until you complete other models or deliverables and then share them all together at once
☐ Review your model(s) or deliverable(s) before sharing
☐ Share your model(s) or deliverable(s) without reviewing them
☐ For each person, you review one of his/her models or deliverables and submit feedback once done
☐ For each person, you review several models or deliverables in parallel and submit all feedback once all models or deliverables are completed
☐ When modifying your models or deliverables that need revisions, you work on each one separately and submit it for another cycle of revision
☐ When modifying your models or deliverables that need revisions, you work on all in parallel and submit for another cycle of revision

- ☐ It takes on average, 1, 2, 3, or ____ cycles of revision to have a model or deliverable accepted (please select number)
- ☐ When designing, you work on your design alone and consult others occasionally
- ☐ When designing, you design collaboratively in teams most of the time
- ☐ When designing, you would like to work collaboratively but others prefer to work alone
- ☐ When reviewing and coordinating design works, you do the coordination and revision on your own and consult others when needed
- ☐ When reviewing and coordinating design works, you do the coordination and revision as a collaborative team most of the time
- ☐ In meetings, you highlight problems and then work on them alone after the meeting
- ☐ In meetings, you work collaboratively and solve problems on the spot
- ☐ Collaboration frequently happens during formal meetings, daily team work, or occasional discussions (please circle what applies)
- ☐ Design requirements are always clear and checked for during design progress
- ☐ Design requirements are NOT always clear and not checked for during design progress
- ☐ Collaborative discussions can enhance my understanding of design requirements and help me achieve better design
- ☐ Collaborative discussions do NOT have much impact on my understanding of design requirements
- ☐ Teamwork helps us resolve conflicts and detect problems with design
- ☐ Teamwork does NOT help us detect or resolve problems
- ☐ Teamwork helps save time when designing, reviewing, or coordinating work
- ☐ Teamwork takes so much time and has little impact
- ☐ Other: ____

Other Notes/ Comments:

____
____
____
____

2. BIM MATURITY MATRICES

BIM COMPETENCY SETS		BIM Competency Areas at Granularity level 1	a INITIAL	b DEFINED	c MANAGED	d INTEGRATED	e OPTIMISED
	TECHNOLOGY	**Software:** applications, deliverables and data	Usage of software applications is unmonitored and unregulated. 3D Models are relied on to mainly generate accurate 2D representations/deliverables. Data usage, storage and exchanges are not defined within organisations or project teams. Exchanges suffer from a severe lack of interoperability.	Software usage/introduction is unified within an organisation or project teams (multiple organisations). 3D Models are relied upon to generate 2D as well as 3D deliverables. Data usage, storage and exchange are well defined within organisations and project teams. Interoperable data exchanges are defined and prioritised.	Software selection and usage is controlled and managed according to defined deliverables. Models are the basis for 3D views, 2D representations, quantification, specification and analytical studies. Data usage, storage and exchanges are monitored and controlled. Data flow is documented and well-managed. Interoperable data exchanges are mandated and closely monitored.	Software selection and deployment follows strategic objectives, not just operational requirements. Modelling deliverables are well synchronised across projects and tightly integrated with business processes. Interoperable data usage, storage and exchange are regulated and performed as part of an overall organisational or project-team strategy.	Selection/use of software tools is continuously revisited to enhance productivity and align with strategic objectives. Modelling deliverables are cyclically being revised/ optimised to benefit from new software functionalities and available extensions. All matters related to interoperable data usage storage and exchange are documented, controlled, reflected upon and proactively enhanced.
		Hardware: equipment, deliverables and location/mobility	BIM equipment is inadequate; specifications are too low or inconsistent across the organisation. Equipment replacement or upgrades are treated as cost items and performed only when unavoidable.	Equipment specifications – suitable for the delivery of BIM products and services - are defined, budgeted-for and standardised across the organisation. Hardware replacements and upgrades are well-defined cost items.	A strategy is in place to transparently document, manage and maintain BIM equipment. Investment in hardware is well-targeted to enhance staff mobility (where needed) and extend BIM productivity.	Equipment deployments are treated as BIM enablers. Investment in equipment is tightly integrated with financial plans, business strategies and performance objectives.	Existing equipment and innovative solutions are continuously tested, upgraded and deployed. BIM hardware become part of organisation's or project team's competitive advantage.
		Network: solutions, deliverables and security/ access control	Network solutions are non-existent or ad-hoc. Individuals, organisations (single location/ dispersed) and project teams use whatever tools found to communicate and share data. Stakeholders lack the network infrastructure necessary to harvest, store and share knowledge.	Network solutions for sharing information and controlling access are identified within and between organisations. At project level, stakeholders identify their requirements for sharing data/information. Dispersed organisations and project teams are connected through relatively low-bandwidth connections.	Network solutions for harvesting, storing and sharing knowledge within and between organisations are well managed through common platforms (e.g. intranets or extranets). Content and asset management tools are deployed to regulate structured and unstructured data shared across high-bandwidth connections.	Network solutions enable multiple facets of the BIM process to be integrated through seamless real-time sharing of data, information and knowledge. Solutions include project-specific networks/portals which enable data-intensive interchange (interoperable exchange) between stakeholders.	Network solutions are continuously assessed and replaced by the latest tested innovations. Networks facilitate knowledge acquisition, storing and sharing between all stakeholders. Optimisation of integrated data , process and communication channels is relentless.

BIM COMPETENCY SETS		BIM Competency Areas at Granularity level 1	a INITIAL	b DEFINED	c MANAGED	d INTEGRATED	e OPTIMISED
	PROCESS	**Infrastructure:** physical and knowledge-related	The work environment is either not recognised as a factor in staff satisfaction or may not be conducive to productivity. Knowledge is not recognised as an asset; BIM knowledge is typically shared informally between staff (through tips, techniques and lessons learned).	The work environment and workplace tools are identified as factors affecting motivation and productivity. Similarly, knowledge is recognised as an asset; shared knowledge is harvested, documented and thus transferred from tacit to explicit.	The work environment is controlled, modified and it's criteria managed to enhance staff motivation, satisfaction and productivity. Also, documented knowledge is adequately stored.	Environmental factors are integrated into performance strategies. Knowledge is integrated into organisational systems; stored knowledge is made accessible and easily retrievable [refer to the 4 levels of knowledge retention (Arif et al., 2009)].	Physical workplace factors are reviewed constantly to insure staff satisfaction and an environment conducive to productivity. Similarly, knowledge structures responsible for acquisition, representation and dissemination are systematically reviewed and enhanced.
		Products & Services specification, differentiation, project delivery approach and R&D	3D models deliverables (a BIM product) suffer from too high, too low or inconsistent levels of detail.	A "statement defining the object breakdown of the 3D model" (Bouygues, 2007) is available.	Adoption of product/ service specifications similar to Model Progression Specifications (AIA, 2008), BIPS 'information levels' (BIPS, 2008) or similar.	Products and services are specified and differentiated according to Model Progression Specifications or similar.	BIM products and services are constantly evaluated; feedback loops promote continuous improvement.
		Human Resources: competencies, roles, experience and dynamics	There is an absence of defined processes; roles are ambiguous and team structures/dynamics are inconsistent. Performance is unpredictable and productivity depends on individual heroics. A mentality of 'working 'around the system' flourishes.	BIM roles are informally defined and teams are formed accordingly. Each BIM project is planned independently. BIM competency is identified and targeted; BIM heroism fades as competency increases but productivity is still unpredictable.	Cooperation within organisations increases as tools for cross-project communication are made available. Flow of information steadies; BIM roles are visible and targets are achieved more consistently.	BIM roles and competency targets are imbedded within the organisation. Traditional teams are replaced by BIM-oriented ones as new processes become part of organisation's / project team's culture. Productivity is now consistent and predictable.	BIM competency targets are continuously upgraded to match technological advances and align with organisational objectives. Human resource practices are proactively reviewed to insure intellectual capital matches process needs.
		Leadership: innovation and renewal, strategic, organisational, communicative and managerial attributes	Senior leaders/ managers have varied visions about BIM. BIM implementation (according to BIM Stage requirements) is conducted without a guiding strategy. At this maturity level, BIM is treated as a technology stream; innovation is not recognised as a independent value and business opportunities arising from BIM are not acknowledged.	Senior leaders/managers adopt a common vision about BIM. BIM implementation strategy lacks actionable details. BIM is treated as a process-changing, technology stream. Product and process innovations are recognised; business opportunities arising from BIM are identified but not exploited.	The vision to implement BIM is communicated and understood by most staff. BIM implementation strategy is coupled with detailed action plans and a monitoring regime. BIM is acknowledged as a series of technology, process and policy changes which need to be managed without hampering innovation. Business opportunities arising from BIM are acknowledged and used in marketing efforts.	The vision is shared by staff across the organisation and/or project partners. BIM implementation, its requirements and process/ product innovation are integrated into organisational, strategic, managerial and communicative channels. Business opportunities arising from BIM are part of team, organisation or project-team's competitive advantage and are used to attract and keep clients.	Stakeholders have internalised the BIM vision and are actively achieving it (Nightingale & Mize, 2002). BIM implementation strategy and its effects on organisational models are continuously revisited and realigned with other strategies. If alterations are needed, they are proactively implemented. Innovative product/ process solutions and business opportunities are sought-after and followed through relentlessly.

BIM COMPETENCY SETS		BIM Competency Areas at Granularity level 1	a **INITIAL**	b **DEFINED**	c **MANAGED**	d **INTEGRATED**	e **OPTIMISED**
	POLICY	**Regulatory**: rules/ directives, standards/ classifications, guidelines/ benchmarks and codes/ regulations	There are no BIM guidelines, documentation protocols or modelling standards. There is an absence of documentation and modelling standards. There is informal or no quality control plans; neither for 3D models nor for documentation. There are no performance benchmarks for processes, products or services.	Basic BIM guidelines are available (e.g. training manual and BIM delivery standards). Modelling and documentation standards are well defined according to market-accepted standards. Quality targets and performance benchmarks are set.	Detailed BIM guidelines are available (training, standards, workflow, exceptions...). Modelling, representation, quantification, specifications and analytical properties of 3D models are managed through detailed modelling standards and quality plans. Performance against benchmarks is tightly monitored and controlled.	BIM guidelines are integrated into overall policies and business strategies. BIM standards and performance benchmarks are incorporated into quality management and performance improvement systems.	BIM guidelines are continuously and proactively refined to reflect lessons learned and industry best practices. Quality improvement and adherence to regulations and codes are continuously aligned and refined. Benchmarks are repetitively revisited to insure highest possible quality in processes, products and services
		Contractual: responsibilities, rewards and risks	Dependence on pre-BIM contractual arrangements. BIM risks related to model-based collaboration (differ in each market) are not recognised or are ignored.	BIM requirements are recognised. "Statements defining the responsibility of each stakeholder regarding information management" (Bouygues, 2007) are now available.	There is a mechanism to manage shared BIM intellectual property, confidentiality, liability and a system for BIM conflict resolution.	Organisation are aligned through trust and mutual dependency beyond contractual barriers.	Responsibilities, risks and rewards are continuously revisited and realigned to effort. Contractual model are modified to achieve best practices and highest value for all stakeholders.
		Preparatory: research efforts/ deliverables, educational programmes/ deliverables and training programmes	Very little or no training available to BIM staff. Educational/ training mediums are not suitable to achieve the results sought.	Training requirements are defined and are typically provided only when needed. Training mediums are varied allowing flexibility in content delivery.	Training requirements are managed to adhere to pre-set broad competency and performance objectives. Training mediums are tailored to suit trainees and reach learning objectives in a cost-effective manner.	Training is integrated into organisational strategies and performance targets. Training is typically based on staff roles and respective competency objectives. Training mediums are incorporated into knowledge and communication channels.	Training is continuously evaluated and improved upon. Training availability and delivery methods are tailored to allow multi-modal continuous learning.

			a	b	c	d	e
			INITIAL	**DEFINED**	**MANAGED**	**INTEGRATED**	**OPTIMISED**
BIM CAPABILTY STGAES	STAGE 1	**Object-based Modelling**: single-disciplinary use within a Project Lifecycle Phase	Implementation of an object-based tool. No process or policy changes identified to accompany this implementation.	Pilot projects are concluded. BIM process and policy requirements are identified. Implementation strategy and detailed plans are prepared.	BIM processes and policies are instigated, standardised and controlled.	BIM technologies, processes and policies are integrated into organisational strategies and aligned with business objectives.	BIM technologies, processes and policies are continuously revisited to benefit from innovation and achieve higher performance targets.
BIM CAPABILTY STGAES	STAGE 2	**Modelling-based Collaboration**: multi-disciplinary, fast-tracked interchange of models	Ad-hoc BIM collaboration; in-house collaboration capabilities incompatible with project partners. Trust and respect between project participants may be lacking.	Single-thread, well-defined yet reactive BIM collaboration. There are identifiable signs of mutual trust and respect among project participants.	Multi-thread proactive collaboration; protocols are well documented and managed. There are mutual trust, respect and sharing of risks and rewards among project participants.	Multi-thread collaboration includes downstream players. This is characterised by the involvement of key participants during projects' early lifecycle phases.	Multi-thread team included all key players in an environment characterised by goodwill, trust and respect.
BIM CAPABILTY STGAES	STAGE 3	**Network-based Integration**: concurrent interdisciplinary interchange of nD models across Project Lifecycle Phases	Integrated models are generated by a limited set of project stakeholders - possibly behind corporate firewalls. Integration occurs with little or no pre-defined process guides, standards or interchange protocols. There is no formal resolution of stakeholders' roles and responsibilities.	Integrated models are generated by a large subset of project stakeholders. Integration follows predefined process guides, standards and interchange protocols. Responsibilities are distributed and risks are mitigated through contractual means.	Integrated models (or parts of) are generated and managed by most project stakeholders. Responsibilities are clear within temporary project alliances or longer-term partnerships. Risks and rewards are actively managed and distributed.	Integrated models are generated and managed by all key project stakeholders. Network-based integration is the norm and focus is no longer on *how* to integrate models/ workflows but on proactively detecting and resolving technology, process and policy misalignments.	Integration of models and workflows are continuously revisited and optimised. New efficiencies, deliverables and alignments are actively pursued by a tightly-knit interdisciplinary project team. Integrated models are contributed to by many stakeholders along the construction supply chain.
ORGANISATIONAL SCALES	MICRO	**Organisations:** dynamics and BIM deliverables	BIM leadership is non-existent; implementation depends on technology champions.	BIM leadership is formalised; different roles within the implementation process are defined.	Pre-defined BIM roles complement each other in managing the implementation process.	BIM roles are integrated into organisation's leadership structures.	BIM leadership continuously mutates to allow for new technologies, processes and deliverables.
ORGANISATIONAL SCALES	MESO	**Project Teams** (multiple organisations): inter-organisational dynamics and BIM deliverables	Each project is run independently. There is no agreement between stakeholders to collaborate beyond their current common project.	Stakeholders think beyond a single project. Collaboration protocols between project stakeholders are defined and documented.	Collaboration between multiple organisations over several projects is managed through temporary alliances between stakeholders.	Collaborative projects are undertaken by inter-disciplinary organisations or multidisciplinary project teams; an alliance of many key stakeholders.	Collaborative projects are undertaken by self-optimising interdisciplinary project teams which include most stakeholders.
ORGANISATIONAL SCALES	MACRO	**Markets:** dynamics and BIM deliverables	Very few supplier-generated BIM components (virtual products and materials representing physical ones). Most components are prepared by software developers and end-users.	Supplier-generated BIM components are increasingly available as manufactures/ suppliers identify the business benefits.	BIM Components are available through highly accessible/searchable central repositories. Components are not interactively connected to suppliers' databases.	Access to component repositories is integrated into BIM software. Components are interactively linked to source databases (for price, availability, etc...).	Dynamic, multi-way generation and interchange of BIM components (virtual products and materials) between all project stakeholders through central or meshed repositories.

3. SNA AND COLLABORATION METRICS

	SNA metrics				Collaboration metrics					
Label	Degree Centrality	Closness Centrality	Betweeness Centrality	Clustering Coefficient	γi (teamwork constant)	βi (decision making constant)	αi (coordination constant)	τi (teamwork scale/node)	δi (decision making scale/node)	χi (coordination scale/node)
PM	25.00	0.74	56.24	0.42	0.7	0.7	0.7	17.80	0.81	18.02
BC/BS	26.00	0.74	56.04	0.42	0.7	0.7	0.7	18.49	0.81	18.72
SL/DC	3.00	0.45	0.49	0.00	0.3	0.3	0.3	0.90	0.14	1.04
AGL/SC	30.00	0.84	89.85	0.35	0.7	0.7	0.7	21.24	0.83	21.59
APA1/MC	27.00	0.79	70.06	0.36	0.7	0.7	0.7	19.15	0.80	19.45
APA2	14.00	0.59	6.26	0.64	0.5	0.5	0.5	7.32	0.61	7.29
APA3	11.00	0.56	2.29	0.76	0.5	0.5	0.5	5.88	0.66	5.78
BSGL	3.00	0.49	0.00	1.00	0.3	0.3	0.3	1.20	0.45	1.05
EGPA1	7.00	0.54	2.37	0.71	0.5	0.5	0.5	3.86	0.63	3.77
EGL	18.00	0.63	27.55	0.53	0.7	0.7	0.7	12.97	0.81	13.04
EPE	19.00	0.63	7.00	0.68	0.5	0.5	0.5	9.84	0.65	9.81
TCGL	12.00	0.60	8.67	0.71	0.7	0.7	0.7	8.90	0.92	8.82
TCPE	17.00	0.62	14.49	0.62	0.5	0.5	0.5	8.81	0.62	8.81
GGL	11.00	0.59	13.56	0.51	0.7	0.7	0.7	8.06	0.77	8.11
GPE1	5.00	0.52	0.37	0.90	0.5	0.5	0.5	2.95	0.71	2.76
LAGL	7.00	0.54	0.60	0.81	0.7	0.7	0.7	5.47	0.94	5.28
LAPE1	5.00	0.50	0.20	0.80	0.5	0.5	0.5	2.90	0.65	2.75
EGPA2	5.00	0.51	1.23	0.70	0.5	0.5	0.5	2.85	0.61	2.76
MEGL1	13.00	0.59	18.55	0.53	0.7	0.7	0.7	9.47	0.78	9.51
MEGL2	27.00	0.73	43.10	0.47	0.7	0.7	0.7	19.23	0.84	19.41
CPM	6.00	0.49	1.74	0.53	0.3	0.3	0.3	1.96	0.31	1.95

REGL	9.00	0.54	0.82	0.86	0.7	0.7	0.7	6.90	0.98	6.68
REPE	12.00	0.58	3.12	0.71	0.5	0.5	0.5	6.35	0.64	6.29
SGL1	14.00	0.61	44.64	0.53	0.7	0.7	0.7	10.17	0.79	10.22
SGL2	6.00	0.51	0.47	0.80	0.7	0.7	0.7	4.76	0.91	4.55
SPE1	13.00	0.59	8.31	0.62	0.5	0.5	0.5	6.81	0.60	6.79
SPE2	7.00	0.54	0.96	0.76	0.5	0.5	0.5	3.88	0.65	3.77
TGL	22.00	0.71	49.52	0.42	0.7	0.7	0.7	15.70	0.80	15.90
TPE1	6.00	0.52	1.60	0.80	0.5	0.5	0.5	3.40	0.66	3.26
TPE2	12.00	0.57	6.25	0.68	0.5	0.5	0.5	6.34	0.63	6.28
MEPE	11.00	0.56	2.89	0.69	0.5	0.5	0.5	5.85	0.63	5.78
MEBS	6.00	0.51	0.21	0.87	0.4	0.4	0.4	2.75	0.55	2.60
TCBS	12.00	0.59	6.26	0.59	0.5	0.5	0.5	6.30	0.59	6.29
IABS	6.00	0.52	0.00	1.00	0.7	0.7	0.7	4.90	1.06	4.56
SPE3	7.00	0.54	0.82	0.81	0.5	0.5	0.5	3.90	0.68	3.77
R&B	5.00	0.47	0.56	0.70	0.5	0.5	0.5	2.85	0.58	2.73
GPE2	6.00	0.51	0.92	0.73	0.5	0.5	0.5	3.37	0.62	3.25
SEBS	1.00	0.38	0.00	0.00	0.4	0.4	0.4	0.40	0.15	0.55
Average Values	11.74	0.58	14.42	0.63				7.47	0.68	7.45
Standard Deviation	7.55	0.09	22.67	0.22				5.57	0.19	5.69
Maximum Value	37	1		1	1	1	1	38	2	38