2016-04-30

The Use of Axiomatic Design in the Development of an Integrated, BIM Based Design Process

Maria del Lourdes Gomez-Lara
Worcester Polytechnic Institute

Repository Citation

Gomez-Lara, M. d. (2016). *The Use of Axiomatic Design in the Development of an Integrated, BIM Based Design Process*. Retrieved from https://digitalcommons.wpi.edu/etd-dissertations/238

THE USE OF AXIOMATIC DESIGN IN THE DEVELOPMENT OF AN INTEGRATED, BIM BASED DESIGN PROCESS

by

Maria del Lourdes Gomez Lara

A Dissertation

Submitted to the Faculty of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Doctor of Philosophy

in

Civil Engineering

April, 2016

APPROVED:

Guillermo Salazar, PhD Major Advisor	Leonard Albano, PhD, Committee Member
Christopher Brown, PhD Committee Member	Tahar El-Korchi, PhD, Department Head

ABSTRACT

Traditionally in the Architectural / Engineering / Construction industry, the design and construction phases are conducted by multiple professional and trade disciplines having minimum interaction among them along a rather sequential process. These parties bring their different objectives to the project that are not necessarily aligned with the overall project objectives. Design professionals do not necessarily work together giving little or no consideration for the requirements or constraints of subsequent functions such as construction and operation and maintenance of the facility. Design documentation that communicates the design intent to the builder, contains errors and inconsistencies, are incomplete or are simply difficult to read. This results in poor designs that have to be changed or modified during the construction phase and even during the long-term facility operation, thus increasing total cost and time of execution.

It has been established that the decisions made at early stages of the design process have the highest impact on the project lifecycle cost and facility performance. For that reason, new project delivery systems, software tools and lean principles have emerged in the industry enhancing collaboration among project participants and reducing the existing gap between the design and construction phases. The increased use of Building Information Modeling (BIM) allows project participants to generate, manage and share information through a 3D digital model to better collaborate, communicate and understand the design intent. Still, design and construction professionals do not necessarily share their models and collaborate in an integrated fashion to accrue the benefits of an early involvement during design.

This research uses the Axiomatic Design (AD) methodology to analyze some essential aspects of the design process to propose an improved process that seeks to produce better designs by adding value and reducing waste. Axiomatic Design is a systems design methodology using matrix methods to systematically analyze the transformation of customer needs into functional requirements, design parameters, and process variables. In AD, design principles or design Axioms govern the analysis and decision making process to develop high quality product or system designs.

This research proposes an integrated, BIM-based design approach embracing compliance with the two AD axioms. Axiom one, the Independence axiom, seeks to maintain the design adjustable and controllable, and implements lean principles, BIM processes and tools following the concepts established by a BIM Project Execution Plan. Computer simulation techniques, the development of metrics and the calculation of Axiom two, the Information Axiom, are used to assess the benefits of an improved process.

ACKNOWLEDGEMENTS

I would like to thank my advisor, Professor Guillermo Salazar, for all his guidance, patience, support and commitment during this research effort.

I also would like to express my gratitude to the other members of my committee, Professor Tahar El-Korchi, head of the Civil and Environmental Engineering Department, for all the support that made possible my stay at WPI. To Professor Leonard Albano of Civil and Environmental Engineering Department, for taking the time to get involved and his valuable contributions that helped me pave the way and organize my work. To Professor Christopher Brown of Mechanical Engineering Department, of whom I am deeply indebted and very grateful for his genuine interest on my research, for all the learning, advising and contributions provided during the last two years of my work and for letting me be part of his busy schedule. Nothing would have been possible without his guidance. My special thanks to Professor Towner for all his support, advice and follow on my research work.

I am also grateful to Cutler Associates staff for all the support and kindness during the development of the case study, which represents a great value to this research. In particular, to Michael Christansen, BIM coordinator at Cutler Associates, for his time, patience, availability, support and for sharing his knowledge of the design-build process and the use of BIM. His contribution to this project is invaluable.

Many thanks to all WPI's professors for sharing their knowledge and experiences. To Marylou Horanzy and Cindy Bergeron for their administrative support. To my friends, Mimi Loria, Wenwen Yao, Crystal Jiang, Ying Zou, Pei-Shan Yen, and Mark Griffin, for their friendship, companionship and support. Especially to Xiaokong Yu for letting me be part of her busy life when I asked her to be my friend. For her simplicity, honesty, and being there when I needed, making easier the difficult times. And to Sergio Alvarez for help me to clear my thoughts and his encouragement. He was another advisor for my research.

Thanks to Worcester Polytechnic Institute (WPI) and Consejo Nacional de Ciencia y Tecnologia (CONACYT) for the financial support for the realization of my doctoral studies.

Lastly, I would like to acknowledge the intangible contribution of my family, who despite the distance, they were closer than ever on this journey. This work and all I could have achieved is for them: Chanin, Mom, Dad, Marce, Migue, Tere, Pedro, Mariela y Pedrito. No words in this sheet of paper can express my gratitude to WGF, who was the first person to encourage me to pursue this dream and has been on the good and bad times since then. Thanks to God, for giving me life and make this happened.

Table of Contents

List of Figures

List of Tables

1. INTRODUCTION

The Construction Industry has traditionally been one of the largest and more fragmented industries in the United States and around the world. The fragmentation in the construction industry started in the Renaissance, when the architectural practice stopped being a technical art to become a fine art because of its aesthetics and symbolic components. This change in the status of the architectural practice led to a change in the process of design and construction: what previously was designed and built by one person with a technical solution in mind, now is designed first, following aesthetics standards and functionality, and then, followed later by, examination of technical solutions that satisfy the design. With the industrial revolution, construction projects began to grow in complexity and scale, due to the development of new materials and construction technologies, and with them the level of specialization and fragmentation of knowledge of designers and contractors, in order to resolve and implement the complex aspects of the building. Finally, the fragmentation of design and construction process was assured in 1926 with the establishment of the first contractual agreement form: the Design Bid Build (DBB). All this has resulted in a misalignment of goals between designers and builders, and sometimes, in an adversarial relationship between them, as well as in poor communication, coordination and collaboration among them, which negatively affects, not only the efficiency of the design and construction process, but also the resulting facility itself, the customer satisfaction and the performance of the industry at large.

It has been established that the decisions made at early stages of the design process have the highest impact on the project lifecycle cost and facility performance. For that reason, new project delivery systems, software tools and lean principles have emerged in the industry enhancing collaboration among project participants and reducing the existing gap between the design and construction phases. The increased use of Building Information Modeling (BIM) allows project participants to generate, manage and share information through a 3D digital model to better collaborate, communicate and understand the design intent. Still, design and construction professionals do not necessarily share their models and collaborate in an integrated fashion to accrue the benefits of an early involvement during design.

1.2. Problem Statement

Traditionally in the construction industry, a successful project is one that was completed on time according to the schedule, within budget, with no accidents and in accordance to the plans and specifications, but this is something difficult to achieve. It is very common to find that, at the end of the construction process, the resulting facility is different from the architect’s original design and from the customer’s expectations, or the construction cost considerably increased. The main two reasons for this issue seems to be because the building design is performed separately and without considerations of the requirements of the subsequent tasks (construction and operation and maintenance), as well as because drawings and specification, which are the primary instrument for communicating the design intent to the builder and then to the owner for its operation and maintenance, have errors, inconsistences, are incomplete or simply difficult to read.

The increasing use of BIM seems to be partially solving the problem, since it allows the project parties to communicate and understand better the design intent; however, the communication and collaboration between designers and builders are still a challenge despite the use of BIM, since the model created for one party for one specific purpose it is not always shared with other parties, causing the need of creating another model from 2D documents, which are still considered the final product of the design.

1.3. Proposed Solution

In the construction industry, a successful project is defined in terms of cost, time, safety, and quality. Essentially, when the project satisfies the owner's needs and is completed within the budget (with a fair price to the owner and a fair profit to the contractor), on time (according to the schedule, and everything available when needed), with no accidents, and in accordance with the plans and specifications, it is considered a successful project, (Maloney 2002, Forbes and Ahmed 2011); however this can only be known until the project is completed, and little or nothing can be done to improve the outcome unless lot of money is spend to change the design.

The focus of this research is to address the existing lack of integration between the design and construction phases, as well as to reduce the existing gap between what the customer wants from the facility and what he/she gets at the end of the construction process This research proposes an integrated, BIM-based design process which delivers the value to the customer. The proposed approach allows project participants to assess the level of success that the design process may attain in satisfying the main project objectives. Axiomatic Design (AD) methodology is used as the formal framework to develop the proposed process, which includes the use of Building Information Modeling (BIM) tools to promote collaboration, improve communication, reduce waste and integrate design, construction and facility operations knowledge in the design process.

1.4. Research Objectives

This research uses AD method to develop an integrated, BIM-based design process that delivers value to the customer, who are the owner and the construction team. Value is delivered when the Project Value Objectives (PVO) are met while reducing the waste of resources in producing the design. Waste in the design process are those activities that don't add or create value to the customer. The following sub-objectives have been identified as a means for sustaining the research objective:

1. Identify the value that can be delivered to the owner and the construction team, at the end of the design stage of a facility
2. Identify the BIM uses that can create and deliver that value during the design stage
3. Identify BIM tools and related activities that reduce the waste of resources in producing the design
4. Develop an approach for an integrated, BIM-based design process

1.5. Scope

This research considers the building life cycle; however, the proposed process is focused on the design stage because this stage can highly influence positively or negatively the final outcome of construction projects. The work developed in this research, which includes the process mapping and data gathering, is based on characteristics of the design process for institutional buildings.

2. LITERATURE REVIEW

2.1. Introduction

This chapter reviews the characteristics of the Construction Industry highlighting those characteristics that make it different compared to other industries, among which are: its fragmented nature and its complexity. These two are discussed in more detail in this section, in order to better understand the challenges, the construction industry is now facing and are impacting its performance. The chapter also describes the building's lifecycle, discusses the current design process for building projects and its importance in order to identify its main issues and inefficiencies that have a negative impact on the on the final outcome and on the owner's expectations. In addition, the chapter proposes an approach and states the research objectives, as well as presents what was found in the literature review regarding to what has been done to solve these inefficiencies.

2.2. Characteristics of the Construction Industry

The Construction Industry has traditionally been one of the largest industries in the United States. It employed approximately 5.64 million of people in 2012 and is projected to grow 2.6 percent annually during the 2012-2022 decade, not including the thousands of construction-related jobs from other industries, like manufacturing. Besides being one of the largest industries, the construction industry is a crucial sector of the economy because other industries and firms are dependent on the performance of the built infrastructure such as roads, rail, power stations, and telecoms to remain competitive. In addition, it has an important impact on the rate at which resources are used, since buildings are responsible for almost half of the country's carbon emissions, half of our water consumption, about one third of landfill waste and one quarter1 of all raw materials used in the economy.

The Construction Industry generally performs poorly when compared with other industries (Faniran et al. 2001; Forbes and Ahmed. 2011). It its estimated productivity growth is 0.78% per year, and most of their improvements have been the results and work in the manufacturing industry related to construction machinery and technology (Forbes and Amhed 2011). Several factors have been identified as contributions to the low productivity in the construction industry. One is the environment, since building projects are not "assembled" in a controlled environment which usually is affected by climatic effects, local conditions, and topography. Another factor is its fragmented nature. A project not only involves the participation of the owner, designers, and contractors in the building design and construction, but also involves the labor force, major suppliers, financial institutions, lawyers and insurers, federal and local regulators, public services, utilities, safety professionals, quality control professionals, coaches/consultants/lean facilitators, who work together, creating a temporary organization, in order to build a "unique" product on a "unique" site, under a high level of uncertainty. In addition, in construction projects the majority of the process is on-site fabrication with low automation, which means that field productivity relies on qualified training of field labor, including craftsmanship (Eastman et al. 2011).

Today, the construction industry is facing the challenge to reduce project delivery times and costs, and to increase the quality, safety and environmental responsibility in construction projects despite increased uncertainties, ambiguities, complexities and multidisciplinary teams that surround the industry.

2.2.1. Fragmentation in the Construction Industry

As was mentioned before, the Construction Industry is highly fragmented and this is the consequence of two major factors (Mitropoulos 1994; Yates and Battersby 2003):

- The separation of the master builder function into design and construction functions.
- The increasing complexity of the constructed facilities and the high degree of specialization.

2.2.2. Separation of the Master Builder Functions

For centuries, there was no distinction between the architect and the builder, since the title referred to the same person: the “master builder”, who was trained in all phases of design and construction, and had sufficient expertise to oversee an entire project from inception to completion (Burr, 2011). Throughout ancient and medieval history, most architectural design and construction were carried out by artisans, rising to the role of master builder. During this time, buildings were designed by the people that built them, the knowledge was transferred through apprenticeships and from father to son, and relied on experience and models which were usually used to design and sizing building structures, since paper appeared at the end of this period, and the techniques and technologies they learned were developed from an understanding of local issues. Within the master builder process, at the time the building was being designed, the master builder not only thought about the aesthetics of the building, but also in how it was going to be built, and each person that contributed to these structures was thinking and working from a unified schema derived from a shared understanding of local patterns (Boecker, et al. 2009).

In the Renaissance an intellectual transformation and artistic development took place (also known as re-birth), which included the role of the architects and the way buildings were designed and built. Architecture, which was previously viewed as a technical art, became something worthy of study; the Master Builder, now called Architect (which means “Chief Builder”), was often an artist, knowledgeable and skilled in all arts and sciences, and highly respected, however with little knowledge of building technology.

Therefore, architects had to provide detailed drawings for the craftsmen, who were responsible for the technical side of architecture, for setting out the disposition of the various parts. It is during the Renaissance when the way problems were approached changed, from approaching a problem with a technical solution in mind (where the process of designing cannot be separated from the process of constructing), to first defining how the end product is expected to look and then, searching for a way of making it work. Even though the architect occasionally would get involved in particularly difficult technical problems, he managed and supervised construction.

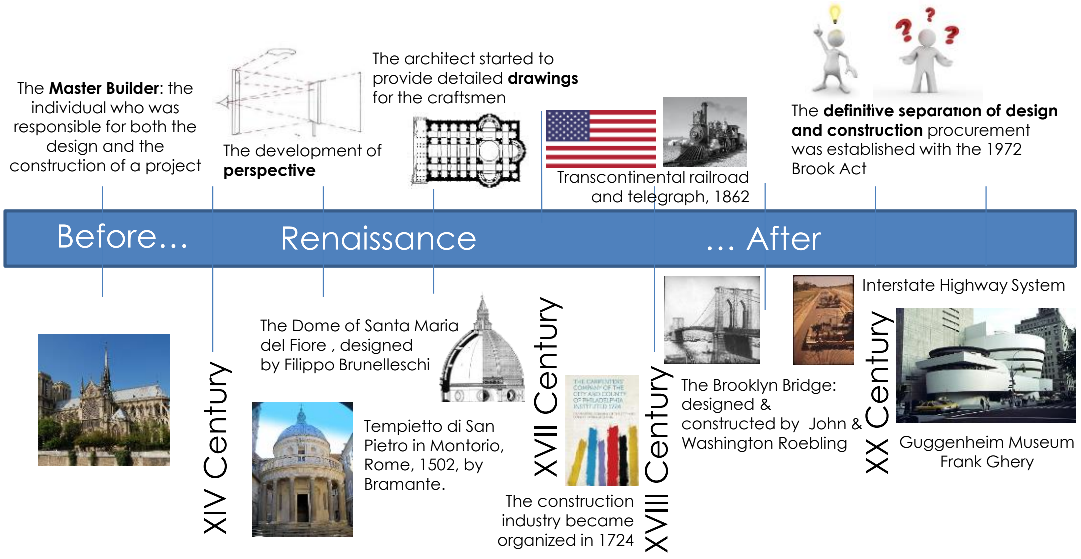


Figure 2-1 Separation of the Master Builder function, time line

In the United States, the concept of "Master Builder" was formally established in the early 18th Century, and was the person responsible for designing, surveying, laying out, and managing construction projects according to the contractual documents. It was until late part of the 19th and the early part of the 20th century, when the function of the master builder fragmented into designer and constructor specialties (Yates and Battersby 2003) which was started by the development of design firms and related specialties, and the emerging professional societies and statutes for professional licensure. This separation of services gained a momentum in 1916, and with it came a number of legal implications, particularly, defining responsibilities and risk of each party, because of that, in 1918 the US Supreme Court decided that when the contractor agrees to do a work for a fixed sum, he will not become entitled to additional compensation because of unforeseen difficulties he may find (soil, weather, etc.); however, if the contractor is bound to build according to plans and specifications prepared by other party, then, the reasonability for the consequences of defects in the plans and specifications falls upon the owner. This decision is known as the Spearin Docrtine (Prentice 2004). In 1926, the separation of the design and construction services in United States became mandatory for federal projects with the Public Buildings Act. This statute required the approval of plans and specifications before the construction of any federal building, leading to a different procurement approach: Design-Bid-Build (Pietroforte and Miller 2002). Figure 2-1 represents in a time line, the gradual separation of the Master builder function into design and construction functions. Today, the term “Master Builder” is used rarely in reference to design/build firms (Cited by Flavell, 2011).

The Design-Bid-Build (DBB) delivery method is the result of the separation of the master builder into design and construction functions. In the DBB project delivery method the design and construction are separate contracts (Figure 2-2). It is a sequential approach which comprises three main phases: the design, the bidding, and the construction phases. In the design phase the client/owner hires an architect, who identifies the owner’s needs and establishes the project’s design objectives, in order to produce a conceptual or schematic design. Then, the architect coordinates a design team (with structural, mechanical and electrical engineers, and other specialists) in order to develop the whole building design, and to communicate the design intent to the builder through contract drawings (complete set of drawings and specifications). Once the contract drawings are completed, the bidding phase starts. This phase involves obtaining bids from general contractors and selecting the one with the lowest responsible bid to build the building in accordance with the design. Before the construction work can begin. It is often necessary for the contractor to redraw some of the drawings to reflect the construction process and the phasing of work. The subcontractors and fabricators must also produce their own shop drawings to reflect accurate details of certain items, such as precast concrete units, steel connections, wall details, piping runs, and the like (Eastman et al. 2011). During the construction period, the architect limits his work to see that the contractor builds according to the plans and specifications, and responds to questions about the design on behalf of the Owner.

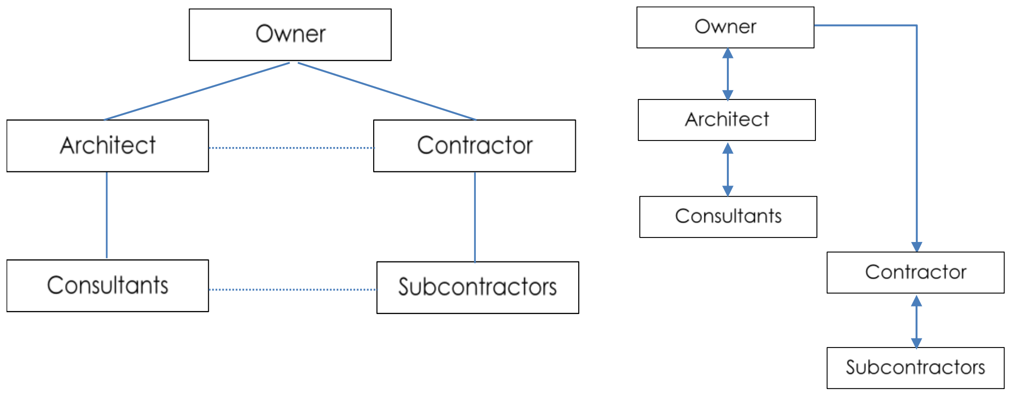


Figure 2-2. Design-Bid-Build organization and contractual relationship

In the DBB approach planning, design, construction operation and maintenance are separated by disciplines and executed in phases and with little interaction between the phases and disciplines, especially between designers and contractors, affecting all stages of the design-construct process (Figure 2-3). The DBB project delivery method became the traditional method in the United States in 1970 (Pietroforte and Miller, 2002) and is still preferred by many owners, particularly in the public sector because this approach clearly separates the risk and responsibilities of the parties, as stated by the Spearin Doctrine, making the Design-Build (DB), Construction Manager, and their variations, difficult to establish in the public sector.

Design I Documentation I Detailing I Construction

Figure 2-3. Design and construction process fragmentation –
Presented by Christof Spieler at BIM Forum October 2010

2.2.3. Building Complexity and Specialization

Fragmentation in the construction industry not only exists across project phases (vertical fragmentation) e.g., design and construction phases, but also within individual phases of the construction process (horizontal fragmentation) e.g., the design phase (Howard, et al. 1989; Mitropoulos 1994, Mitropoulos and Tatum 2000), because of the high levels of specialization of designers and builders, causing fragmentation of knowledge.

Specialization is a direct result of the division of labor and task among organizational positions and among organizations (Mitropoulos 1994). In the Construction Industry this started during the nineteenth century, with the Industrial Revolution, when construction projects began to grow in complexity and scale due to the development of new materials and construction technologies. As new materials and technologies were rapidly and increasingly introduced, specialists were needed to resolve and implement the complex aspects of building, such as electricity, lighting, HVAC, landscaping, and more, which led to a higher levels of specialization, resulting in a large number of project participants, each with different knowledge, points of views and objectives, as its seen in Figure 2-4 (Mitropoulos 1994; Yates and Battersby 2003; Boecker, et al. 2009; Burr 2011), in other words, what once was a unified intelligence, now involves hundreds of companies and individuals in designing our buildings and their components from anywhere. For example, in large-scale projects ($10 M or more) there are 420 participant companies, including all suppliers and sub-sub-contractors and 850 individual participants (Eastman et al. 2011)

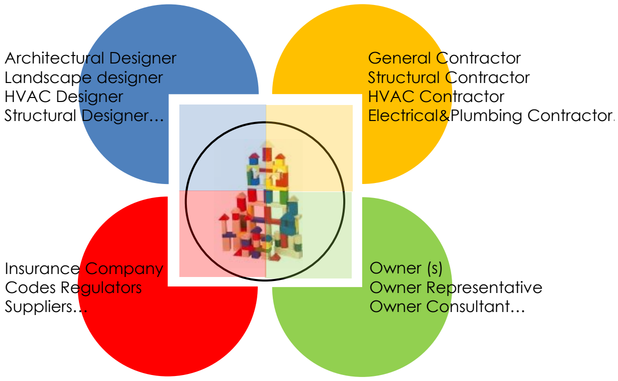


Figure 2-4. Construction Industry Specialization

Specialization allows each discipline to develop a deeper insight and understanding in their field of action but it leads to fragmentation of knowledge among designers and builders, who perform their tasks without consideration of the requirements or constraints of subsequent functions. It also increases the interdependency between specialists where coordination becomes essential.

2.2.4. Customer satisfaction in the construction industry

Customer satisfaction is a measure or degree to which the customer expectations are met or exceeded by a product or a given service. In the construction industry, customer satisfaction refers to how well a contractor meets the customer's expectations and plays an important role in building strong contractor-customer relationships, influencing the customer's willingness to select a contractor for future work (Maloney 2002, Karna 2004). For construction projects, the customer satisfaction is the result of how well the customer's expectations of the product and the service provided by the contractor are met, since it is a hybrid process which involves not only the constructed facility itself, but also the service that designers and contractors deliver during the design and construction processes of the building (Maloney 2002).

The expectations of the customer regarding the service provided by the contractor are those related to the firm's performance and competencies, like progress reports, warranties and culture, among others. On the other hand, the expectations of the customer regarding the product are primarily related to the delivery of the physical facility built according to the specified design and within the budget and schedule.

Commonly, two elements are the most important to the customer regarding the product: when the facility will be available and how much it will cost; however, because of the inefficiencies in the design process (previously identified) and that the main type of communication is through drawings (which frequently have inconsistencies), often the results are buildings more expensive than planned and even different from the original design, so that, owners feel that they receive less value than they should since their goals and needs regarding the constructed facility are not met, resulting in large gaps between expectations and results as perceived by them (Forbes and Ahmed, 2011).

2.3. Building's Lifecycle

Building project's lifecycle consists of five main stages: Feasibility, Design, Construction, Operation and Maintenance, and facility retrofit/deconstruction. The feasibility stage starts with an idea or client/owner need to build something new. This idea is evaluated in order to make a decision whether to move forward or not with the project. If it was decided to continue with the project, then the design stage starts. This stage comprises the pre-design (PD), schematic design (SD), design development (DD), and construction documents (CD) and during these phases thousands of decisions regarding the building shape, functionality, materials, costs, and so on, are made. The design phase ends when the owner/client agrees to the plans that will guide construction. The construction phase refers to the actual construction of the facility, and includes the planning of the construction process and a more detailed cost estimate based on the drawings and specifications given by the designer. These three stages (Feasibility, Design, and Construction) take approximately from 1 to 5 years of the building lifecycle, while the operation and maintenance takes approximately twenty years (sometimes more) of the building lifecycle. The operation and maintenance stage starts the day the project is ready for occupancy and use by users, and it never ends until the building cannot continue to fulfill the functions for which it was created. It is during this stage where the satisfaction with the project is determined by the persons who ultimately use it.

2.3.1. Importance of the Design Process

The successful completion of a construction project requires a good understanding of all stages and phases of the project; however, the design stage has great influence on the total project cost and value (Senescu et al. 2013). Many projects don't succeed as well as desired because often, critical aspects of the design are poorly executed and/or overlooked (O'Connor et al. 2007). The design process is a complex process by which the needs, wishes, and desires of the owner are defined, quantified and qualified (Sanvido and Norton 1994). It involves the thoughts and creativity of the designer and his/her technical knowledge to convey those creative ideas into drawings and specifications as specific instructions for construction of the project.

Design is the most central point of definition for a project and is the process which generates value to the customer because it is when a major part of the information about the project is defined and a lot of critical decisions are made (Eastman et al. 2011).

Changes in the scope of the project are easier to implement in early stages of design at a lower cost than those changes made during most advance stages, such as CD phase, or construction and operation stages. The chart shown in Figure 2-5 is attributed to Patrick MacLeamy (Eastman et al. 2011), contrasts the traditional design process, in which many decisions and effort are made between the late part of the Design Development (DD) phase and Construction Documentation (CD) phase, with a preferred approach promoting early design decisions and more effort made between the Schematic Design (SD) and the early part of Design Development (DD) phases, because early design decisions have greater value and a better impact on the overall functionality, costs, and benefits of the building project. In addition, the chart shows the growth in the cost of making changes within the project lifetime (Eastman et al. 2011).

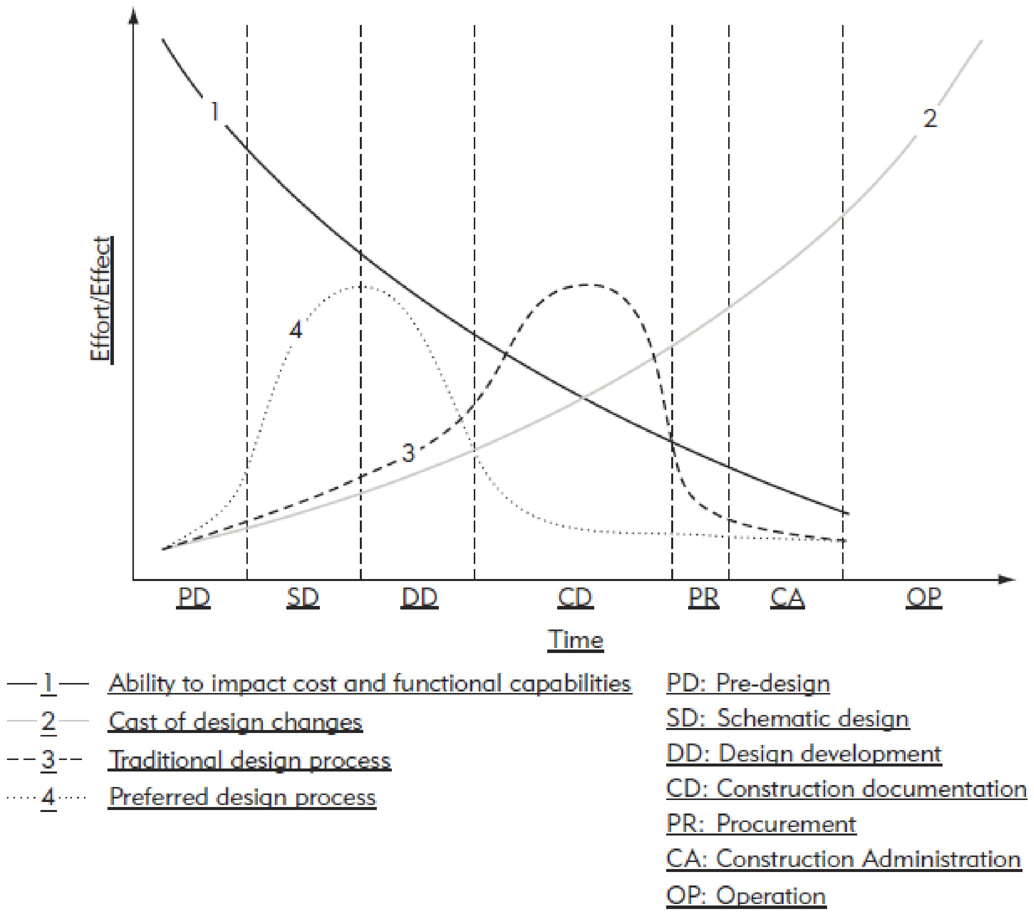


Figure 2-5 MacLeamy curve (Eastman et al. 2011)

2.3.2. Traditional Design Process

As was mentioned before, the design process comprises the pre-design (PD), schematic design (SD), design development (DD), and construction documents (CD). In the pre-design phase the client/owner hires an architect, who identifies the owner's needs and establishes the project's design objectives. Space, functionality and expansion requirements as well as site issues and code constraints are addressed in this stage. During the schematic design phase, the designer uses his/her creativity to produce possible solutions that satisfy the customer's needs. These solutions must be feasible, and in accordance with the regulations and constraints imposed by the type of building and its location. The plans of the preliminary project design is reviewed in this phase in order to assure it meets the space and functional requirements (building program). In addition, the shape of the building is defined, including possible materials and finishes.

Once the schematic design is complete and approved by the client, usually after several changes of scope and revisions, the architect coordinates a design team (with structural, mechanical and electrical engineers, and other specialists) in order to develop the whole building design (DD). During this stage, the project drawings are sent to each member of the team of professionals assembled by the architect in order to design and optimize their systems, and it is common that each specialist performs its task in isolation and with multiple iterations (Figure 2-6).

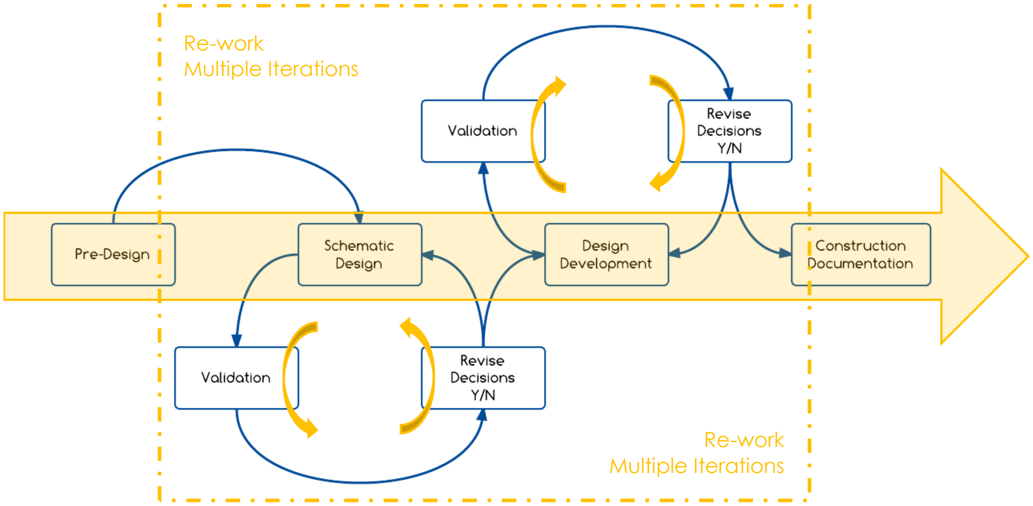


Figure 2-6. Traditional Design Process

The design development phase includes the production of detailed floor plans and elevations, including all major systems of the building (foundation, structure, mechanical, electrical, and so on), with general details, materials and finishes. Then, this set of drawings and specifications is developed in more detail during the construction detail phase, in order to communicate the design intent to the builder through contract drawings (complete set of drawings and specifications). The contract drawings should include detail plans regarding the site, specifications and materials, components sizing and specifications for all the major systems of the building. Essentially, the designer is paid, at the end of the design process, to produce a design that is expressed in a large amount of drawings and specifications, which are used as a means of communication between the designer and the builder in order to construct facility.

2.3.3. Inefficiencies of the Traditional Design Process

Despite the importance of the design process amongst all processes of construction projects, the management of the design process is one of the most neglected area in construction projects (Marzouk et al. 2012). Most of the project issues arise when critical aspects of design were poorly executed or overlooked altogether (O'Connor et al. 2007). Previous studies identified that 40% of design changes result from issues arising in the design phase (Chang et al. 2007 cited by Chien-Ho and Neng-Fu 2014) and up to 30% of construction costs are due to inefficiencies, mistakes, delays, and poor communication during the design phase (Forbes and Ahmed 2011).

In the traditional design process it is common to find the following deficiencies:

- High number of design iterations
- Lack of integration among project participants (poor collaboration, coordination, and communication between project participants)

During the schematic design phase, the designer produces a number of possible solutions that satisfy the owner's needs. These solutions are presented to the owner to be evaluated since all solutions can respond and satisfy the same need. The owner (or owner's representative) often is responsible for selecting what he/she believes is the most suitable design among all possible solutions. This decision is made after several evaluations, in each of which the owner gives feedback to the designer, more information is then added to the initial specifications of the project, and therefore, generates a new definition of the need, modifying project's scope and objectives. These iterations are repeated during the design development phase, when the architect gives the selected design to a group of designers who are going to design all different systems of the building. Producing possible solutions for each iteration, during the schematic design and design development phase, consumes a great amount of resources that results in waste (rework) of the design process (Moreno 2012).

In addition, during the design development phase, the number of iterations increase because the groups of designers work individually, which means that they develop their own possible solutions without the consideration of other systems of the building or the requirements of the subsequent functions. This situation is the result of the lack of integration among designers and designers and builders. Lawrence and Lorch (1967), define integration as “the process of achieving unity of effort among the various organizational subsystems in the accomplishment of the organization's tasks” (Cited by Mitropoulus 1994). The lack of integration often results in sub optimization and inefficiencies in the design (Mitropoulos 1994, Boecker, et al. 2009), in projects above the budget or in excessive costs to correct design deficiencies. Therefore, techniques such as “Value Engineering” are used, essentially, to make the building less expensive by removing pieces of the design, reducing scope and quality, or all of them, or eliminating things that the owner originally wanted and delivering a building with unexpectedly high life cycle and operating costs (Nam and Tatum 1992). Furthermore, to this situation is added that the contractor responsible for construction develops its own strategy in selecting the construction methods, which are detailed and take in consideration factors that are often passed over during the design, because of the lack of construction knowledge and field operations expertise, resulting in more expensive design changes and rework at early construction phase because, efforts are then directed to make corrections in the design and not to improve project performance (Howard et al. 1989, Mitropoulus 1994).

Integration requires a good level of *coordination* and *communication* or exchange of information and knowledge of the various participants and disciplines (Mitropoulus 1994), as well as continual collaboration in making decisions. The first component is communication, which basically consists of in the exchange of information, knowledge, and ideas among project participants, and occurs principally through drawings (because drawings are the primary mean to communicate the design). This type of communication often does not work as well as it should, since it needs a large amount of time and makes the design process longer and prone to errors, resulting in complications like drawings and specifications are not ready on time, are inaccurate or incomplete, or they are based on drawings that already contain errors, inconsistencies, or omissions as a result of the fragmented process mentioned above. This causes expensive, time-consuming conflicts to arise in the field, like costly mistakes, request for information, and changes that the client has to pay for as change orders, because whether the builder interprets the design differently as the architect's intentions, or the builder builds an error made on the design (Burr 2011, Eastman et al. 2011, Forbes and Ahmed 2011).

Coordination, the second component, is defined as “the act of managing interdependencies between activities performed to achieve a goal” (Raposo et al. 2001). Tasks during the design and construction process are highly interdependent, and the project participants don’t necessarily work as coordinated as expected, because often, participants spend more time in repetitive tasks (rework) due to the lack of communication. Often, they only share the minimum required information for others to do their own work, resulting in delays in the subsequent tasks or in tasks performed (and decisions made) without complete information.

The third component is collaboration, which is defined as “multiple individuals working together in a planned way in the same production process or in different but connected production processes” (Raposo et al. 2001). Because in construction projects a large number of participants are often organized on a project basis to work together, collaboration exists among them, however, in a collaborative work the project participants are committed to common goals, and the communication and coordination of interdependent tasks become very important in order to guarantee the efficiency of collaboration, and therefore accomplish those goals.

To the above is the uncertainty in the design process, especially in early stages when little data about the project is available (like site information, suppliers, and so on) and key decisions have to be made. Designers are prepared to deal with different levels of uncertainty in design; however, it is increased because of the lack of integration during the design process, resulting in errors that are difficult, even impossible, to identify through hundreds of 2D drawings.

2.4. Efforts to Integrate the Design and Construction Processes

This section presents a review of the literature of what has been done to achieve the integration of the design and construction processes. Three areas of integration were identified during the literature review, these are: organizational integration; integration through the improvement of the design process; and integration through information technology (Nam and Tatum 1992; Jorgensen and Emmit 2007).

2.4.1. Organizational/Contractual Integration

Organizational integration discusses the integration between functions within the same organization and between organizations. (Nam and Tatum 1992, Mitropoulos 1994, Jorgensen and Emmitt 2007). Under this area were found the alternative contractual agreements (or delivery methods) that have emerged allowing and promoting greater involvement of engineers and contractors at the design stage. This study presents the most dominant contractual methods in the United States along with the DBB approach which are Construction Manager (CM), Design-Build (DB) and Integrated Project Delivery (IPD); the latter is a relatively new procurement method, but is gaining popularity since it can support the use of Building Information Modeling (BIM) and integrated teams. In addition to the contractual agreements, this area of integration also includes the integrated design approach which seeks to optimize project results through the creation and integration of a multi-disciplinary team since early design.

2.4.1.1. Construction Manager (CM)

The Construction Manager contractual agreement was introduced in 1960 as a solution to the problem of fragmented project teams and information (Kent and Becerik-Gerber 2010). Construction management at risk (CM@R) project delivery is a method in which an owner retains a designer to furnish design services and also retains a construction manager to provide construction management services for a project throughout the preconstruction and construction phases (Eastman et al. 2011) (Figure 2-7). The construction manager acts as a consultant to the owner in the development and design phases (preconstruction services), and as a general contractor during construction, and is committed to deliver the project within a guaranteed maximum price or GMP. The value of the delivery method stems from the early involvement of the contractor in the design phase in order to reduce errors and omissions, and the reduced liability of the owner for cost overruns.

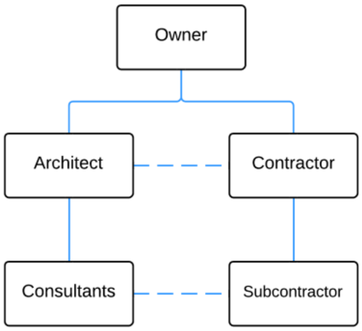


Figure 2-7. Construction Manager @ Risk Structure

2.4.1.2. Design Build (DB)

In 1990 Design-Build (DB) delivery method was established (Kent and Becerik-Gerber 2010). In this approach, the owner contracts directly with the design-build team (normally a contractor with a design capability or working with an architect) to develop a well-defined building program and a schematic design that meets the owner’s needs (Figure 2-8). The DB contractor then estimates the total cost and time needed to design and construct the building. After all modifications requested by the owner are implemented, the plan is approved and the final budget for the project is established. Then, the DB contractor establishes contractual relationships with specialty designers and subcontractors as needed. These are usually based on a fixed price, lowest bid basis. After this point, construction begins and any further changes to the design (within predefined limits) become the responsibility of the DB contractor. The owner's role is critical because this contracting strategy requires contractor's selection not on the basis of price, but on reputation, trust, and ability to have successful cooperation.

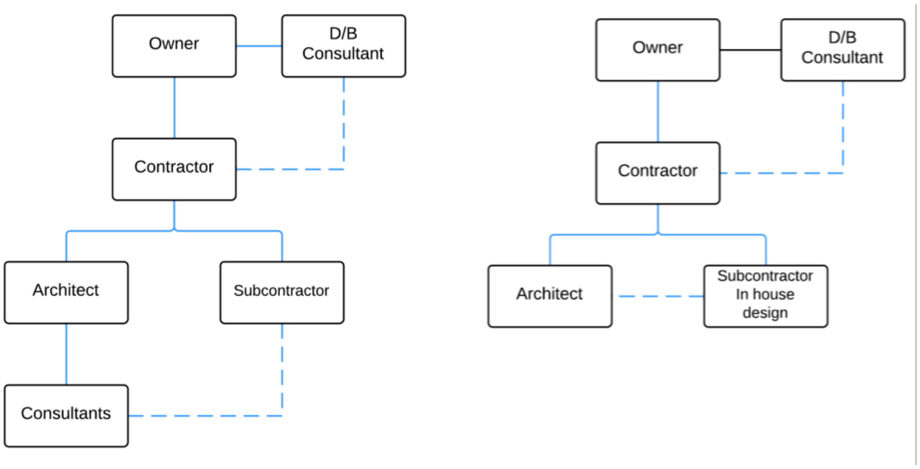


Figure 2-8. Design-Build (DB) Structure

This model appears to be one positive solution to achieve design and construction integration (Nam and Tatum, 1992) because it allocates the task of designing and constructing the facility to a single organization or a single contracting entity, placing the architect and the builder on the same team, hopefully eliminating the adversarial relationship, and elevating the level of communication and collaboration. Major advantages of the design-build approach are close cooperation between design and production from start to finish and the possibility of using the fast-track construction method, since construction can start before the design is completed, as well as it is not necessary for detailed construction drawings to be complete for all parts of the building prior to the start of the construction (Eastman et al. 2011). In addition, it allows the contractor to participate in design, offering opportunities for constructability improvement, modifications of the building's design earlier in the process, and for increasing time and cost effectiveness.

2.4.1.3. Integrated Project Delivery (IPD)

Integrated Project Delivery or IPD is a relatively new procurement process that is gaining popularity in the construction industry since is well suited to BIM. The American Institute of Architects (AIA) defines IPD as a project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction (AIA 2007).

IPD is characterized by an effort to improve the project outcome through a collaborative approach that aligns the incentives and goals of the project team (which includes members well beyond the basic triad of owner, designer and contractor) through a single multiparty agreement (Figure 2-9), in which risks are shared and methods of compensations tie the participant's success to the overall success of the project. As a result all parties are focused on project outcome rather than on their individual goals (AIA 2007, Kent and Becerik-Gerber 2010, Mounir et al. 2013). In a multiparty agreement, the primary project participants execute a single contract specifying their respective roles, rights, obligations, and liabilities, creating a temporary, virtual, or formal organization to realize a specific project where each party understands its role in relationship to the other participants (AIA 2007).

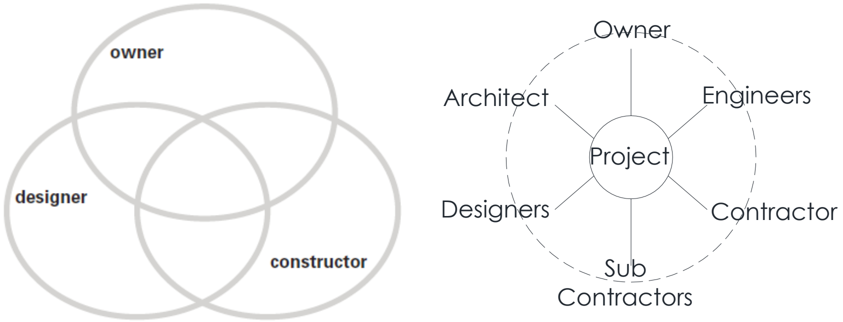


Figure 2-9. IPD Multiparty Diagram

IPD is characterized by the early involvement of all parties, typically before the design even starts, encouraging early contribution of knowledge and experience. In IPD all project participants commit to collaborative process, to work together effectively and to embrace the following principles (AIA 2007): 1) Mutual respect and trust; 2) Mutual benefits and rewards; 3) Collaborative innovation and decision making; 4) Early involvement of key participants; 5) Early goal definition; 7) Intensified planning; 8) Open communication; 9) Appropriate technology; 10) Organization and leadership.

IPD results in greater efficiencies. Owners obtain projects that meet their business goals, including the achievement of project schedule, life cycle costs, quality and sustainability; contractors are allowed to contribute their expertise in construction techniques early in the design process, providing the opportunity for strong preconstruction planning resulting in less rework and changes, fewer request for information, shorter schedule, and less construction administration; and finally designers benefit from the early contribution of constructor's expertise during the design phase allowing them to make better design decisions based on accurate budget estimates, and to design more buildable facilities. In addition the high level of effort during early design phases, results in reduced documentation time, and improved cost control and budget management. Other IPD benefits are less stress and friction, more productivity, and more enjoyable projects (AIA 2007, Kent and Becerik-Gerber 2010, Mounir et al. 2013).

2.4.1.4. Integrated design approach

According to the American Institute of Architects (AIA) Integrated Design is an "approach that integrates people, systems, business structure, and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction". Integrated design emerged as an approach because of the increasing need to design and build energy-efficient buildings while maintaining functionality, interior comfort, and aesthetics. These goals that require the early participation of architects, designers, engineers, builders, installers, and operators of all of the different systems that form the facility to work together in cross-disciplinary teams, in order to achieve a high performance and sustainable buildings, to ensure that all systems are optimized for the whole building at lower cost, and still satisfy occupants' needs (Brunsgaard et al. 2013).

Integrated Design approaches differ from the traditional design process because it is an iterative process (instead of a linear process) distinguished by the effective communication and collaboration of the design team, which discusses all design issues and fully understands the concerns of all the other parties involved at early stages of the project, allowing the design team to make decisions that would otherwise be difficult to reverse later on (Reed and Gordon 2010). One of the most important elements of integrated design approach is that the cross-disciplinary team works together in intensive workshops and using the best collaborative tools at their reach to ensure the project meets the owner requirements at significantly reduced time and cost. Although Integrated Design has gained traction with the rise of sustainable design, its benefits are not limited to the improvement of environmental performance.

2.4.2. Integration through the Improvement of the Design Process

The improvement of the design process focuses on the application of different techniques and methodologies, most of them originally developed in the manufacturing industry with successful results, to enhance communication and collaborative practices among the project participants, and therefore, increase project value and reduce waste. This section presents the state of the art of lean principles applied to the construction industry.

2.4.2.1. Lean Process and its Application to Construction

Lean is a customer-centric methodology to deliver value to a customer through the effective use of resources, engagement, respect for people, and continuous improvement (Sayer and Anderson 2012). It was first originated in Japan in the 1950's but the most prominent application was in the manufacturing industry with the Toyota Production System (TPS). The TPS is often used interchangeably with the term Lean Production and is defined as "a quantity control production system, based on a foundation of quality, whose goals are to deliver better (best quality), faster (Reducing lead times), and cheaper products (at lowest cost) through the elimination of waste" (Jorgensen 2006, Wilson 2010). The concept of lean includes identify and deliver value to the customer, eliminate anything that does not add value (waste), organize production as a continuous and reliable flow, and pursue perfection. It is based on two principles:

- Supplying exactly the right quantity, at exactly the right time, and at exactly the correct location – Just in time (JIT)
- No bad parts are allowed to progress down the production line – Jidoka

Waste is defined as any activity that adds cost or time without adding/creating value as defined by the primary customer; and value refers to the fulfillment of customer requirements. In the lean approach, there are seven activities, previously identified, that don't add or create value, or seven types of waste: 1) overproduction; 2) transportation; 3) waiting; 4) inventory; 5) making defective products; 6) movement; and 7) excess processing.

The application of lean production, principles and tools to the construction industry is commonly known as lean construction, and since the 1990s has been promoted as an approach that could bring performance improvement to the construction industry (Koskela 1992; Howell and Ballard 1998; Green and May 2005; Jorgensen and Emmitt 2007; Sayer and Anderson 2012). A wide variety of definitions of lean construction were found on the literature review. The term is often used indistinctly of the project stage (design, construction or delivery process), making the concept difficult to understand, this is because at the beginning, the concept was only applied to the construction phase, but now the concept is intended to cover the entire process of a project, therefore, this research will use the Lean Construction Institute (LCI) definition, which is "a lean production management based approach to project delivery – a new way to design and build capital facilities – applied to project design and delivery (LCI 2004)[1], because this definition is intended to cover the application of lean thinking, principles and tools to the entire process of a project from concept through decommissioning (Sayer and Anderson 2012).

According to the above, three areas of application of lean principles in the construction industry were identified:

- Lean focused on the production aspect of construction, also known as lean construction;
- Lean focused on the construction design, also known as lean design; and
- Lean focused on the project delivery practice, also known as lean production management or lean design management.

---

[1] http://www.leanconstruction.org/about-us/what-is-lean-construction/

Because this research focuses on the design process, the following section concentrates on efforts that have been done regarding the application of lean on the construction design or lean design.

Lean design, also discussed as lean design management, in the context of this research, is the application of lean principles and methods for managing the design process of building projects, in order to reduce design errors, to enhance design accuracy, and to increase the reliability of the design process. Jorgensen (2006) identified two categories of the application of lean in the design management, both of them with the goal of integrating designers and builders and delivering value to the customer. One category focuses on identifying waste and on improving the design process itself by the application of lean tools in four phases (Chien and Neng 2014; Freire and Alarcon 2002, Marzouk, et al. 2012):

- *Evaluation*, where value stream map is used to analyze the current design process and better identify waste and its causes (non-value and value activities);
- *Implementation*, where lean concepts and improvement tools are applied in the current design process in order to eliminate waste, achieve flow, and increase efficiency and reliability of the design process;
- *Verification/control*, where the proposed changes are verified in order to determine changes in the process performance;
- *Adjust/standardization*, where corrective actions identified or permanent improvements are introduced.

The second category focuses on the use of specific techniques, already tested, to directly address customer value aspects other than those affiliated with the consumption of resources and completion/delivery times, like target value design (TVD), whose main principle is to make cost and value drive the design process instead of calculating the cost after the design is complete. This technique is based on target costing (TC) principles which appeared in the manufacturing industry in the early 1930 (Zimina et al. 2012), and basically consists of defining the value of the facility or the desired features and functions, and then establishing the financial constraints: 1) what the client is able and willing to pay to get that value or allowable cost, 2) the expected cost of the project or the amount that the project is expected to cost, and 3) the target cost. The different costs can be expressed in the following equation:

$$\text{Allowable Cost} \geq \text{Expected Cost} \geq \text{Target Cost}$$

During the TVD process, targets are established for all relevant components (e.g., building envelope; structural system; interior finishes; mechanical, electrical and plumbing systems; etc.), and once the project team has committed to them, they become an input of the design process, instead of an output as in the traditional design process, in order to achieve the value objectives. In other words, cost dictates the design and continuous cost estimations are made by multidisciplinary teams throughout close collaboration, in order to constant monitor and ensure that the target cost is not exceeded (Zimina et al. 2012, Tiwari et al. 2009).

In both of the categories it is concluded that there is a need for multidisciplinary teams at early design with mechanisms/tools that facilitate their communication and coordination, and it is highlighted that the quality of the outcome depends on the capabilities and expertise of professionals (Zimina et al. 2012; Ballard 2011; Ko and Chung 2014; Freire and Alarcon 2002, Marzouk et al. 2012).

2.4.2.2. CII Design Effectiveness

The Construction Industry Institute (CII) research on Design Effectiveness (DE) (CII, 1986) (CII, 2007) developed a method to enhance project value by identifying suitable practices that promote effective design on a given project. This method helps the design team to identify and determine the priority of application of thirty different design effectiveness practices (DEPs) based on eleven previously identified project's desired benefits or project value objectives (PVO). These serve as the basis to prioritize the most important project outcome parameters. The level of suitability of the 30 DEPs is determined by a score, which reflects the combination of the PVO, the design phase, and the project characteristics; a high score means that the DEP is highly recommended for implementation, a medium score means that it might be beneficial, and a low score means that the DEP is hardly recommended. Once the DEPs for the project are identified, the design team is encouraged to further discuss the merits of the DEPs and processes that can be used to better attain the PVOs. However, this approach doesn't provide guidance to the project team on the detailed implementation process needed for the execution of those DEPs. The study was performed using data from the CII Benchmarking Database by a team mostly comprised of individuals involved in the industrial sector rather than in the commercial building sector, however, the results of this research can be generally applied as effective measures in design for all type of projects.

2.4.3. Integration through Information Technology

Efforts to integrate the design and construction phases have typically focused on using Information Technologies (IT) to improve the flow of data and information between project participants with the perceived benefits of reducing errors, improving coordination, increasing data integrity, improving communication between project participants and product quality (Faniran, et al. 2001), like 2D and 3D Computer Aided Design (CAD) systems, and Building Information Modeling (BIM). This section focuses on the use of BIM within the industry, because it emerged as a tool that can support communication and early collaboration of project participants through the building lifecycle, and now has become one of the most popular tools that, when adopted well, can facilitate project participants to work side by side with one other sharing information, and therefore, to achieve an integrated design and construction process.

Building Information Modeling (BIM) is one of the most powerful tools in supporting integrated processes, because it can combine the design, fabrication information, erection instructions and project management logistics in one database, providing a platform for collaboration and communication throughout the project's design and construction (AIA 2007). The National BIM Standard-United States defines BIM as follows: "Building Information Modeling is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition". BIM supports an integrated and collaborative process that involves all disciplines (designers, constructors, fabricators and owners) for generating and managing data during a building's life cycle (Eastman et al. 2011). The concept of BIM started to be recognized as such in the early 2000s and is moving forward, gaining traction worldwide in the industry. As shown in Figure 2-10, in 2012, 71% of the architects, engineers, contractors and owners, reported they have become engaged with BIM on their projects (Smart Market Report 2012a).

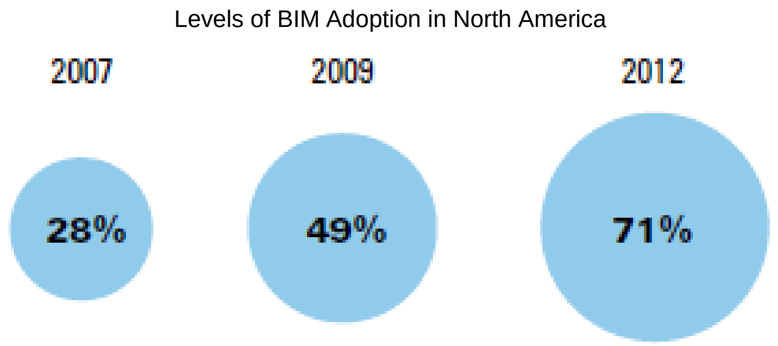


Figure 2-10. Levels of BIM Adoption in US (Smart Market Report 2012*)*

The adoption of BIM has occurred differently among project participants. Design is the longest standing-application of BIM and architects have been consistently the heaviest BIM users; however at this time, architects, engineers, and contractors are reaching the same levels of adoption, leaving owners behind; by 2012, 70 % of the architectural firms have adopted BIM, The engineering community has increased its adoption from 42% in 2009 to 67% in 2012, and contractors have surpassed architects in the use of BIM with a reported 74 % of BIM adoption in 2012. Owners are the group with the lowest level of adoption, with only 30% of them using BIM in 2012 (Smart Market Report 2012a).

In spite of the substantial incremental adoption of the technology within the industry, BIM is not used effectively and consistently at the present time (AIA 2007). Architects and contractors within the industry have identified four levels of integration of BIM, which are not formally defined but are commonly used in BIM discussions; these are: the Hollywood BIM, the lonely BIM, the social BIM, and the intimate BIM.

- Hollywood BIM is a term used to describe the practice when BIM is used as a fancy tool to create 3D models for accurate photo-realistic renderings
- Lonely BIM is a term used to describe the practice where BIM models are not exchanged between project participants, don't interact through models with other companies, or when only a mono-discipline model is created for a project
- Social BIM is a term used to describe the practice where two or more BIM models (Multi-Discipline Models) are generated and collaboratively exchanged between Project Participants.
- Intimate BIM is a term used to describe the practice where information created during "modeling" is shared with and maintained by the larger teams that finance, build, and operate buildings.

In current practice, BIM has been used as a "lonely BIM", because each party uses BIM in an isolated way, for specific purposes or for its own benefits; architects and contractors don't necessarily share their models in a collaborative fashion as would be the ideal. In fact, architects and engineers are the least likely to share their models, a common complaint by contractors because it causes them additional work to recreate model from 2D deliverables that were originally authored in BIM (Smart Market Report 2012). The architect may develop a design model for visualization and document generation; the contractor may develop a model for visualization of site logistics and construction simulation, while fabricators develop their models exclusively for fabrication as its shown in Figure 2-11, Therefore many of the potential benefits of using BIM in a project are not fully realized, and the expected productivity not materializing (Faniran et. al. 2001).

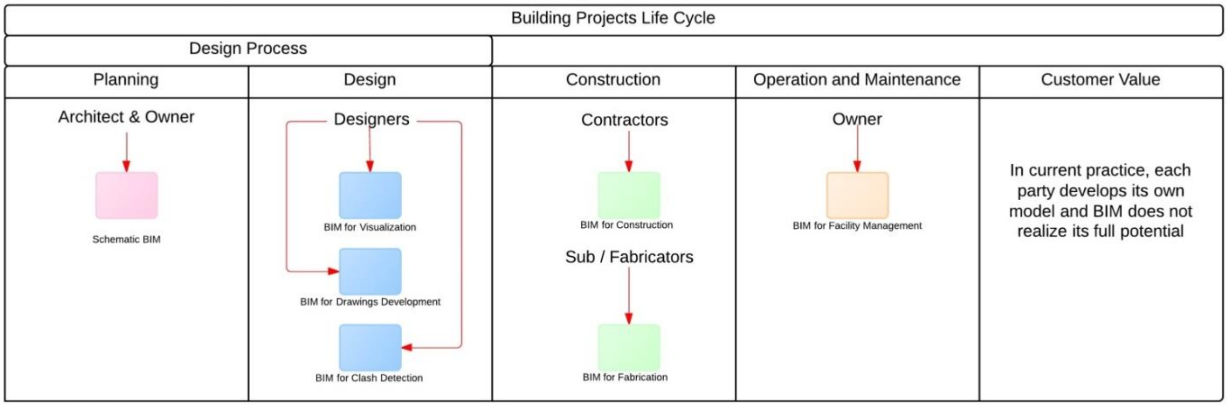


Figure 2-11. Current Use of BIM

BIM has different uses during project planning, design, construction and operational phases and can provide many benefits for Owners, Designers, Contractors and Subcontractors during the building lifecycle. By developing a BIM model during the design phase, the project constructability is improved by discovering design errors and omissions before construction starts with spatial interference checking or clash detection, and other analyses and simulations that provide feedback to the design development process, reducing conflicts, changes during construction, waste, risk and increases the overall quality of the building. In addition, architects are potentially able to provide models earlier in the procurement process that contractors can use for estimating, coordination, clash detection, construction planning, fabrication, procurement, and other functions during the construction phase. Then, during the construction phase, contractors and fabricators can better plan and visualize the construction process (and progress), as well as automate the cost estimations by using 4D and 5D models; the elimination of almost all design coordination errors, supports preassembly and fabrication and enables virtual construction prior the actual construction starts (Alvarez and Gomez 2012). Finally, owners can realize significant benefits on projects by using BIM. They can have a better understanding of the project (design, time, and cost) throughout the use of 3D, 4D and 5D models instead of the use of traditional drawings and their associated delays. In addition, the financial risk associated with the project can be reduced because cost estimates can be performed earlier and more accurately through automatic quantity takeoff from the model, allowing better decisions since early design. Because the model and database can exist for the life of a building, the owner may use BIM to manage the facility well beyond completion of construction for such purposes as space planning, furnishing, monitoring long term energy performance, maintenance, and remodeling. Finally, owners experience a more efficient delivery process, with shorter project schedules, higher quality, and better performing buildings (Eastman et al. 2011).

2.5. Summary

The fragmented nature of the construction industry makes the communication, coordination and collaboration among all the project participants more challenging. Several efforts have been done towards integration of the project participants during the design phase in the construction industry, in order to construct and delivery projects with the desired quality, time, and without costs overruns. These efforts are classified in three groups:

- Organizational/contractual integration
- Process improvement integration
- Information technology integration

Despite all efforts made to this day, the integration of design and construction has not been fully achieved. This could be because previous efforts generally address one perspective of the integration leaving out of consideration the other two. For example, BIM tools can support integrated processes and its greatest benefits can be achieved when it is used under IPD; however, IPD is not fully adopted and implemented within practitioners. Even though IPD has been used for several projects, the project team still behaved and work as a DBB or DB approach, therefore, architects and engineers don’t share their model, mainly because liability and intellectual property concerns, resulting in that the potential value of BIM is not fully realized because it is being used as no more than tool to automate a specific process.

Beyond the type of contractual agreement, the actual integration depends on the quality of teamwork and the degree of coordination, communication, and integration of the project participants (Mitropoulos 1994), and the use of appropriate tools that support this type of teamwork. In other words, owners, designers and contractors need to change the traditional way to construct facilities and embrace the technology and processes where everyone shares the same goals, which is to build better buildings and deliver value to the customer.

3. METHODOLOGY

3.1. Introduction

In order to address the needs previously recognized, the following research objectives were identified:

- Identify the value that can be delivered to the owner and the construction team, at the end of the design stage of a facility
- Identify the BIM uses that can create and deliver that value during the design stage
- Identify BIM tools and related activities that reduce the waste of resources in producing the design
- Develop an approach for an integrated, BIM-based design process

These objectives were attained by using the Axiomatic Design (AD) method (Suh 1990) which consisted of the following major steps:

- Develop the hierarchical decomposition and check for axiom 1 compliance
- Conduct a case study of the design process in a Design-Build (DB) company
- Develop a proposal for an integrated, BIM-based design process
- Validate the proposal through simulation and axiom 2 compliance
- Perform a comparative analysis between a Design-Build (DB) process and the proposed an integrated, BIM-based design process

AD is a design methodology first developed in the field of mechanical engineering by Suh in the 70’s and formalized in the 90’s with the objective to establish a scientific basis for design. AD consists of three important elements: the structure or domains, the zigzagging decomposition and, most important, the two axioms: the independence axiom and the information axiom. The independence axiom, or axiom one, seeks to maintain the design adjustable and controllable using the design matrix. The second, the information axiom, helps in selecting the best design solution by calculating the information content (IC). It has been accepted that all good designs are consistent with these two axioms (Suh 1990, Brown 2011a, Brown 2011b). The AD method is explained in more detail in Appendix A.

AD was selected as the methodology of this research because it provides a systematic process to clearly understand and define the requirements for the problem to be solved throughout the zigzagging decomposition. The zigzagging decomposition allows breaking the problem down into parts that are easier to understand and conceive, and to select a design solution for each of those parts, creating a one-to-one relationship between what is to be achieved and how to achieve it. The second advantage of using the AD method is the use of the design matrix, which provides a systematic method to optimize the design. Finally, the AD method provide a means to objectively select the best design solution and to compare it against benchmark designs (Towner 2013).

On the other hand, during the application of AD some challenges were encountered. Among the most important are that the application of the AD method is more common in the areas of product design, decision making and manufacturing systems, with a little application in the design of process design. In the civil engineering area, most of the applications focus on specifics areas of architectural and structural design, like modular design and structural performance. Other areas of civil engineering include transportation and water treatment (Thompson 2013a). But regardless of the area of application, most of the studies that include AD approach focus primarily on the use of the independence axiom, leaving axiom two out of consideration and with little reference to its application (Kulak et al. 2010).

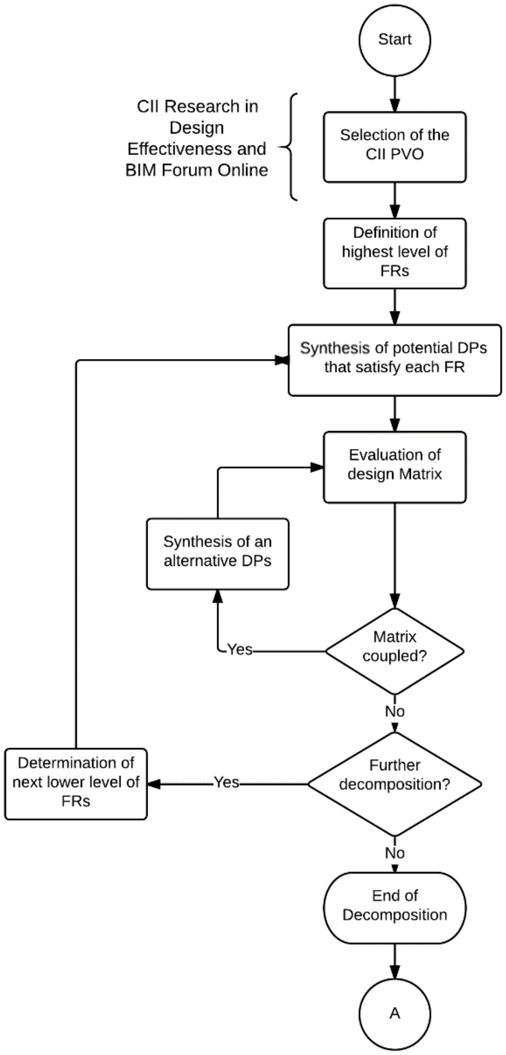


Figure 3-1 Steps of the axiomatic design decomposition and axiom one compliance

Figure 3-1 and 3-2 show in more detail the methodology followed in this research. Figure 3-1 illustrates the steps for the development of the AD decomposition and axiom one compliance, explained in more detail later in Chapter 4. These steps have the main objective to identify the BIM uses and other tools and applications that could satisfy the achievement of the functional requirements[2] (FRs) in the design domain (DPs). Figure 3-2 illustrates the steps followed to develop the proposed integrated, BIM-based design process, which are contained in the first horizontal block, and the steps followed to perform the calculation of axiom two of the DB process and the proposed integrated, BIM-based design process, which are contained in the second and third horizontal blocks.

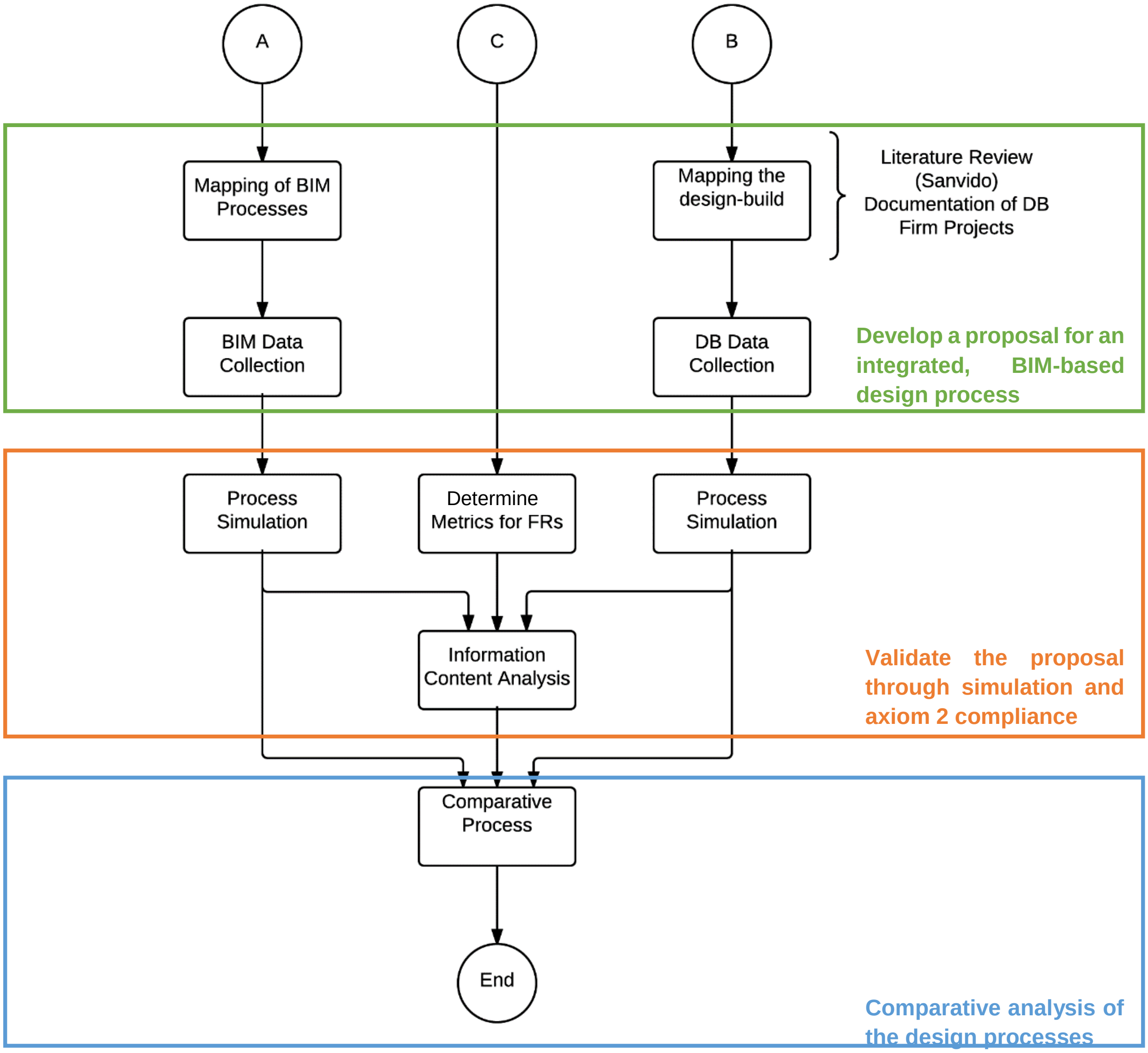


Figure 3-2 Steps followed to develop the proposed integrated, BIM-based design process and axiom two

---

[2] Functional Requirement: a minimum set of independent requirements that completely characterizes the functional needs of the product (or software, organizations, systems, etc.) in the functional domain. By definition, each FR is independent of every other one at the time the FRs are established – Taken from Nam Suh, 1998

In the vertical direction, once the AD decomposition has been completed (Figure 3-1), the mapping and simulation of the resulted BIM processes starts using the BIM Project Execution Planning Guide (CIC 2010) as a reference (shown with the letter "A" in Figure 3-2 and presented in Chapter 6 of this document). Simultaneous to this process, the mapping and simulation of the Design-Build (DB) process is performed by documenting the actual design process of a DB Company in Worcester, MA (shown with the letter "B" in Figure 3-2 and presented in Chapter 5 of this document). The process of comparison of both design processes (the DB and the integrated, BIM-based process) is shown with the letter "C" in Figure 3-2. For this process, first, the metrics to measure the fulfilment of each FR are determined. The results of the processes simulations may feed the calculation of the information content since some metrics are time-based; The steps for the process simulation steps are discussed in chapter 5 and 6. Also, they are used to compare the performance and execution times of both processes in the comparative analysis box shown in Figure 3-2. The information content is calculated for both processes and explained in Chapter 7.

3.2. Develop the hierarchical decomposition and axiom one compliance

The hierarchical decomposition started with the identification of the major stakeholders and their needs. This is important because failing to execute this step properly can result in an incorrect, incomplete, excessive or unnecessary solution (Thompson 2013c). Then, the next step is to express these needs in terms of FRs by first defining the highest-level FR or FR0, and continuing with the zigzagging process to define FR1, FR2, FR1.1, FR2.1 and so on, until no further decomposition can be done and the solution becomes obvious.

The first approach to the AD decomposition developed in this work identified the FR0 as "deliver the design option with the highest value" and used the eleven project value objectives (PVO) proposed by the Construction Institute (O'Connor et al. 2007) to further decompose FR1 "Maximize customer satisfaction", since these PVOs represent the desired outcome for all construction projects. However, having eleven FRs, which in turn would be further decomposed in more detail, would have resulted in a highly complex matrix, difficult to understand, manage and resolve. For that reason, a second decomposition was developed, as well as two surveys were applied to the industry participants in order to determine and select only those PVOs that are most important and relevant for the industry practitioners. Appendix B shows the first approach to the AD decomposition developed in this work.

The PVO's selection process for this study was based on the results obtained from two separate surveys developed and conducted together with Norwich University prior to two BIMForum conferences: one on Design Optimization (Boston, MA, April 2014) and one on Construction Optimization (Dallas TX, October 2014). Both surveys were created and administrated electronically using Qualtics® through WPI, which is a software that enables users to do online surveys and supports data collection and analysis. Appendix C shows the questionnaires applied in both conferences. The BIMForum started as a group of practitioners who got together in 1980, in order to share their BIM-related experiences with the industry practitioners like the use, adoption and benefits of BIM technology. Now, this group organize one of the most important and recognized international conferences in BIM, with the main objective of facilitating and accelerating the adoption this technology and addressing each relevant industry sector and topic under the BIM point of view.

The second decomposition developed in this work proposes to "produce a design of a building effectively and efficiently" as the FR0. The three PVO resulted from the BIMForum surveys are used to further decompose "FR1 Achieve the desired value-added of the design" and the design inefficiencies identified in Chapter 2 to decompose "FR2 Reduce the cost (waste) in producing the design", resulting in a total of forty-three FRs and Design Parameters[3] (DPs) organized in four levels. In this decomposition, BIM uses are selected as DPs to achieve the desired value of the design and increase process effectiveness, while other collaborative techniques are selected as DPs to reduce the waste of the design process and to increase efficiency. Finally, the dependencies between all DPs and FRs were evaluated with the design matrix to assure compliance with axiom one.

There are three types of evaluation matrices in AD. The coupled, the uncoupled and the decoupled matrix. The coupled matrix represents an undesirable condition, because it means that one or either DP affect one or more FR, making the design difficult to control and adjust. The uncoupled matrix represents the most desirable condition because it means that the design maintains the independence of the FRs, in other words, each DP only affects one FR, making the design controllable and adjustable. The decoupled matrix represents an acceptable condition because it allows the exact adjustment of the FRs by rearranging them in the right order.

The results of the decomposition and evaluation matrix are discussed in more detail in Chapter 4.

3.3. Case Study of the design process in a DB Company

One of the key elements to propose an integrated, BIM-based design process is to have an in-depth understanding of the design process. Because of that, a case study was conducted with the support of a DB company in Worcester, Ma. The case study consisted

---

[3] Design Parameter: design parameters are the key physical (or other equivalent terms in the case of software design, etc.) variables in the physical domain that characterize the design satisfying the specified FRs – Taken from Nam Suh 1998

of a thorough review of the design process of the company through the following activities:

1. Identification of the components of the design work flow
2. Mapping the flow of the design process
3. Collecting execution times of the different activities involved in the design process
4. Determining the average amount/number of errors in each activity (if any)
5. Determining the amount of rework and/or number of times the activity is executed in an iterative fashion before it is completed
6. Identifying the type of resources that are necessary to perform each activity

To facilitate the first and second activities, access to the company's projects and close collaboration with the company's staff was granted. The objective of these activities was to identify the design activities and to understand the workflow in the firm's DB process without necessarily developing the FR-DP mapping process stated in axiom one. The case study provided an excellent opportunity to learn more and better understand how a real DB process works. It was found that the company's design process is supported BIM technology only for coordination/constructability purposes. The other project objectives are supported and performed in the traditional fashion. The results and observations from these activities are presented in Chapter 5 and the detailed process maps are included in Appendix D.

Activities three to six were conducted by means of distributing online questionnaires to collect data regarding the execution times, errors, rework, iterations and resources, with the objective of gathering the data needed to feed the simulation model. These questionnaires were created and distributed to the company's staff using Qualtrics® software through WPI platform, and are included in Appendix E of this document.

3.4. Develop a proposal for an integrated, BIM-based design process

The objective of this step was to suggest an integrated, BIM-based design process that produces a design effectively and efficiently. The development of the proposal consisted in the incorporation of the DPs resulting from the AD decomposition developed in Chapter 4 into the lessons learned from the case study analysis conducted in Chapter 5. For the implementation of the BIM uses, this research follows the BIM Execution Planning Guide (CIC, 2010). The BIM Project Execution Planning Guide is a set of documents developed and maintained by a research group at Pennsylvania State University (CIC, 2010). This document has the objective to guide the project team in successfully creating and implementing a BIM Project Execution Plan that allows them to get the most value out of the use of the BIM technology. The guide consists of four major steps: 1) identify what BIM uses have more value to the project lifecycle; 2) create the corresponding process maps; 3) define the BIM deliverables; and 4) develop the infrastructure to support the implementation. The results of the implementation are presented in the form of process maps and discussed in more detail in Chapter 6.

3.5. Simulation of the design processes

For the purposes of technical reliability, the design processes were simulated. Process simulation has been widely used in the manufacturing field for the design, development, analysis, and improvement of the operations of the production system. In addition, it has been used to represent a process flow of a business so it can be monitored, analyzed and improved. In the construction industry, process simulation has been used, among other purposes, as a tool to for assessing the feasibility of improvement and impact of applying lean principles to the design process (Marzouk et al. 2011; Sangwon et al. 2012; Ko and Chung. 2014).

In this step, both, the case study's DB process and the integrated, BIM-based design process proposed in this research were modeled and simulated using Arena®. Arena® is a discrete event simulation software that uses a flowchart modeling methodology, where the process logic is built by placing boxes that represent activities or processes, which are then linked together by connector lines. Each box has to be populated with data that represents real time durations and resources. At the end of the run, Arena® generates a report (the Category Overview Report) which summarizes the results across all replications. Other reports can be generated in order to provide more detail for each replication.

Other software simulation packages were considered for the development of this work, like Simcad Pro®, GoldSim® and ProModel® software. However, it was decided to use Arena® mainly because of its accessibility through WPI student license. The results of the processes simulations are presented and discussed in detail in Chapter 7.

3.6. Axiom two: the information axiom

In the AD method, axiom two is used to help the designer to identify the best design solution when two or more comply with axiom one. Axiom two states that among all designs that satisfy axiom one, the design with less information content (IC) has more probability of success and therefore, is the best design (Albano 1993; Suh 1998, Suh 2000; Brown 2011b; Towner 2013).

In the context of this research, axiom two is used to objectively compare the level of complexity and the probability of success of both the DB process presented in Chapter 5 and the proposed integrated, BIM-based design process developed in Chapter 6, by calculating their IC using the equation below:

$$I = Log\ (\frac{1}{P})$$

Where:

I is the amount of IC for a given FR

P is the probability of success that a given DP will satisfy its corresponding FR

In order to calculate the IC, each FR should be independently and objectively evaluated. This was accomplished by developing appropriate metrics to quantitatively measure the degree of success of each FR and for the whole system given the selected DPs. These metrics also allow the designer to compare results over time, or to compare values from one design process against benchmarks (Towner 2013) with the purpose to objectively control and improve the system. In this research, twelve metrics were proposed for the first, second and third levels of FRs, which are discussed in more detail in Chapter 7. The fourth level FRs were left out of the scope of this research due to complexity and time constraints. Among the twelve metrics, six are construction performance metrics and financial metrics identified from the literature. In the other six cases where a useful metric was not found, it was necessary to develop a measurement function that, clearly and objectively, evaluate how well the selected DPs are fulfilling their corresponding FR.

In order to calculate the IC, the probability of success needs to be determine. This can be done by using the system probability density function (PDF) where the probability of success is represented by the intersection of the design range defined by the designer to satisfy the FRs and the ability of the system to produce the part within the specified range (Suh 2003). The system range of the DB process was determined based on outcome data provided by the DB Company as a range form. On the other hand, the system range of the integrated, BIM-based design process was estimated on data found on statistics of the literature review. Then, based on the DB Company projects real outcomes, the design range was determined on an estimated percentage of improvement. The same system range was used in both processes to calculate their IC, in order to know which one is more likely to succeed. The results of this activity are discussed in more detail in Chapter 7.

4. AXIOMATIC DESIGN DECOMPOSITION AND EVALUATION MATRIX

4.1. Introduction

This chapter documents the application of axiom one of the Axiomatic Design (AD) methodology to the building design process. It presents the decomposition of the functional requirements (FR) and design parameters (DP) up to four levels with their corresponding evaluation matrixes. The process starts by identifying the key stakeholders and translating their needs into FR0 to be used at the highest level of the design decomposition. At the second, third and fourth levels of the decomposition, the evaluation matrix was developed to evaluate and understand the implications of the relationships between FRs and DPs. The resulting DPs are then implemented into the design build (DB) process in Chapter 5 to develop the integrated, BIM-based design process proposed in this research which is presented in Chapter 6.

4.2. Identifying the key stakeholders of the design process

The first step to propose an integrated, BIM-based design process that delivers value is to clearly identify who is involved in the design process, so that their needs and what is considered as value to them can be identified and defined (Thompson 2013c). It is well known that the development of construction projects involves the participation of many people with diverse professional and commercial background, which go from lawyers and manufacturers to design professionals and contractors. A book publication (Forbes and Ahmed 2011) identifies who are the parties involved during the design and construction, however not all project participants make key decisions that are highly related with the overall achievement of the project objectives and customer needs. The decisions makers who create value during the design phase were identified in this research as the key stakeholders.

Table 4-1 Definition of the key stakeholders and their needs

Design Process Key Stakeholders

Key Stakeholder	Function	Needs	Requirements
Owner / Investor	They originate the need for projects, determine the locations and purpose of facilities, and arrange for design, financing, and construction	To have facility ready on time, cost and according to drawings and specifications (which are considered the final product of the design)	An effective process
Designers	They are usually architects and/or engineers of all the different disciplines involved, who interpret the owner's wishes into drawings and specifications that may be used to guide facility construction	To achieve a good design performance that allows them to fulfill owner's goals and expectations, while making a profit	An efficient process

Table 4-1 shows the key stakeholders and their needs as considered in this research. As shown in the table, the owner/investor is more concerned about having the desired building (in terms of aesthetics, functionality and performance) ready for operations as opposed to of the designers who are more concerned with achieving a good process performance while meeting owner, codes and project requirements. This research takes into consideration the needs of the construction and operation and maintenance phases, but leaves out of consideration the end users, since in many instances they are the same as the owner or they are represented by the owner. Therefore, the needs directly associated with the functionality of the building itself, like the development of the architectural program[4], are considered more as a constraint. In the AD method, the constraints have a special relationship to the domains since they represent boundaries for the acceptable DPs. Constraints may include cost, time, weight, legal considerations and other design specifications. All DPs that fall within those bounds are acceptable while the others cannot be considered as a solution (Brown 2006; Thompson 2013b).

4.3. Definition of the highest (first) level functional requirement – FR0

Once the key stakeholders and their needs are identified, the next step is to express them in terms of FR0 which is the highest level FR and the most important, therefore it has to be properly defined otherwise, the solution will be for another problem (Towner 2013). According to Table 4.1, what the designers and owners want is to produce a project that meets the specified objectives (effective) wasting less time and money (efficient); therefore, the FR0 and its corresponding DP were proposed in Table 4-2:

Table 4-2 Definition of the highest level of functional requirement – FR0

Funtional Requirements		Design Parameters	
FR0	Produce a design of a building (effectively and efficiently)	DP0	System for producing a design project (effectively and efficienlty)

The FRs represent what is to be achieved, in other words, FRs define the problem that the system must satisfy. The AD method requires that for each FR a unique DP is selected. The DPs are the physical solution that satisfy the specified FR within its constraints and tolerances, which are bounds on acceptable solutions.

4.4. Definition of the second level functional requirements – FR1 and FR2

At this level of decomposition the DP is expressed in terms of a system to indicate that the specific solution is not yet defined and it can be a process, a tool or a combination of both. The decomposition continued with the specification of the next top level FRs (FR1 and FR2) that were derived from manufacturing principles proposed by Brown (Brown 2011b) these are:

---

[4] The architectural program is a report that includes documentation of the methodology used, value and goal statements, data analysis conclusions, and the program requirements, which include space listings by function and size, relationship diagrams, space program sheets, space requirements, stacking plans, precept drawings, and flow diagrams, a preliminary cost estimate and project schedule – Supplemental Architectural Services, AIA 2000

- FR1 – Maximize the value-added to the product
- FR2 – Minimize the cost in the production process

These two FRs represent a triangular matrix, since there are costs that must be incurred in order when implementing the DP1 System to maximize the value-added to the product. Therefore, DP1 must be applied before DP2 System to minimize the cost in the production process (Brown 2011b).

This research proposed to analyze the building design process as a manufacturing system, where operation machines and tool are arranged to transform the resources and produce a product that delivers value by meeting the human needs. In the building design process, the resources (creative thinking) are transformed to produce the design of the building in the form of plans and specifications that meet the owner's needs. Under this approach, the two top level FRs proposed by Brown (Brown 2011b) that can be applied to all manufacturing processes, can also be used in the design process as shown in Table 4-3 with their corresponding DPs shown in Table 4-4.

Table 4-3 Definition of the second level of functional requirements

Functional Requirements	
FR1	Achieve the desired value added of the design (3 objectives)
FR2	Reduce the waste in producing the design

Table 4-4 Definition of the second level of design parameters

Design Parameters	
DP1	BIM system for increasing value added of the design project
DP2	System for reducing the cost (waste) of producing the design

The decomposition continued with the specification of the third level FRs which were derived from the project value objectives (PVO) proposed by the CII (O'Connor et al. 2007).

4.5. Definition of the third level functional requirements

4.5.1. Decomposition of FR1

The goal of the FR1 is to deliver value-added to the customer. Following the lean manufacturing principle where the customer is not only the final buyer, but also the suppliers are customers at some point of the supply chain, then, in the building design process, the owner is supplier and customer (because is the final buyer) of the design team, who in turn is the supplier of the construction team, therefore, the goal of FR1 is to deliver value to the owner and builders.

Continuing the decomposition for the third level of FRs, FR1 was first decomposed using the eleven project value objectives (PVO) proposed by the Construction Industry Institute (O'Connor et al. 2007) shown in table 4-5 which represent the project's desired benefits or desired outcome for all project participants (owners, designers, contractors and users). These eleven PVO were later reduced to three which focus on deliver value to the owner and builders. A short description of the eleven PVO was proposed based on the CII report and presented in Appendix C.

Table 4-5 CII Eleven PVO – Design effectiveness report (O'Connor et al. 2007)

CII Project Value Objectives			
1	Security	7	Product / plant / service quality
2	Operation and maintenance safety	8	Design and construction quality
3	Construction safety	9	Schedule reduction
4	Regulatory and standard compliance	10	Enviromental stweardship
5	Capital cost efficiency	11	Flexibility for future use
6	Operation and maintenance efficiency		

The AD method demands that all FRs have to be collectively exhaustive, mutually exclusive and stated in a minimum form (CEMEmin)[5] in order to prevent redundancy in the design. In other words, the sum of the children must be equal to the parent and they cannot overlap (see Appendix A). The eleven PVO shown in the Table 4-5 clearly don't meet with the CEMEmin rule, since, for example, the operation and maintenance (O&M) safety objective overlaps with regulatory and standard compliance objective, because the latter includes O&M safety codes, regulations and standards. Another example is the environmental stewardship objective that overlaps with O&M efficiency objective in the sense that both of them address the building resource consumption. Finally, according with the AD theory, cost and time should be considered as constraints rather than real FRs (Thompson 2013b), so that the selected DP must accomplish its corresponding FR within the specified time and cost. For that reason and in order to monitor and supervise in depth the level of fulfillment of each PVO, it was necessary to redefine their scope to avoid overlapping and select, among the 11 PVO, only those that are most important for the industry participants. The results of the project objectives selection process and their definition are presented in the following sections.

The PVO's selection process was supported by the elaboration and distribution of a survey questionnaire which was sent to all participants of the two BIMForum conferences mentioned in section 3.2 two weeks before the conferences started. At the BIMForum conferences were attended by a variety of people involved in the construction industry,

---

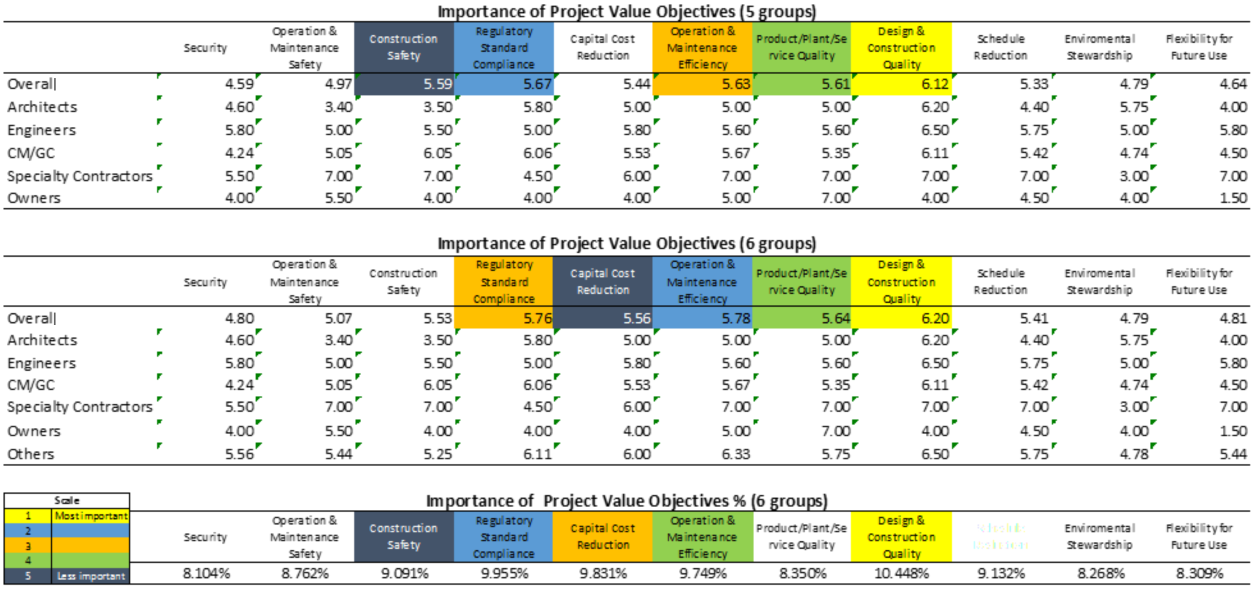
[5] CEMEmin is a convenient acronym used for "collectively exhaustive, mutually exclusive, minimum list" (Brown 2006)

which were classified in the following 6 groups:

1. Architects
2. Engineers
3. Contractors
4. Specialty contractors
5. Owners
6. Others (Software vendors, suppliers, academics, and so on)

In the survey, the respondents were asked to provide information about their professional their background in terms of their position, type of work, size of their firm, etc., as well as to rank the typical importance of the eleven CII PVO on any given project (from 1 being the least important, to 7 being the most important). The surveys are presented in detail in Appendix C. In total 43 responses were obtained from both conferences. The overall results were analyzed in three different approaches. The first approach considered the first five groups, leaving out of consideration the group named "other"; the second approach took all 6 groups into the analysis; and finally the third approach was an analysis of the 6 groups based on percentages.

Table 4-6 Results of the PVO survey



Importance of Project Value Objectives (5 groups)

	Security	Operation & Maintenance Safety	Construction Safety	Regulatory Standard Compliance	Capital Cost Reduction	Operation & Maintenance Efficiency	Product/Plant/Service Quality	Design & Construction Quality	Schedule Reduction	Enviromental Stewardship	Flexibility for Future Use
Overall	4.59	4.97	5.59	5.67	5.44	5.63	5.61	6.12	5.33	4.79	4.64
Architects	4.60	3.40	3.50	5.80	5.00	5.00	5.00	6.20	4.40	5.75	4.00
Engineers	5.80	5.00	5.50	5.00	5.80	5.60	5.60	6.50	5.75	5.00	5.80
CM/GC	4.24	5.05	6.05	6.06	5.53	5.67	5.35	6.11	5.42	4.74	4.50
Specialty Contractors	5.50	7.00	7.00	4.50	6.00	7.00	7.00	7.00	7.00	3.00	7.00
Owners	4.00	5.50	4.00	4.00	4.00	5.00	7.00	4.00	4.50	4.00	1.50

Importance of Project Value Objectives (6 groups)

	Security	Operation & Maintenance Safety	Construction Safety	Regulatory Standard Compliance	Capital Cost Reduction	Operation & Maintenance Efficiency	Product/Plant/Service Quality	Design & Construction Quality	Schedule Reduction	Enviromental Stewardship	Flexibility for Future Use
Overall	4.80	5.07	5.53	5.76	5.56	5.78	5.64	6.20	5.41	4.79	4.81
Architects	4.60	3.40	3.50	5.80	5.00	5.00	5.00	6.20	4.40	5.75	4.00
Engineers	5.80	5.00	5.50	5.00	5.80	5.60	5.60	6.50	5.75	5.00	5.80
CM/GC	4.24	5.05	6.05	6.06	5.53	5.67	5.35	6.11	5.42	4.74	4.50
Specialty Contractors	5.50	7.00	7.00	4.50	6.00	7.00	7.00	7.00	7.00	3.00	7.00
Owners	4.00	5.50	4.00	4.00	4.00	5.00	7.00	4.00	4.50	4.00	1.50
Others	5.56	5.44	5.25	6.11	6.00	6.33	5.75	6.50	5.75	4.78	5.44

Scale	
1 🟨	Most important
2 🟦	
3 🟧	
4 🟩	
5 ⬛	Less important

Importance of Project Value Objectives % (6 groups)

Security	Operation & Maintenance Safety	Construction Safety	Regulatory Standard Compliance	Capital Cost Reduction	Operation & Maintenance Efficiency	Product/Plant/Service Quality	Design & Construction Quality	Schedule Reduction	Enviromental Stewardship	Flexibility for Future Use
8.104%	8.762%	9.091%	9.955%	9.831%	9.749%	8.350%	10.448%	9.132%	8.268%	8.309%

Table 4-6 summarizes the results of each analysis derived from the surveys, highlighting in different colors the top five ranking PVOs for each of the three different approaches in which the results of the survey were analyzed. It clearly shows that "Design and Construction Quality" was selected as the most important objective in all three cases. The criteria for selecting the second and third top ranking PVOs was based on the overall level of importance and its appearance in the three analyses. Figure 4-1 shows the level of importance of the selected PVOs by group of practitioner. Overall, regulatory and standard compliance and operation and maintenance efficiency are ranked by the respondents as the second and third most important PVOs.

As a result of the analyses conducted, it was concluded that the following three PVO were the most important for the industry practitioners and to cover all stages of the building life cycle and all customers of the design process, who are the owner (because is the final buyer) and the construction team (because the design team is the supplier of construction). These are:

- Design and Construction Quality, which was renamed as “constructability”, which addresses construction concerns.
- Regulatory and Standard Compliance, which addresses safety and design concerns.
- Operation and Maintenance Efficiency, which addresses owner concerns about the building performance and maintenance.

Each of these three PVOs are defined in scope to meet the CEME rule as discussed in more detail in section 4.5.3 of this document. The design decomposition developed in section 4.6 is based and consistent with the definition developed in section 4.5.3.

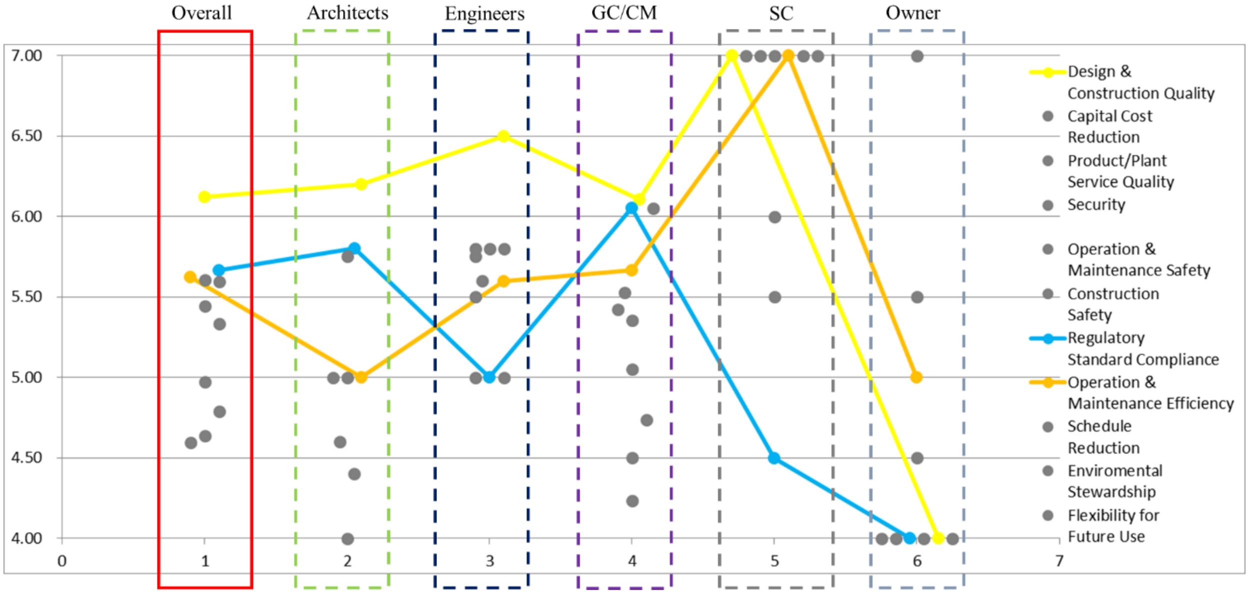


Figure 4-1 Importance of the PVOs by group of Practitioner

4.5.2. Decomposition of FR2

FR1, as discussed above, deals with the design effectiveness requirements. On the other hand, the goal of the FR2 deals with the design efficiency by looking at ways to reduce the transactional costs[6] of producing the design. This can be achieved by reducing the waste of the design process. Waste under the lean manufacturing approach, is defined as everything that does not add value; therefore, the children of the FR2 were defined in terms of the seven wastes of lean manufacturing defined by Ohno[7] (Wilson 2010), that can also be applied to the design process as is shown in Table 4-7.

Table 4-7 Seven Lean Wastes

7 Wastes of Lean Manufacturing			
1	Transportation	5	Over-processing
2	Inventory	6	Over-production
3	Motion	7	Defects
4	Waiting		

In the lean manufacturing theory, waste is also known as "Muda" and, as was mentioned before, is everything that does not add value to the process. The definitions of the seven types of wastes are presented in Appendix F of this document.

4.5.3. Project value objectives (PVO) definition

This section seeks to provide a definition of the three PVO previously selected in section 4.5.1 to be used on the AD decomposition, which includes an overview of each objective, the result that aims to achieve, and what are the aspects that should be considered during the design phase to achieve the desired results.

4.5.3.1. Regulatory and Standard Compliance

The PVO Regulatory and standard compliance refers to a set of regulations adopted by a jurisdiction to provide the minimum requirements that the design, construction and operations of the building must comply with, with the goal of protecting the health, safety, and welfare of the public. These are primarily created to avoid loss and damage to human life and include other social values to improve the quality of life and of the environment such as accessibility, energy efficiency, indoor air quality, and sustainability.

Regulatory and standard compliance is a project objective that organizations involved in the design, construction and operation of each facility must achieve in their efforts to ensure that they know and are aware of the applicable codes and standards as well as of the processes that must be followed to comply with them. Codes and standards can be classified in two groups: the federal and national codes, and the state and local codes.

In designing a project, the architect or the designer of record shall take into account all

---

[6] The cost paid for tasks that add no value to the process

[7] Taiichi Ohno, the father of the Toyota Production System, later known in the US as Lean Manufacturing

applicable federal, state and municipal building laws and regulations that apply to the building based on the building's location, type, use, and so on, early in the design phase, so that, construction permits can be approved. However, reviewing the design against the code and creating the required documents to properly communicate the design to the corresponding authorities are time consuming due to the project scope, and the complexity of interpreting the codes. Despite this, and no matter what, all designs must be code compliant; otherwise, the construction permits cannot be approved, which results in the delay of the start of the construction. For that reason, achieving an efficient code checking process becomes an important challenge for the project team during the design phase, so that, the time spent in code checking is used in this research as design tolerance.

4.5.3.2. Operation and Maintenance Efficiency

The Operation and Maintenance (O&M) stage of a constructed facility starts at the moment in which the builder transfers control of the facility to the owner, and it never ends until the building cannot continue to fulfill the functions for which it was created. It is the longest and most expensive stage in the project lifecycle, since long-term costs of managing, operating, maintaining, repairing and updating the building are directly associated with this phase.

Operation and maintenance (O&M) efficiency project objective, as the name says, is the efficiency with which the facility management (FM) staff, responsible for the long-term use of the facility, properly perform the building's operation and maintenance activities, with the purpose of control and upkeep the property and equipment in accordance with the documented design intent and the owner's operational needs, and having more durable and sustainable buildings.

O&M efficiency project objective, in the context of this research, is directly related with maintenance and operating activities. The first type encompasses all actions and day-to-day activities required to maintain the building and its surrounding infrastructure in proper operating conditions, to prevent equipment and systems from failures, and to plan for service provision based on business demands. The operating activities are all actions focused on the scheduling of the equipment, procedures, optimization of energy efficiency, and control of user comfort.

A study in Hong Kong (Chew et al. 2004) revealed that 40% of maintenance problems were related to design problems. Another study developed in UK (Meng 2013) revealed that 58% of the building failures were originated from faulty or poor design. A third study (Arditi 1999) identified the major maintenance-related complaints that designers reported receiving from clients, being the most frequent air circulation issues, followed by humidity control, repair/replacement, noise protection, indoor air quality, and heat loss/heat gain, lighting, access to cleaning area, functional layout, choice of equipment and cleaning, issues that are commonly reviewed and addressed during the design stage, like the energy efficiency analysis.

All of the above has resulted in the need to include operational and maintenance aspects, as well as the early involvement of the FM staff, in the design process in order to reduce unnecessary costs during the operation phase (Hungu 2013). Another study identified several FM-specific tasks that should be performed in building planning and design in order to facilitate operation and maintenance, highlighting as the most important the incorporation of considerations for operation and sustainability (Per Anker 2009). The CII (2007) identified energy efficiency and the facility life-cycle cost as the main activities performed during the design process that can positively affect O&M efficiency. Also, the use of BIM during O&M stage has proven to be a promising and valuable practice to support and enhance the IT commonly used by the FM staff. BIM improves FM practices by incorporating in the 3D model the information needed since early design, which includes technical information of the building systems and rooms like brand, name, model type, serial number, spare parts, warranty, and operation and maintenance manuals for systems, and room size, material and finishes specifications, and space use for other building components, among others (Hungu 2013; Alvarez 2014).

After a short literature review, the aspects and features that must be considered in the design in order to make the building easier and less expensive to operate and maintain were identified. These aspects were used in the AD decomposition to further decompose the O&M efficiency objective (section 4.7 of this chapter), which are:

- Incorporation of equipment accessibility and ergonomics into the design
- Design documentation with accurate space information
- Design documentation with accurate location of major equipment and specs
- Design promotes standardization of equipment
- Energy efficiency

4.5.3.3. Design and construction quality / Constructability

The design and construction quality objective refers to the accuracy and completeness of design drawings, the frequency of design changes and request for information (RFI) during construction, as well as inspecting the quality of the materials (testing) and other aspects that are highly related with constructability. For that reason and to avoid possible misunderstandings, the term constructability is used in this work instead of design and construction quality.

There are many definitions of constructability, all of them with some degree of similarity which can be summarized as a project management practice where the integration of construction knowledge at early design stage is very important in order to facilitate easy and efficient construction and therefore, achieve project objectives. Some of the most common definitions of constructability are:

- The capability of being constructed – *The Construction Management Committee of the ASCE Construction Division*
- The effective and timely integration of construction knowledge into the conceptual planning, design, construction, and field operations of a project to facilitate efficient construction and achieve the overall project objectives in the best possible time and accuracy at the most cost-effective levels – *Construction Industry Institute* (*CII)*
- The extent to which the design of the building facilitates ease of construction, subject to the overall requirements for the completed building – *CIRIA*
- The integration of construction knowledge in the project delivery process and balancing the various project and environmental constraints to achieve the project goals and building performance at the optimal level – *CIIA*

Even though constructability is a project management practice, this research uses the term of constructability objective to refer to the extend by which the design considers the construction process of the building in order to identify any possible difficulties and errors and omissions of the design in the drawings before construction begins, with the objective of facilitating easy construction, preventing delays, cost overruns, and reducing potential Request for Information (RFI) and change orders during construction.

Traditionally, constructability reviews are performed throughout the design development and construction documentation phases. It focuses on reviewing a large amount of drawings and specifications trying to find potential design problems and inconsistencies during construction in five major systems: structural, building envelope, interior architectural, Mechanical, Electrical and Plumbing (MEP), and site work; however, constructability is more than just only reviewing a complete set of drawings, it is thinking about how to build a project even before it is designed. As a result, several researchers have focused on identifying the most important principles/factors that should be included at early design in order to increase constructability. From selected material of the literature review, the following principles were considered and used in the AD decomposition to further decompose the constructability objective (section 4.7 of this chapter):

- Overall project and procurement schedules are construction sensitive
- Site layout facilitates efficient construction
- Design is coordinated and enables efficient construction
- Design promotes standardization and prefabrication
- Design documentation facilitates efficient construction

4.6. First iteration of the design decomposition and evaluation matrix

There can be different types of iterations in AD. The zigzagging process of defining a FR and its corresponding DP at any level, in other words, defining each level of the decomposition is one type iteration. Checking compliance with axiom one at each level is also referred as an iteration, since DP are adjusted to eliminate coupling and meet customer needs. Iteration in this research refers to the second type of iteration.

The first iteration of the design decomposition used the three project value objectives as children of FR1 – Achieve the desired value-added of the design. Each of these FRs are stated as what the customer (owner, designers and contractors) want to achieve for the building during the design phase. The seven lean wastes were used as children of FR2 Reduce the cost in producing the design, based on the premise that if the waste is reduced, the cost associated to that waste is also reduced.

The zigzagging process consisted in selecting for each FR (what), a DP (how) that satisfies it. In other words, to cycle between the functional domain (characterized by FR) to the physical domain (characterized by DP). This process is repeated down to the next lowest level until no further decomposition can be done and the solution becomes obvious. Table 4-8 shows the FRs under FR1 and their corresponding DPs that represent the system that will fulfill them.

The FR1.1 through FR1.3 focused on the effectiveness of the design process, in other words, the degree to which the design process produces a building design that meets the three PVOs. Their corresponding DPs are BIM systems/technology for achieving the FRs. BIM systems/technology were intentionally selected for the achievement of the FR, so that they can be used to develop the proposed integrated, BIM-based design process in Chapter 5 and compare it against other design process that are not supported by the use of BIM technology, in terms of its effectiveness and efficiency.

Table 4-8 Design parameters for the functional requirements FR1.1, FR1.2, and FR1.3

			Funtional Requirements
FR0			Produce a design of a building (effectively and efficiently)
	FR1		Achieve the desired value added of the design (3 objectives)
		FR1.1	Achieve a design that meets the desired level of constructability objective
		FR1.2	Achieve Regulatory & Standard Compliance objective
		FR1.3	Achieve a design that meets the desired level of O&M efficiency objective
			Design Parameters
DP0			System for producing a design project (effectively and efficienlty)
	DP1		BIM system for increasing value added of the design project
		DP1.1	BIM system for achieving a design w/the desired level of constructability objective
		DP1.2	BIM system for achieving Regulatory and Standard Compliance objective
		DP1.3	BIM system for achieving a design w/the desired level of O&M efficiency objective

Table 4-9 Design parameters for the functional requirements FR2.1 through FR2.7

		Funtional Requirements
FR2		Reduce the waste (cost) in producing the design
	FR2.1	Reduce unncessary transportation waste of the design processes
	FR2.2	Reduce unnecessary inventory waste of design information
	FR2.3	Reduce unnecessary motion waste of people and information within a process
	FR2.4	Reduce waiting waste due to non-value added activities in the building design process
	FR2.5	Reduce non-value added processing waste from using BIM in the building design process
	FR2.6	Reduce unnecesary overproduction waste of drawings and specifications
	FR2.7	Reduce defects waste in the building design documentation
		Design Parameters
DP2		System for reducing the cost (waste) of producing the design
	DP2.1	System for reducing the unnecesary transportation waste in the building design process
	DP2.2	System for reducing the unnecessary inventory waste of design information
	DP2.3	System for reducing the unnecessary motion waste in the building design
	DP2.4	System for reducing the waiting waste in the building design process
	DP2.5	System for reducing the inappropiate processing waste in the building design process
	DP2.6	System for reducing the overproduction waste of drawings and specifications
	DP2.7	System for reducing the defect waste in the building design

Table 4-9 shows the FRs under FR2 and their corresponding DPs that represent the system that will fulfill them. The FRs from FR2.1 through FR2.7 shown in Table 4-10 focus on improving the efficiency of the design process by reducing waste. According to the lean manufacturing principles, there are two types of waste: the non-value-added activities but necessary; and the non-value-added activities which are not necessary. The decomposition of FR2, is targeted to reduce the last type of waste which are the seven wastes of lean.

4.6.1. Evaluation matrix

Analysis of the relationship between the FRs and the DPs was conducted through the evaluation matrix. The evaluation matrix shows if one DP is affecting more than one FR so that it goes out of tolerance, which results in a coupling matrix and in a violation of the axiom 1. Tolerances are characteristics of the FRs, defined in terms of the design range[8], which can influence the quality and cost of the final solution and are needed to calculate the information content.

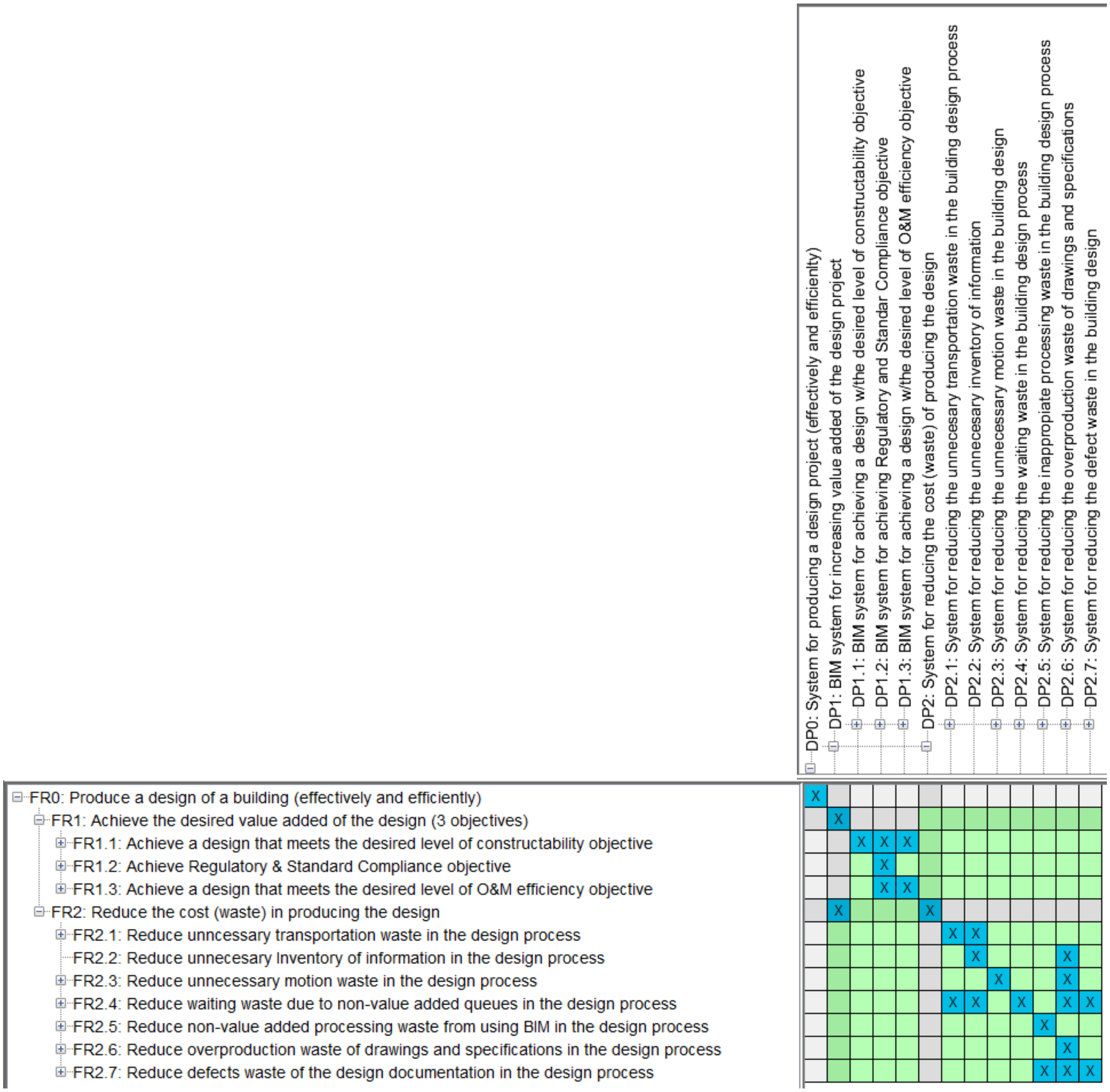
Figure 4-2 shows the evaluation matrix after conducting the first iteration of the design of the building design process using Acclaro® software[9]. The left-hand side of the matrix (rows) show the FRs with what is desired to be achieved, while the top right-hand side (columns) show the DPs indicating how the FRs could be achieved. The matrix clearly shows an undesirable condition where coupling exists (a coupled matrix). This coupling

---

[8] Design range represents a rage value of what is intended to take place by the designer for a successful design outcome

[9] (Axiomatic Design Solutions, Inc. 2012).

condition can be improved by rearranging the matrix or by introducing new DPs in an effort to get the decoupled matrix with the triangular form, or even better the uncoupled matrix with the diagonal form. Since at this point the solution is not obvious, the matrix was reconfigured without changing any FR. The second iteration of the design of the building design process is explained in section 4.7 of this Chapter. Section 4.6.2 explains the rational thinking behind the interactions between FRs and DPs. Section 4.6.3 explains the rearranged design matrix at that specific level (third level).



	DP0: System for producing a design project (effectively and efficienlty)	DP1: BIM system for increasing value added of the design project	DP1.1: BIM system for achieving a design w/the desired level of constructability objective	DP1.2: BIM system for achieving Regulatory and Standar Compliance objective	DP1.3: BIM system for achieving a design w/the desired level of O&M efficiency objective	DP2: System for reducing the cost (waste) of producing the design	DP2.1: System for reducing the unnecesary transportation waste in the building design process	DP2.2: System for reducing the unnecesary inventory of information	DP2.3: System for reducing the unnecessary motion waste in the building design	DP2.4: System for reducing the waiting waste in the building design process	DP2.5: System for reducing the inappropiate processing waste in the building design process	DP2.6: System for reducing the overproduction waste of drawings and specifications	DP2.7: System for reducing the defect waste in the building design
FR0: Produce a design of a building (effectively and efficiently)	X												
FR1: Achieve the desired value added of the design (3 objectives)		X											
FR1.1: Achieve a design that meets the desired level of constructability objective			X	X	X								
FR1.2: Achieve Regulatory & Standard Compliance objective				X									
FR1.3: Achieve a design that meets the desired level of O&M efficiency objective				X	X								
FR2: Reduce the cost (waste) in producing the design		X				X							
FR2.1: Reduce unncessary transportation waste in the design process							X	X					
FR2.2: Reduce unnecesary Inventory of information in the design process								X				X	
FR2.3: Reduce unnecessary motion waste in the design process									X			X	
FR2.4: Reduce waiting waste due to non-value added queues in the design process							X	X		X		X	X
FR2.5: Reduce non-value added processing waste from using BIM in the design process											X		
FR2.6: Reduce overproduction waste of drawings and specifications in the design process												X	
FR2.7: Reduce defects waste of the design documentation in the design process											X	X	X

Figure 4-2 Evaluation matrix of the first iteration

4.6.2. Interactions between functional requirements and design parameters

Interactions between FRs and DPs refers to the influence that a DP might have on one or more FR. This section explains in detail the rationale for determining the interactions of each DP on the FRs at the third level of decomposition using the evaluation matrix, in order to identify and resolve possible coupling. As was mentioned before, a coupled matrix represents an undesirable condition because it results in designs that are difficult to control, adjust and are not compliant with axiom one.

The interaction analysis was conducted based on the definition of the project objectives presented in the section 4.5 of this chapter and on whether or not the design solution affects a FR in such a way that it can be moved out from its tolerances. The tolerances for the third level of FRs were set based on business statistics and, since tolerances are used to calculate the information content, the FRs tolerances are explained in more detail in Chapter 7 along with axiom two.

Table 4-10 shows how, the DP1.1 only affects its corresponding FR1.1, since the system for achieving the constructability PVO doesn't affect the achievement of the other two FRs.

Table 4-10 Relationship between DP1.1 and FR1.1 through FR1.3

Interaction between DP1.1 BIM system for achieving a design with the desired level of constructability objective and FR1.1 through 1.3

Functional requirements	Matrix symbol	Design parameter	Reason of coupling
FR1.1: Achieve a design that meets the desired level of constructability objective	X	Intended coupling	The system is intended to affect FR 1.1
FR1.2: Achieve Regulatory & Standard Compliance objective	None		
FR1.3: Achieve a design that meets the desired level of O&M efficiency objective	None		

Table 4-11 shows coupling between the system for achieving a regulatory and standard compliant design and the FR1.1 and FR1.3. This coupling is mainly because the code includes minimum requirements of some aspects of constructability and operation and maintenance that can affect FR1.1 and FR1.3. Also, another reason is that if the design does not meet the code it can't continue its development. Finally, any feature or system implemented to help increasing the level of constructability or O&M efficiency must be code compliant, if not, they can not be used in the project. Therefore, it is clear that the achievement of the regulatory and standard compliance objective should be addressed first in the design process, and the considerations of constructability and operation and maintenance efficiency should reflect the applicable codes and regulations according to the type of project and location. Even though, the Regulatory and Standard Compliance objective is measured in this research in terms of the time spent on reviewing the design against the code; therefore, is not considered as a constraint.

In table 4.12 shows that the BIM system for achieving O&M efficiency objective affects its corresponding FR and FR1.3. Even though the efficiency of the O&M mainly refers to maintainability activities and these activities don't affect the affect the major construction methods and flow sequence, the maintainability aspects should be considered in the design before the coordination of the building systems and design reviews take place, so that, during this review, the maintainability aspects are also considered. Therefore, O&M efficiency objective has to be prioritized and should have constructability considerations.

Table 4-11 Relationship between DP1.2 and FR1.1 through FR1.3

Interaction between DP1.2 BIM system for achieving Regulatory and Standard Compliance objective and FR1.1 through 1.3

Functional Requirements	Matrix Symbol	Design Parameter	Reason of coupling
FR1.1: Achieve a design that meets the desired level of constructability objective	X	Unintended coupling	For the building design, DP1.2 is needed for the achievement of the FR1.1 since constructability considerations must happen within the code
FR1.2: Achieve Regulatory & Standard Compliance objective	X	Intended coupling	The system is intended to affect FR 1.2
FR1.3: Achieve a design that meets the desired level of O&M efficiency objective	X	Unintended coupling	For the building design, DP1.2 is needed for the achievement of the FR1.3 since O&M considerations must happen within the code

Table 4-12 Relationship between DP2.1 and FR2.1 through FR2.7

Interaction between DP1.3 BIM system for achieving a design w/the desired level of O&M efficiency objective and FR1.1 through 1.3

Functional Requirements	Matrix Symbol	Design Parameter	Reason of coupling
FR1.1: Achieve a design that meets the desired level of constructability objective	X	Unintended coupling	For the building design, the system for achiving O&M efficiency should consider constructability
FR1.2: Achieve Regulatory & Standard Compliance objective	None		
FR1.3: Achieve a design that meets the desired level of O&M efficiency objective	X	Intended coupling	The system is intended to affect FR 1.3

The next discussion deals with the interaction between FR2 and corresponding DP2. FR2.1 refers to the transportation waste that takes place during the design process which involves the transportation of resources in terms of people and information between different offices and other locations. In addition to influencing FR2.1, the system for reducing the unnecessary transportation waste also affects the waiting time waste directly associated with the time invested for transporting that people and physical information during the design process, as it is shown in Table 4.13.

Table 4-13 Relationship between DP2.1 and FR2.1 through FR2.7

Interaction between DP2.1 System for reducing the unnecesary transportation waste in the building design process and FR2.1 through 2.7

Functional Requirements	Matrix Symbol	Design Parameter	Reason of coupling
FR2.1: Reduce unncessary transportation waste of the design process	X	Intended coupling	The system is required to achieve this FR
FR2.2: Reduce unnecesary Inventory of information	None		
FR2.3: Reduce unnecessary motion waste in the design process	None		
FR2.4: Reduce waiting waste due to non-value added queues	X	Unintended coupling	By reducing transportation, the waiting time is also reduced
FR2.5: Reduce non-value added processing waste from using BIM in the building design process	None		
FR2.6: Reduce overproduction waste of drawings and specifications	None		
FR2.7: Reduce defects waste in the design documentation	None		

The unnecessary inventory of information type of waste is the storage of physical design information, like mock-ups and other printed documents that are created during the building design process and maintained until the project is completed. This physical information has to be transported for storage; therefore, DP2.2 – System for reducing the unnecessary inventory of information, besides influencing its corresponding FR2.2 as shown in Table 4-14, also influences the waiting time associated with transporting the information for storage (FR2.1 and FR2.4).

Table 4-14 Relationship between DP2.2 and FR2.1 through FR2.7

Interaction between DP2.2 System for reducing the unnecesary inventory of information and FR2.1 through 2.7

Functional Requirements	Matrix Symbol	Design Parameter	Reason of coupling
FR2.1: Reduce unncessary transportation waste of the design process	X	Unintended coupling	By reducing the inventory of physical design information, the transportation of this information also reduces
FR2.2: Reduce unnecesary Inventory of information	X	Intended coupling	The system is required to achieve this FR
FR2.3: Reduce unnecessary motion waste in the design process	None		
FR2.4: Reduce waiting waste due to non-value added queues	X	Unintended coupling	Reducing the unnecessary inventory, the waiting time associated with the transportation and handlign of that information also reduces
FR2.5: Reduce non-value added processing waste from using BIM in the building design process	None		
FR2.6: Reduce overproduction waste of drawings and specifications	None		
FR2.7: Reduce defects waste in the design documentation	None		

Although nowadays in the design process most of the drawings and specifications are produced in digital format, some other information like mock-ups, printed drawings and material samples are physical. The use of physical information can be replaced by using digital mock-ups and prototypes in the building design process, thereby, reducing the transportation, waiting time and storage wastes associated with the physical information. However, this practice increases the virtual storage space required to keep that information. In the building design process this kind of waste is needed since it not a physical storage and provides a record of evidence of how the design develops and other important changes and revisions of the project. Due of the above and since the use of digital information and prototypes is considered as a solution for reducing the unnecessary transportation waste (Table 4-21, section 4.7 of this Chapter), the inventory waste is no longer included in the second iteration of the design decomposition.

Motion is very similar as the transportation waste but in a lower scale. In the context of this research, motion waste is identified as the movement of people and information within the design office. Table 4-15 shows that DP2.3 only influences its corresponding FR to fulfill it.

Table 4-15 Relationship between DP2.3 and FR2.1 through FR2.7

Interaction between DP2.3 system for reducing the unnecessary motion waste in the building design and the FR2.1 through 2.7

Functional Requirements	Matrix Symbol	Design Parameter	Reason of coupling
FR2.1: Reduce unncessary transportation waste of the design process	None		
FR2.2: Reduce unnecesary Inventory of information	None		
FR2.3: Reduce unnecessary motion waste in the design process	X	Intended coupling	The system is required to achieve this FR
FR2.4: Reduce waiting waste due to non-value added queues	None		
FR2.5: Reduce non-value added processing waste from using BIM in the building design process	None		
FR2.6: Reduce overproduction waste of drawings and specifications	None		
FR2.7: Reduce defects waste in the design documentation	None		

The waiting waste due to non-value-added queues refers to the amount of time the design information spend before value-added work is performed with it. This mainly includes the waiting time incurred due to unnecessary checking the information, the waiting time for the information to be available and accessible, and the waiting time for the information to be properly transferred and exchanged because the communication channels are inefficient. Table 4-16 shows that DP2.4 only influences its corresponding FR.

Table 4-16 Relationship between DP2.4 and FR2.1 through FR2.7

Interaction between DP2.4 system for reducing the waiting waste in the building design process and the FR2.1

Functional Requirements	Matrix Symbol	Design Parameter	Reason of coupling
FR2.1: Reduce unncessary transportation waste of the design process	None		
FR2.2: Reduce unnecesary Inventory of information	None		
FR2.3: Reduce unnecessary motion waste in the design process	None		
FR2.4: Reduce waiting waste due to non-value added queues	X	Intended coupling	The system is required to achieve this FR
FR2.5: Reduce non-value added processing waste from using BIM in the building design process	None		
FR2.6: Reduce overproduction waste of drawings and specifications	None		
FR2.7: Reduce defects waste in the design documentation	None		

Inappropriate processing is adding more value to a product than the customer actually requires. Since this work proposes the use of BIM technology for the achievement of the PVOs. The non-value-added processing waste refers to the right use and selection of the BIM technology and software during the design process for a specific project, as well as the development of BIM models with the right level of development (LOD) according to the project and BIM uses. In addition, by defining the right LOD and information the probability of defects, errors and omissions also reduce. Table 4-17 shows that the system for reducing the inappropriate processing waste in the building design process influences its corresponding FR2.5 and FR2.7.

Table 4-17 Relationship between DP2.5 and FR2.1 through FR2.7

Interaction between DP2.5 system for reducing the inappropiate processing waste in the building design process and the FR2.1 through 2.7

Functional Requirements	Matrix Symbol	Design Parameter	Reason of coupling
FR2.1: Reduce unncessary transportation waste of the design process	None		
FR2.2: Reduce unnecesary Inventory of information	None		
FR2.3: Reduce unnecessary motion waste in the design process	None		
FR2.4: Reduce waiting waste due to non-value added queues	None		
FR2.5: Reduce non-value added processing waste from using BIM in the building design process	X	Intended coupling	Intended coupling
FR2.6: Reduce overproduction waste of drawings and specifications	None		
FR2.7: Reduce defects waste in the design documentation	X	Unintended coupling	

In this research, overproduction of drawings and specification includes the production of more building plans than needed for the project, the production of drawings with redundant or repeated information, and the production of excessive detail in the drawings. Table 4-18 clearly shows that the system for reducing the overproduction waste of drawings and specification influences several FRs. First, by reducing overproduction the inventory and storage of that information also reduces. Motion, waiting time and defects associated with the excessive production of drawings and specifications are also reduced.

Commonly, the transportation waste is also reduced when reducing the overproduction; however, in this research, transportation refers to the movement of people and physical information other than drawings and specifications which are mostly produced in digital format. For that reason, it was the interaction between the system for reducing overproduction waste and the FR2.1 reduce unnecessary transportation that was marked as none.

Table 4-18 Relationship between DP2.6 and FR2.1 through FR2.7

Interaction between DP2.6 system for reducing the overproduction waste of drawings and specifications and the FR2.1 through 2.7

Functional Requirements	Matrix Symbol	Design Parameter	Reason of coupling
FR2.1: Reduce unncessary transportation waste of the design process	None		
FR2.2: Reduce unnecesary Inventory of information	X		Reducing overproduction reduces the need to storage
FR2.3: Reduce unnecessary motion waste in the design process	X		Reducing overproduction reduces the need to move a lot of information
FR2.4: Reduce waiting waste due to non-value added queues	X		Reducing overproduction reduces the need to wait for the information to be ready and avalable
FR2.5: Reduce non-value added processing waste from using BIM in the building design process	None		
FR2.6: Reduce overproduction waste of drawings and specifications	X	Intended coupling	The system is required to achieve this FR
FR2.7: Reduce defects waste in the design documentation	X	Unintended coupling	Reducing overproduction reduces the probability of defects

The system for reducing the defect waste in the building design influences FR2.4 waiting waste due to non-value activities and FR2.7 defects in the design documentation since the time spent in checking the information also reduces as shown in Table 4-19. Defect waste refers to the advancement of incomplete, inaccurate and ambiguous design documentation.

Table 4-19 Relationship between DP2.7 and FR2.1 through FR2.

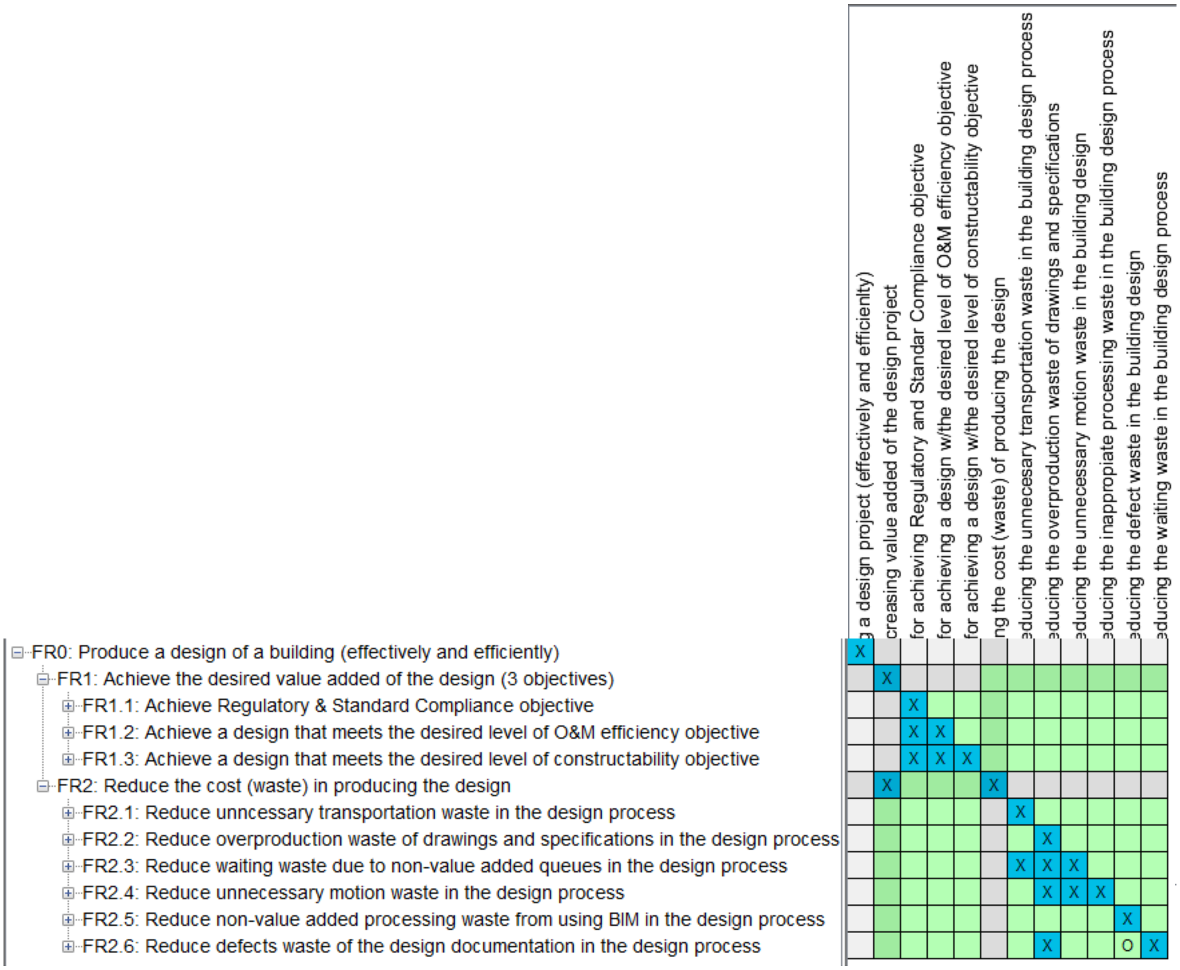
Interaction between DP2.7 system for reducing the defect waste in the building design and the FR2.1 through 2.7

Functional Requirements	Matrix Symbol	Design Parameter	Reason of coupling
FR2.1: Reduce unncessary transportation waste of the design process	None		
FR2.2: Reduce unnecesary Inventory of information	None		
FR2.3: Reduce unnecessary motion waste in the design process	None		
FR2.4: Reduce waiting waste due to non-value added queues	X	Unintended coupling	Reducing defects in the design documentation influences on the time spent on checking
FR2.5: Reduce non-value added processing waste from using BIM in the building design process	None		
FR2.6: Reduce overproduction waste of drawings and specifications	None		
FR2.7: Reduce defects waste in the design documentation	X	Intended coupling	The system is required to achieve this FR

4.6.3. Achieving a triangular matrix for the third level functional parameters

As was mentioned before, the evaluation matrix can be reconfigured to form a diagonal or triangular matrix in the lower left corner. This arrangement was accomplished by decomposing the process to a third level and examining in detail the relationships between FRs and DPs at that level. The matrix is shown in Figure 4-3. Because the design process is a complex process, with sequential, parallel and interdependent activities, it is difficult to get a diagonal matrix where all the DPs are independent and controllable, therefore, the goal in this research is to achieve the triangular form. The resulting triangular matrix should clearly show the proper sequence for implementation of the DPs throughout the design process. The resulting sequence DP implementation is described in detail in Chapter 5.

This space has been intentionally left blank.



	g a design project (effectively and efficienlty)	creasing value added of the design project	for achieving Regulatory and Standar Compliance objective	for achieving a design w/the desired level of O&M efficiency objective	for achieving a design w/the desired level of constructability objective	ng the cost (waste) of producing the design	educing the unnecesary transportation waste in the building design process	educing the overproduction waste of drawings and specifications	educing the unnecessary motion waste in the building design	educing the inappropiate processing waste in the building design process	educing the defect waste in the building design	educing the waiting waste in the building design process
⊟ FR0: Produce a design of a building (effectively and efficiently)	X											
⊟ FR1: Achieve the desired value added of the design (3 objectives)		X										
⊞ FR1.1: Achieve Regulatory & Standard Compliance objective			X									
⊞ FR1.2: Achieve a design that meets the desired level of O&M efficiency objective			X	X								
⊞ FR1.3: Achieve a design that meets the desired level of constructability objective			X	X	X							
⊟ FR2: Reduce the cost (waste) in producing the design		X				X						
⊞ FR2.1: Reduce unncessary transportation waste in the design process							X					
⊞ FR2.2: Reduce overproduction waste of drawings and specifications in the design process								X				
⊞ FR2.3: Reduce waiting waste due to non-value added queues in the design process							X	X	X			
⊞ FR2.4: Reduce unnecessary motion waste in the design process								X	X	X		
⊞ FR2.5: Reduce non-value added processing waste from using BIM in the design process											X	
⊞ FR2.6: Reduce defects waste of the design documentation in the design process								X			O	X

Figure 4-3 Re-arranged evaluation matrix of the first iteration

4.7. Second iteration of the design decomposition

The second iteration of the design decomposition starts with the decomposition of the third level of FRs, in other words, the decomposition of FR1.1 to FR1.3 and FR2.1 to FR2.6.

FR1.1 through FR1.3 were decomposed using the aspects of the PVO that can be addressed during the design phase, as previously described in section 4.5 of this chapter. Table 4-20 shows the functional requirements under FR1.1 through FR1.3 (fourth level) and their corresponding DPs that represent the system that satisfies them. Each of these FRs are stated as what the customer (owner, designers and contractors) want to achieve for the building during the design phase.

Table 4-20 Decomposition of FR1.1 through FR1.3

Functional Requirements

- FR0: Produce a design of a building (effectively and efficiently)
  - FR1: Achieve the desired value added of the design (3 objectives)
    - FR1.1: Achieve Regulatory & Standard Compliance objective
      - FR1.1.1: Achieve a regulatory, code and standard compliant design
      - FR1.1.2: Achieve design documentation that communicates code compliance and facilitates timely acquisition of permits
    - FR1.2: Achieve a design that meets the desired level of O&M efficiency objective
      - FR1.2.1: Achieve facility management knowledge in the design
      - FR1.2.2: Achieve a design with accurate the accurate use of the space
      - FR1.2.3: Achieve a design with clearly understanding of the physical location of equipment
      - FR1.2.4: Achieve a design that facilitates equipment accessibility to perform maitenaince operations
      - FR1.2.5: Achieve a design that enables efficient O&M thorugh standarization (to minimize specialized maintenance skills)
      - FR1.2.6: Achieve an energy efficient design
    - FR1.3: Achieve a design that meets the desired level of constructability objective
      - FR1.3.1: Achieve construction knowledge and experience in the design
      - FR1.3.2: Achieve a design that considers the major construction methods and procurement to enable efficient construction
      - FR1.3.3: Achieve a site and building layout that promotes efficient construction
      - FR1.3.4: Achieve a coordinated design to enable efficient construction
      - FR1.3.5: Achieve a design that promotes standarization and prefabrication to facilitate efficient construction
      - FR1.3.6: Achieve a design documentation that facilitates efficient construction

Design Parameters

- DP0: System for producing a design project (effectively and efficienlty)
  - DP1: BIM system for increasing value added of the design project
    - DP1.1: BIM system for achieving Regulatory and Standar Compliance objective
      - DP1.1.1: BIM code validation process
      - DP1.1.2: BIM process for creating drawings for building permits
    - DP1.2: BIM system for achieving a design w/the desired level of O&M efficiency objective
      - DP1.2.1: BIM project execution planning guide for identifying project participants
      - DP1.2.2: BIM design reviews process for evaluating the space program
      - DP1.2.3: BIM design reviews process for understanding the physical location of the equipment
      - DP1.2.4: BIM design reviews process for evaluating the space and ergonomics requirements
      - DP1.2.5: BIM design reviews to assess the degree of repetition / modularity of equipment
      - DP1.2.6: BIM energy analysis process to assess the building energy operation costs
    - DP1.3: BIM system for achieving a design w/the desired level of constructability objective
      - DP1.3.1: BIM project execution planning guide for identifying project participants
      - DP1.3.2: BIM phase planning (4D modeling)
      - DP1.3.3: BIM Site utilization planning process
      - DP1.3.4: BIM 3D coordination process
      - DP1.3.5: BIM design reviews to assess the degree of repetition / modularity
      - DP1.3.6: BIM process for creating drawigns and specifications

During the literature review presented in Chapter 2, it was found that several authors have identified the inefficiencies of the design process. In this research, these inefficiencies were classified and grouped according to the type of waste, so that, they can be used as children of the FR2.1 through FR2.6. The compilation of the inefficiencies of the design process found in the literature review and their classification by type of waste is presented in the Appendix G. Table 4-21 shows material extracted from different sources that was used to define the FRs under FR2.1 through FR2.6 and their corresponding DPs.

Table 4-21 Decomposition of FR2.1 through FR2.7

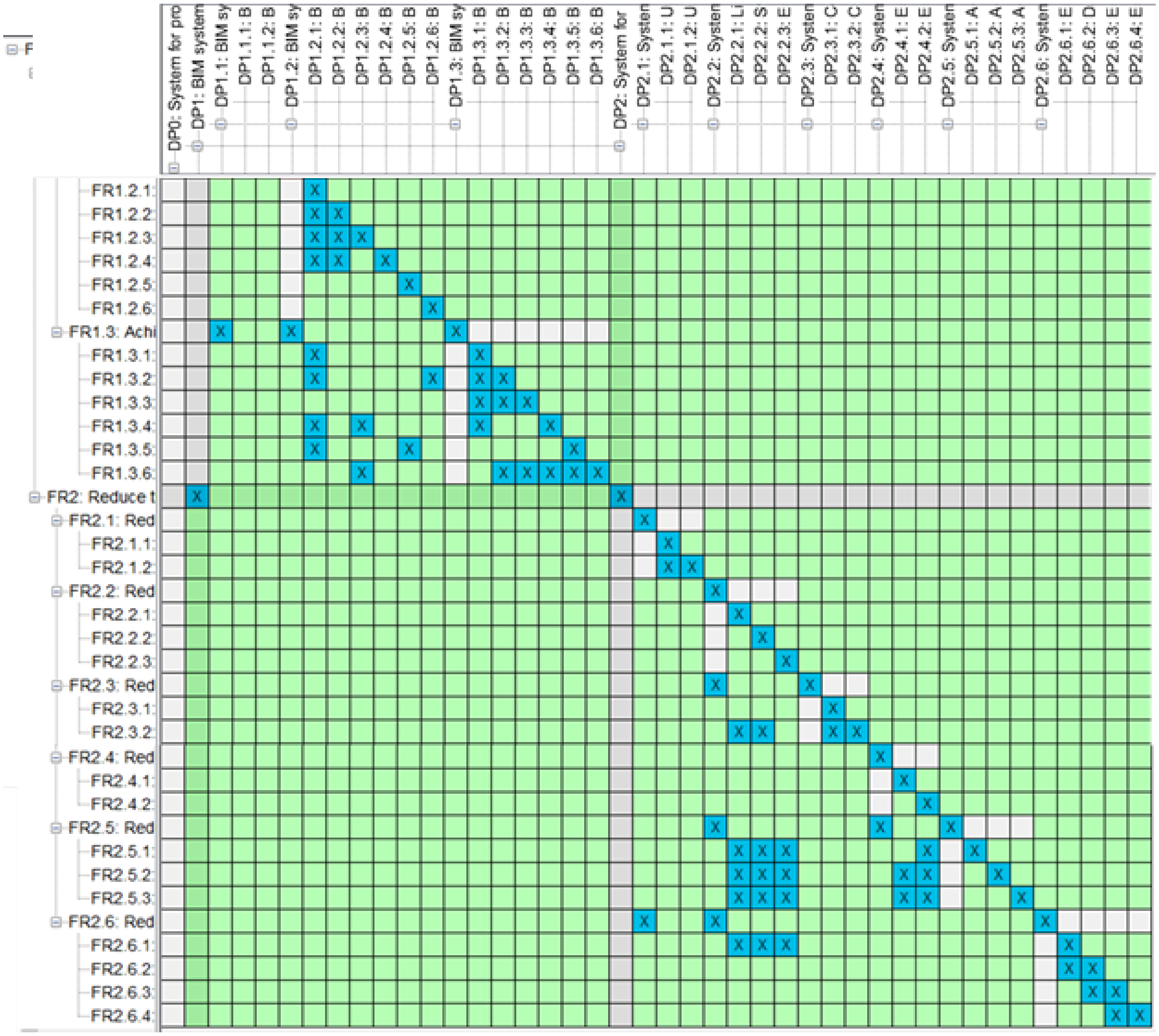
Functional Requirements

- FR0: Produce a design of a building (effectively and efficiently)
  - FR2: Reduce the cost (waste) in producing the design
    - FR2.1: Reduce unncessary transportation waste of the design process
      - FR2.1.1: Reduce transportation waste due to different locations of the design team
      - FR2.1.2: Reduce transportation waste of physical design data/information
    - FR2.2: Reduce overproduction waste of drawings and specifications
      - FR2.2.1: Reduce unnecesary building's plans
      - FR2.2.2: Reduce redundant detail on drawings
      - FR2.2.3: Reduce unnecesary detailing on drawings and specifications
    - FR2.3: Reduce unnecessary motion waste in the design process
      - FR2.3.1: Reduce unnecesary motion of people within the design office
      - FR2.3.2: Reduce incomplete design reviews meetings
    - FR2.4: Reduce non-value added processing waste from using BIM in the building design process
      - FR2.4.1: Reduce unnecessary use of BIM softwares and technologies in the building design
      - FR2.4.2: Reduce unncessesary development of the BIM models for the building design
    - FR2.5: Reduce defects waste in the design documentation
      - FR2.5.1: Reduce defects waste due to premature advancement of incomplete design documentation
      - FR2.5.2: Reduce defects waste due to premature advancement of innacurate design documentation
      - FR2.5.3: Reduce defects waste due to premature advancement of ambiguous design documentation
    - FR2.6: Reduce waiting waste due to non-value added queues
      - FR2.6.1: Reduce waiting waste due to unnecessary checking of design information
      - FR2.6.2: Reduce waiting waste due to information is not available /accessible by all project participants
      - FR2.6.3: Reduce waiting waste due to information is not properly tranfered between project participants
      - FR2.6.4: Reduce waiting waste due to information is not properly exchanged

Design Parameters

- DP0: System for producing a design project (effectively and efficienlty)
  - DP2: System for reducing the cost (waste) of producing the design
    - DP2.1: System for reducing the unnecesary transportation waste in the building design process
      - DP2.1.1: Use of virtual meetings during the buildign design process
      - DP2.1.2: Use of digital information and prototypes in the building design process
    - DP2.2: System for reducing the overproduction waste of drawings and specifications
      - DP2.2.1: List of building's plans required according to the type of project and location
      - DP2.2.2: Standarization of drawing information content
      - DP2.2.3: Establishing appropiate level of design detailing for project type
    - DP2.3: System for reducing the unnecessary motion waste in the building design
      - DP2.3.1: Co-location of the design team within the office area
      - DP2.3.2: Creating design meetings agenda, schedule and minutes
    - DP2.4: System for reducing the inappropiate processing waste in the building design process
      - DP2.4.1: Establishing the appropiate IT and software to use during the building design - BIM Exec Planning Guide
      - DP2.4.2: Establishing the appropiate level of development of the BIM models - LOD document
    - DP2.5: System for reducing the defect waste in the building design
      - DP2.5.1: Activity for Inspecting completness of drawings and specifications
      - DP2.5.2: Activity for Inspecting accuracy of drawings and specifications
      - DP2.5.3: Activity for Inspecting clarity of drawings and specifications
    - DP2.6: System for reducing the waiting waste in the building design process
      - DP2.6.1: Establishing design milestones and times for checking
      - DP2.6.2: Data and document management system repository
      - DP2.6.3: Establishing information and communication mapping workflow in the design process
      - DP2.6.4: Establish BIM information exchange protocol - BIM Execution Planning Guide

The evaluation matrix of the second iteration shows a diagonal form, which means that the design solution satisfies axiom one, and for its correct implementation is necessary to first implement DP1 to fulfill FR1 and then, implement DP2 and so on. Figure 4-4 shows the complete triangular matrix for the second iteration of the design of the building design process down to level 4, using Acclaro® software



	DP0: System for pro	DP1: BIM system	DP1.1: BIM sy	DP1.1.1: B	DP1.1.2: B	DP1.2: BIM sy	DP1.2.1: B	DP1.2.2: B	DP1.2.3: B	DP1.2.4: B	DP1.2.5: B	DP1.2.6: B	DP1.3: BIM sy	DP1.3.1: B	DP1.3.2: B	DP1.3.3: B	DP1.3.4: B	DP1.3.5: B	DP1.3.6: B
FR1.2.1:							X												
FR1.2.2:							X	X											
FR1.2.3:							X	X	X										
FR1.2.4:							X	X		X									
FR1.2.5:											X								
FR1.2.6:												X							
FR1.3: Achi			X			X							X						
FR1.3.1:							X							X					
FR1.3.2:							X					X		X	X				
FR1.3.3:														X	X	X			
FR1.3.4:							X		X					X			X		
FR1.3.5:							X				X							X	
FR1.3.6:									X						X	X	X	X	X
FR2: Reduce t		X																	
FR2.1: Red																			
FR2.1.1:																			
FR2.1.2:																			
FR2.2: Red																			
FR2.2.1:																			
FR2.2.2:																			
FR2.2.3:																			
FR2.3: Red																			
FR2.3.1:																			
FR2.3.2:																			
FR2.4: Red																			
FR2.4.1:																			
FR2.4.2:																			
FR2.5: Red																			
FR2.5.1:																			
FR2.5.2:																			
FR2.5.3:																			
FR2.6: Red																			
FR2.6.1:																			
FR2.6.2:																			
FR2.6.3:																			
FR2.6.4:																			

	DP2: System for	DP2.1: System	DP2.1.1: U	DP2.1.2: U	DP2.2: System	DP2.2.1: Li	DP2.2.2: S	DP2.2.3: E	DP2.3: System	DP2.3.1: C	DP2.3.2: C	DP2.4: System	DP2.4.1: E	DP2.4.2: E	DP2.5: System	DP2.5.1: A	DP2.5.2: A	DP2.5.3: A	DP2.6: System	DP2.6.1: E	DP2.6.2: D	DP2.6.3: E	DP2.6.4: E
FR1.2.1:																							
FR1.2.2:																							
FR1.2.3:																							
FR1.2.4:																							
FR1.2.5:																							
FR1.2.6:																							
FR1.3: Achi																							
FR1.3.1:																							
FR1.3.2:																							
FR1.3.3:																							
FR1.3.4:																							
FR1.3.5:																							
FR1.3.6:																							
FR2: Reduce t	X																						
FR2.1: Red		X																					
FR2.1.1:			X																				
FR2.1.2:			X	X																			
FR2.2: Red					X																		
FR2.2.1:						X																	
FR2.2.2:							X																
FR2.2.3:								X															
FR2.3: Red					X				X														
FR2.3.1:										X													
FR2.3.2:						X	X			X	X												
FR2.4: Red												X											
FR2.4.1:													X										
FR2.4.2:														X									
FR2.5: Red					X							X			X								
FR2.5.1:						X	X	X						X		X							
FR2.5.2:						X	X	X					X	X			X						
FR2.5.3:						X	X	X					X	X				X					
FR2.6: Red		X			X														X				
FR2.6.1:						X	X	X												X			
FR2.6.2:																				X	X		
FR2.6.3:																					X	X	
FR2.6.4:																						X	X

Figure 4-4 Evaluation matrix of the second iteration

4.8. Summary

The design process is complex, having sequential, parallel and interdependent activities. The use of AD method allowed for the development of a systematic and a better understanding of what is to be achieved in the design process and how it can be achieved. More importantly, it allowed better identification and understanding the implications and the effects that one design solution or DP may have in the fulfillment of another PVO or FR. It is important to mention that the decomposition developed in this research only considers three project objectives for the decomposition to be fulfilled using BIM. These objectives seem to be the most important for the industry practitioners and encompass the major stakeholders (the owner, the design team and the construction team), for that reason and due to the scope of this research, they meet the CEMEmin rule of AD. If other project objective wants to be fulfilled using BIM tools, it could be included in the decomposition as third level FR and then to be decomposed and analyzed following the AD method described above.

The zigzagging decomposition of the AD method allowed better definition and understanding of what must be achieved in order to deliver value (expressed in terms of FRs) and how it can be achieved (expressed in terms of DPs) by identifying the BIM uses and other tools that can be implemented during the design phase. The final decomposition showed a triangular matrix, which represents a decoupled design. As was mentioned before, decoupled designs are acceptable solutions in which the correlations between DPs and FRs are clearly established and identified allowing for a clear understanding of the dependencies of the selected BIM uses and tools in order to propose recommendations and considerations for their implementation.

5. THE DESIGN-BUILD PROCESS

5.1. Introduction

Before implementing the resulting Design Parameters (DP) into the design process and in order to provide a suitable approach, it was necessary to understand the design process. This chapter presents an in-depth case study of the building design process within a Design-Build (DB) company in Worcester, Ma. DB companies are characterized for providing design and construction services under one single contract. The development of the case of study was completed after the AD decomposition, and it is needed to develop the integrated, BIM-based design process.

The case study was conducted with the support of Cutler Associates (CA), who provided access to their projects, staff for interviews and to other valuable documentation. The case study was conducted in two parts. The first part reviewed in detail the DB company organization and its design process flow. The second part gathered valuable data and information generated on specific components of the company's design process such as task execution times, typical errors that could occur, type of rework, number of required iterations, and the resources needed to perform each activity during the building design process. As a result of those activities, the design process flow was mapped graphically and then simulated using Arena® software, to verify that the process flow was captured correctly and it was a valid representation of the actual company's design process.

5.2. The design-build company organization and design process flow

As was mentioned in Chapter 2, the DB delivery method is characterized by the creation of a single contract in which one entity, usually known as the design builder, is contracted to perform the design and construction services. Therefore, this entity is fully responsible for all the design and construction work on the project and to deliver a complete project to the owner. Among its advantages are: 1) the owner has only one contract (instead of separate contracts) for the design and construction of the facility simplifying communication; 2) the project schedule can be fast-tracked, since construction starts before the complete set of detailed construction drawings is produced; and 3) the use of BIM within the DB model is suitable because collaboration, communication and sharing knowledge are better supported by having only one responsible entity.

CA was identified as a resource for this research because of their experience with DB contracts, their use of BIM technology and their openness in supporting educational activities. Established in 1972, the firm is a DB company with construction management, general contracting and sustainable design and construction services. It employs more than one hundred in-house architects, engineers, cost estimators, construction professionals, field personnel and support staff distributed in their two major offices located in Worcester, Massachusetts and Tampa, Florida. With more than forty years of experience, CA is expert in the institutional, healthcare, hospitality and educational markets among others. In the educational market, the company has developed extensive campus work experience, which includes the new construction and renovation of residence and dining halls, athletic facilities, classrooms and labs, and outdoor spaces.

5.2.1. Cutler Associates' Organization and use of BIM

The case study was conducted in the CA office located in Worcester, Massachusetts. Their professional activities are organized in four major areas (see Figure 5-1):

- Sales and Marketing
- Design
- Operations
- Financial Office

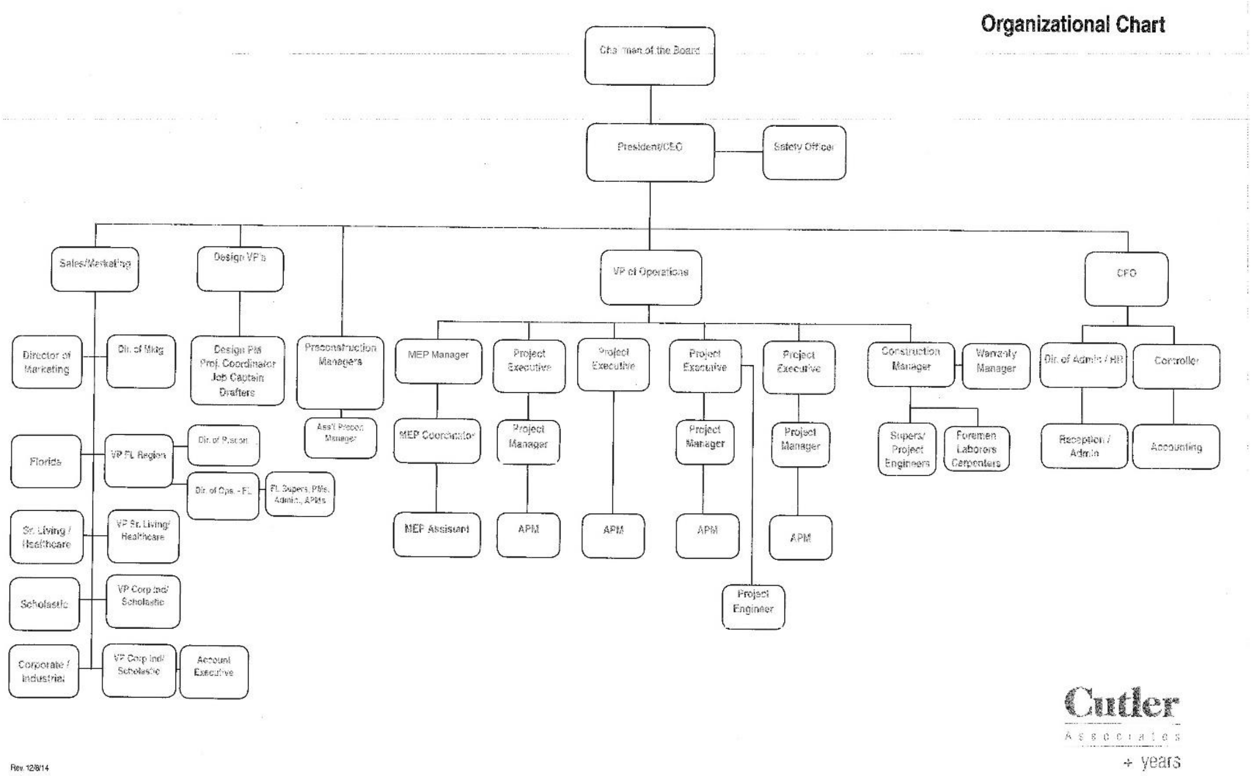


Figure 5-1Cutler Associates Organizational Chart – Courtesy of Cutler Associates

The sales and marketing area includes a team of sales marketing in Florida and in the Northeast who have the responsibility of overseeing and growing Cutler's activities within the senior living, healthcare, scholastic and institutional, corporate and industrial, and tourism marketplaces.

The design area consists of the in-house design team (designers and project coordinators) and consultants who work in close collaboration with the owners and with CA construction team (operation area) to provide architectural design solutions that meet the goals and practical objectives of each owner.

The operation area is in charge of the overall performance of CA's operations, including control activities, to successfully completing the project on schedule and within budget. CA typically includes a team of MEP Manager, Project Executives and Construction Manager.

The financial area is responsible for the administrative, financial, and risk management operations of the company. It develops financial and operational strategies with the goal of assuring the financial integrity of the company and preserving company assets. This area includes the administration, human resources office, controller and accounting.

CA's business philosophy is committed to deliver value to the client by working collaboratively and completing successful projects. This commitment is reflected in the mission statement of the company, as well as in the implementation of and ongoing training in new technology like BIM to support their collaborative work and to establish and maintain a competitive edge. The adoption of BIM in CA has been gradually evolving since it was first used for architectural design and drafting purposes. In 2006 the company started a program to implement and formally integrate BIM in their projects. Now, they create and develop detailed architectural, structural and MEP models especially for coordination purposes in all their projects. Other BIM models are created for different purposes when required by the owner.

The use of BIM for coordination has given many benefits to the company, such as better team communication and collaboration, faster decision making during construction, fewer Change Orders (CO) and internal Requests for Information (RFI). The use of BIM for coordination has also allowed the design team to work in close collaboration with the construction team, making a shift in the way they design and build by gradually replacing the construction documentation phase (CD) by the 3D coordination phase. The latter is explained in detail in section 5.2.2.3.

5.2.2. The design-build process flow

In order to have a clear understanding of the company's design process and how the three Project Value Objectives (PVO) identified in section 4.1[10] are addressed for their institutional projects, several meetings with CA staff were conducted. The first contact with the company took place in June 2015. During this meeting the objectives of this research as well as the objectives of the meetings with the company (what information

---

[10] The three PVO are Regulatory and Standard Compliance, Operation and Maintenance Efficiency and Constructability

the research was looking for) were introduced to a selected group of the company's personnel. Subsequent meetings focused on developing a thorough understanding of the company organization and in mapping their design process. In total, four versions of the process map were developed, until the DB Company approved a map that reflected, accurately and robustly, what is actually practiced by the company.

The mapping of the design process was done for the three project phases: 1) the Schematic Design (SD) phase, 2) the Design Development (DD) phase, and 3) the Construction Document (CD) phase. Other project phases like planning, programming and preconstruction services were left out of consideration of this research because those phases are not included in the architect's basic services as defined by the American Institute of Architects (AIA).

The first version of the process map was based on the traditional design process as described by the AIA (AIA Exhibits, 2013). The graphic protocol for the mapping of each of these three phases followed the format proposed in the BIM Project Execution Planning guide published by the Penn State Computer Integrated Construction Research Program (CIC, 2010). This guide mapping technique consists in three categories of information and all the corresponding elements (activities, documents and other information) included in those three categories. These are:

- Reference Information, which is the structured information required to start or perform a process. The origin of this information can be external (from owner or other entities) or internal (within the company). The reference information is located horizontally in the top line of the map and is represented with a document icon.
- Processes, which are all the activities that constitute a particular procedure. Processes are located horizontally in the middle line of the map and are represented by boxes.
- Information exchange, which contains all the deliverables generated from one activity or process and that may be required as a resource for downstream r processes or activities. Information exchange is located horizontally at the bottom line in the map and represented with a document icon.

Figure 5-2 shows part of the graphic protocol developed by the CIC for the mapping of the BIM processes. The first version of the mapping of the design process (described above) was used as a baseline for the work that followed with CA's DB process. The second, third and fourth versions of the DB process were produced in close collaboration with CA's personnel who reviewed and modified according to their own practices and design process flow. The mapping process was complemented by a set of questions directly related to the ways in which the firm meets the three PVO identified in section 4.1

of this document. The following sections discuss this process in more detail.

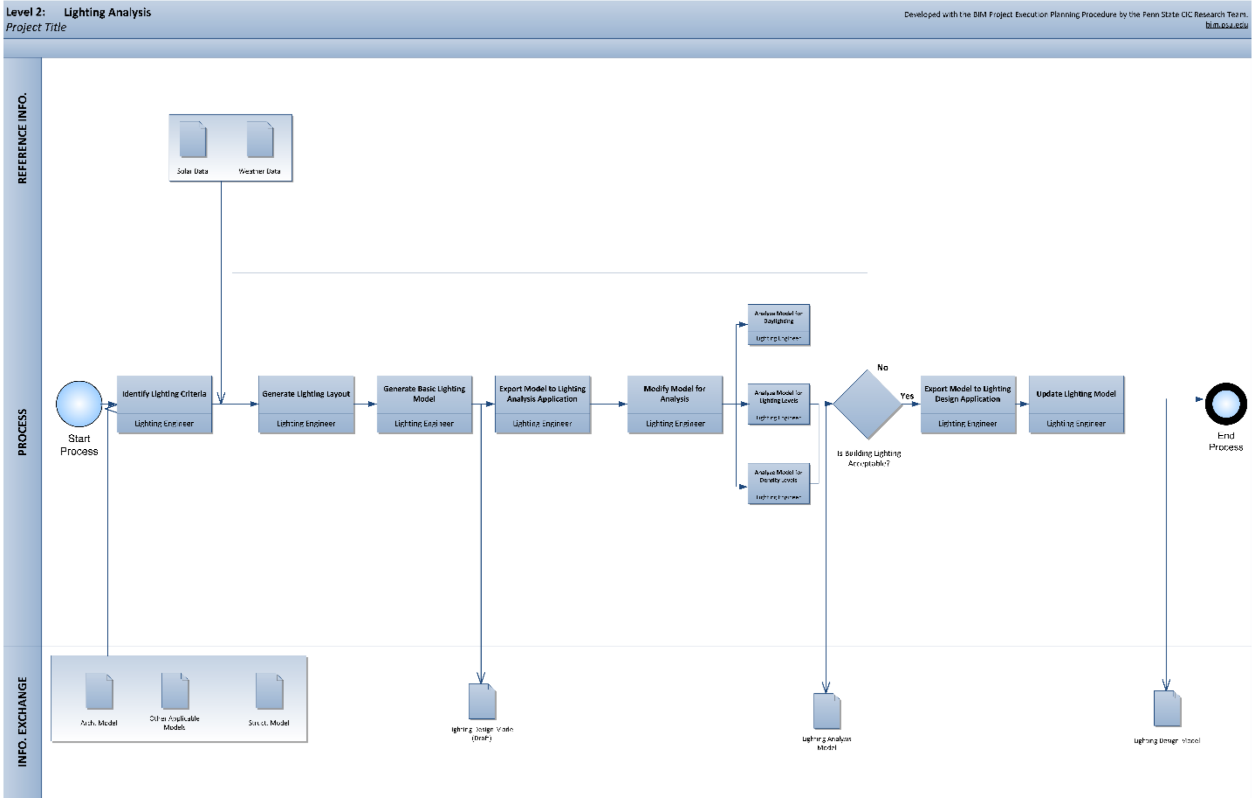


Figure 5-2 Example of the graphic protocol proposed in the BIM Project Execution Planning guide (CIC, 2010)

5.2.2.1. Development of CA schematic design process map

The schematic design (SD) phase is characterized by the establishment of the project goals and by the development of several design alternatives that satisfy those goals. These alternatives are then evaluated by the owner who generally selects one. At this point, only preliminary site and architectural drawings are produced and the other building systems are considered and explained in narratives. This phase usually starts with the analysis of the architectural program and other relevant information, and finishes with the owner's and the correspondent agency's approval of the SD proposal.

The meetings with CA staff revealed that not all of their projects start from scratch. In other words, sometimes the owner brings his/her own architectural project (designed by a third-party architect) to CA to further develop and finish the building design and construction based on the design narratives. Otherwise, during the schematic design, Cutler's design division is responsible for development of the proposal to the client that meets his/her goals, with little involvement of the operation division at this point.

Figure 5-3 shows the SD process map developed for CA's design process flow. This flow is very similar to the traditional AIA SD phase documented for the design-bid-build method. The design team starts carrying out activities directly related to the fulfillment of the three PVO selected in section 4.1, which are regulatory and standard compliance, operation and maintenance efficiency, and constructability. These activities are discussed in section 5.3. The use of BIM during this phase is limited to the creation of the first architectural model by the architect, which has considerations for accommodations of the structure and MEP components; later, this model will serve as basis for the creation of the other models.

5.2.2.2. Development of CA design development phase process map

The Design Development (DD) phase is considered an extension of the schematic design, in which the selected design is further developed along with the major building systems schemes: site work, structural MEP/FP, as well as cost and schedules. Once the systems schemes are evaluated, the first layout drawings and specifications of the building systems are created

The meetings with the company's staff revealed that the DD phase starts with the review and upgrade of the SD option selected by the owner, along with the selection of the MEP and FP trade contractors. This is a very important milestone in CA process flow, because from this point forward, the MEP and FP contractors are responsible to further develop the MEP design and the required documentation for permits, as well as the BIM models for the HVAC and sprinkler systems. On the other hand, the structural design is still carried out by design consultants who, most of the times, develop their structural BIM model.

The first building system coordination meeting also occurs during the design development phase. This coordination is typically performed using 2D drawings, usually generated by the BIM models. This is because at this stage, even though the BIM models had been created, they don't have all the information needed for 3D coordination, like pipes slope, beam sizes, and so on. Also, at this time, the main concern of the design team is to generate design documentation with enough level of design development to obtain the building permits as soon as possible. Along with this 2D coordination, an internal code review is performed by the lead architect, followed by a third-party code review. If the project meets all the requirements, then it is submitted to the client and to the corresponding agencies for approval and issuance of permits typically at the same time. If further changes are required by the owner, these are included as design addenda. The design development phase in CA finishes with the acquisition of the construction permits.

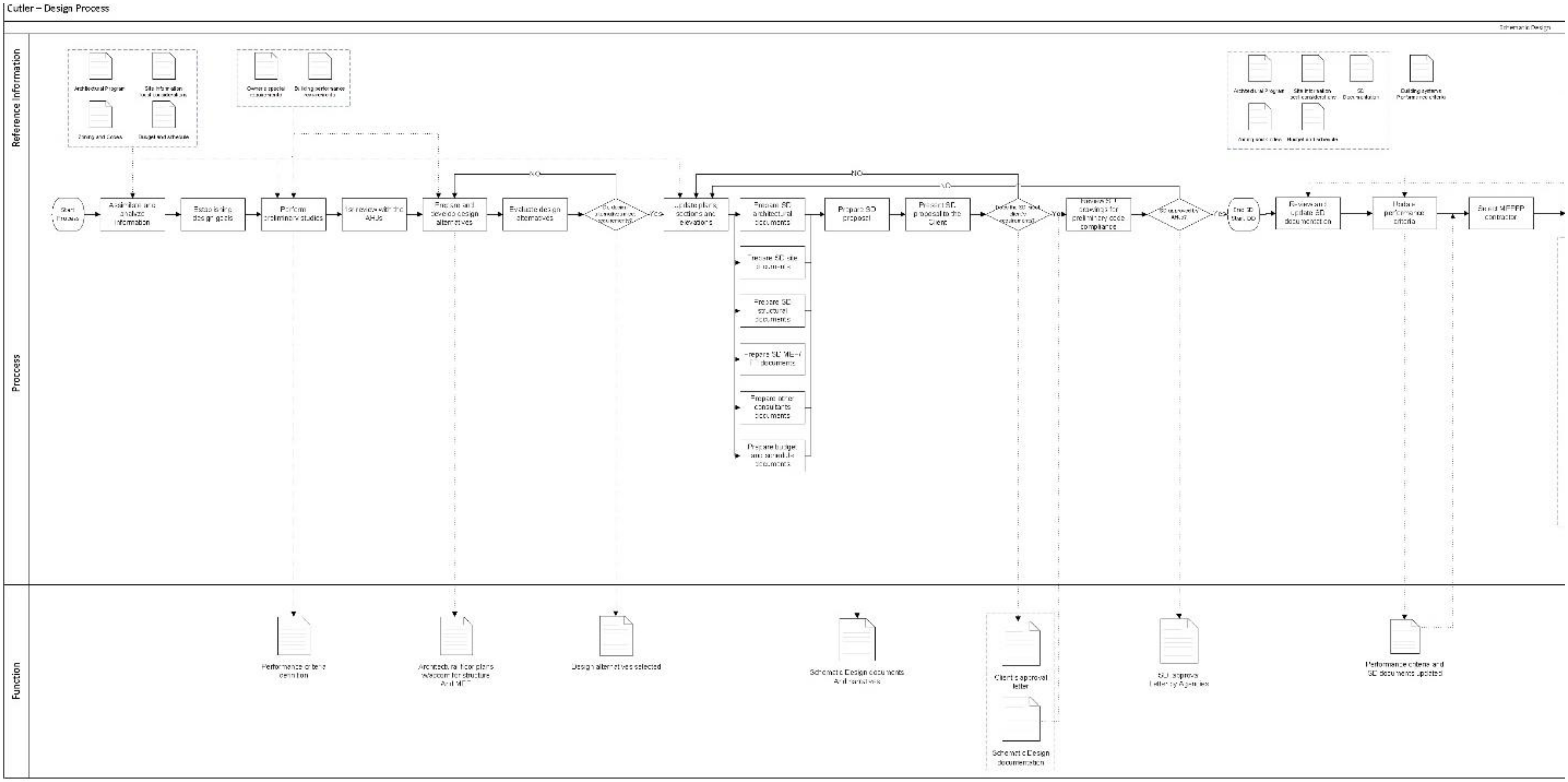


Figure 5-3 Cutler Associates schematic design phase

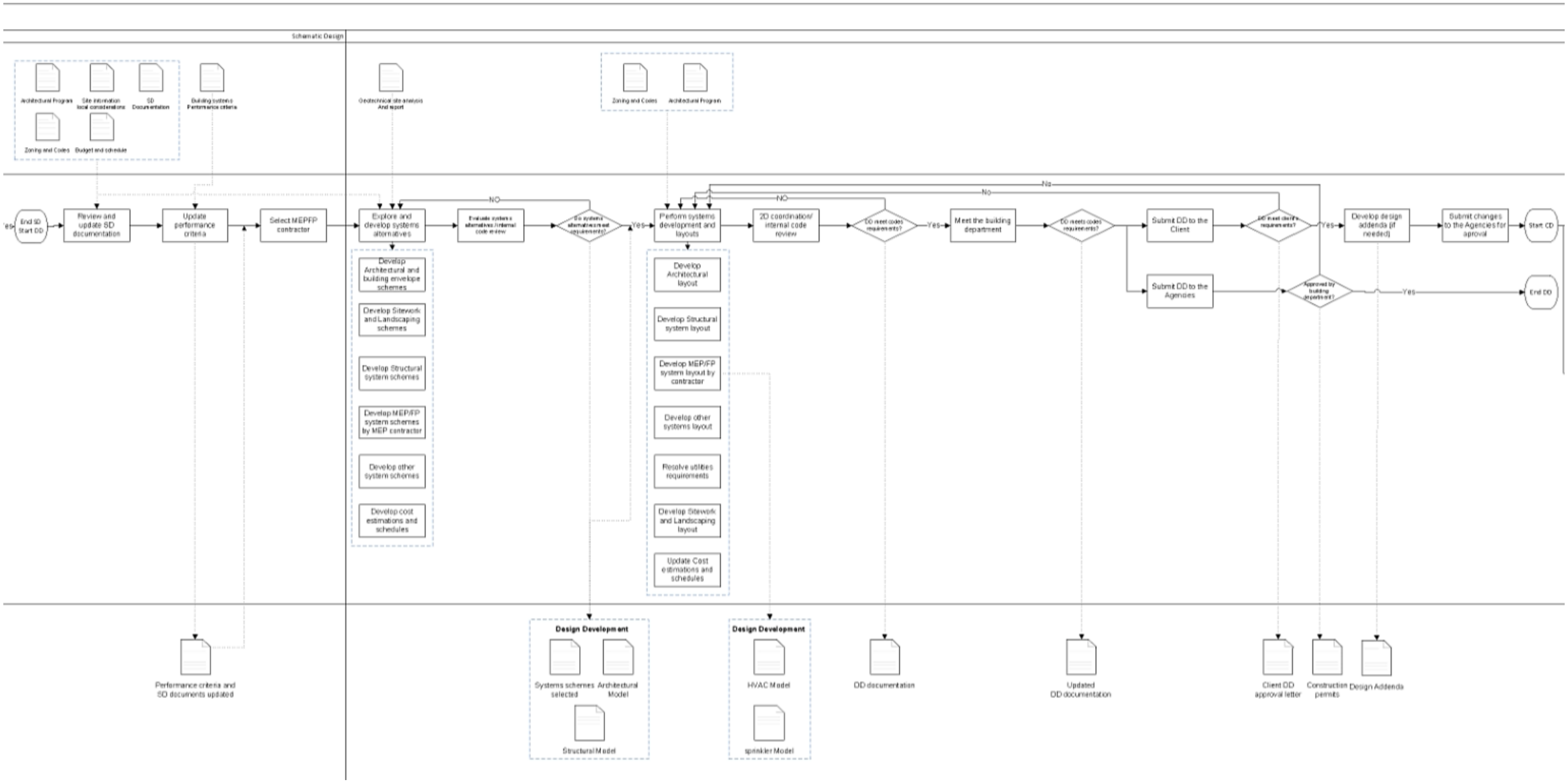


Figure 5-4 Cutler Associates design development phase

Figure 5-4 shows the design development process map of CA. As was mentioned before, sometimes the owner brings his/her own architectural project (designed by a third-party architect) to CA to develop and finish the building design and construction. When this happens, the main difference is that the architectural and structural models are first created in this phase by the design team, since they are not always shared or created by the owner's architect. The MEP model is created and updated by the MEP/FP contractor(s) who are selected at the beginning of the DD phase.

5.2.2.3. Development of CA construction documentation phase process map

The construction documentation (CD) phase is a continuation of the design development phase to further refine the design and complete a set of drawings, specifications and other detailed information that communicates the all the pertinent information to build the project to the builders. Traditionally, the construction documents are considered the final product of the design phase, and are used by the owner to obtain construction bids by potential builders. In CA, the CD phase is conducted differently than the traditional way. During this phase, the 3D coordination of the building systems is performed, replacing the construction documents for coordinated drawings to be used for construction.

Figure 5-5 shows the process map of CA construction documentation phase under the DB approach. This phase begins with selecting the structural contractor and setting up the schedule for the meetings and a protocol to address possible three-dimensional geometric interferences or collisions between systems. The MEP and structural contractors are responsible for updating their models for coordination. The coordination process followed by CA is conducted by floor levels starting from the lowest level of the building to the highest, in other words, CA stats coordination of the basement, then first level, second level, and so on. At the beginning of this process the coordination model includes the architectural, structural and HVAC models. When the models are 80% coordinated on the first level, then the models for the electrical and plumbing systems for the first level are incorporated and the coordination of the second level begins. This process continues in the same way for the upper levels; therefore, it is common to coordinate two or more levels at the same time until no clashes are found and all parties sign the coordination drawings. Under this approach, the coordination documents become the construction documents.

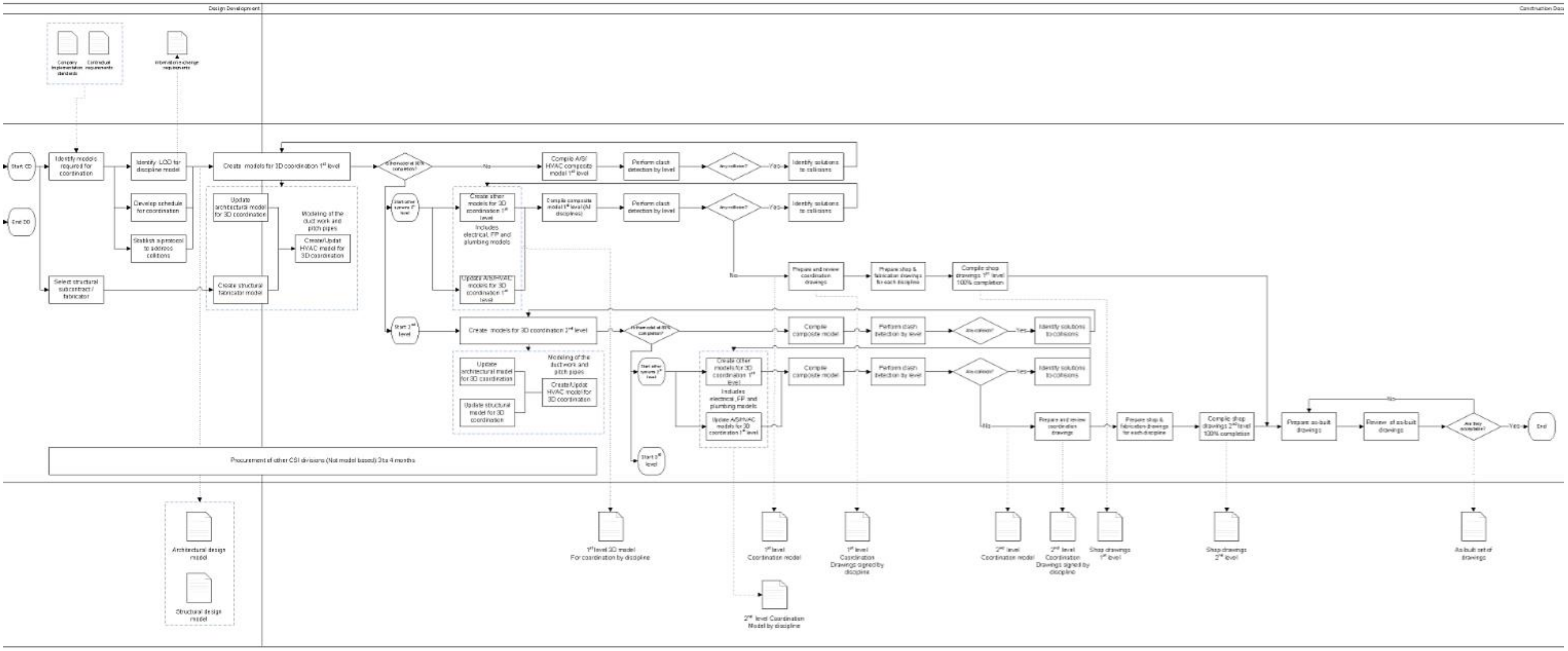


Figure 5-5 Cutler Associates construction documentation phase

5.3. Data collection of CA design-build process

The process analysis as described in this chapter required the collection of information related to the execution of the different activities performed during design and directly related to the achievement of the three PVO identified in Chapter 4. This information was collected through a set of questions distributed to the firm's design staff in the form of an online questionnaire. This section summarizes and discusses in more detail the results obtained from the online questionnaires.

The survey was structured based on the three PVOs. Appendix E shows the complete set of questions and their corresponding answers. The online survey was implemented using Qualtrics® software available to the researcher through WPI. The questionnaires aimed to identify the activities performed by CA during the design process towards the fulfillment of the three PVO previously selected in section 4.5, which are: regulatory and standard compliance, operation and maintenance efficiency, and constructability.

The questionnaires were structured to answer the following questions (see Table 5-1):

- Was the specific PVO considered, addressed and reviewed during the design phases?
- What activities are necessary to attain the PV?
- What was the duration for the execution of each of the activities of the DB process?
- How many times was any of the activities in the DB process executed in an iterative fashion?
- Was a special tool or software used to assist in the process?

Table 5-1 displays a segment of the survey with questions related to the attainment of PVO: regulatory and standard compliance.

Table 5-1 Example of the regulatory and standard compliant objective's questionnaire

Objective: Understand and know the process of addresing codes and regulations	
What does the process do?	Do you include or consider emerging standards, codes, and regulations in the building design?
How does it do it?	Describe the steps followed to include emerging codes in the building design
	What/when usually starts the code review/validation process?
	What/when usually finishes the code review/validation process?
	In order to check the design against project specific codes, how the code review/validation process is conducted?
	Who is usually involved in the code review/validation process described above?
	Is any special tool or software used to assist the design team in the code review/validation process? Specify it
How long it takes?	How often is the code review/validation process conducted? OR
	Indicate at what percentage of design completion is the code review/validation process conducted?
	Is the code review/validation process conducted in one iteration or in multiples iterations? OR
	How often is the code review validation process repeated at any % of design completion? Is it conducted in 1 or multiple iterations?
	How many iterations does each code review/valitadion process ussually take? (specify as minimum and maximum iterations
	How many working hours does each code review/validation process (eash iteration) ussually take?

5.3.1. Regulatory and standard compliance objective

Complying with the required building codes and regulations is essential for the design and construction of any type of project, since they are created not only to provide protection from disaster due to fire or structural collapse but also to provide environmental protection. Building codes become a law and failing to comply with them can lead to longer design phase due to revision-approval cycle or even stopping the project completely. For that reason, the design must be subjected to timely and proper reviews for code compliance.

In CA, the lead architect within the office is professionally responsible for design code conformance and conducts a code analysis and audits the design, from the very beginning and throughout the design process. Usually, the process of reviewing the design against the code during the different phases of the design process are as follows:

- SD phase

The first meeting with the building officials takes place during this phase, so that code considerations can be properly addressed. In this phase, the design is reviewed against the code once after the 2D drawings have been created. During this revision, the architect, construction project manager, structural and MEP consultants are involved.

- DD phase

As the design develops in more detail, more specific aspects of the codes and regulations may need to be addressed. During this phase, the design is reviewed against the code once again, however, the time spent is considerably more than during the schematic design phase because of two reasons: 1) the design has more detail and information; and 2) after the review, the design is submitted to the corresponding agencies for construction permits approval.

The code review process at this phase is performed using 2D drawings and 3D models when available, and the architect, structural consultant, MEP contractor and the construction project manager are involved.

- CD phase

The construction documentation phase, as was mentioned before, consists of the coordination of the major building systems while at the same time the design continues to develop. Therefore, during the whole coordination process the design is also reviewed against the code, using mostly the 3D models and 3D fly-through review when elements are difficult to see on the 2D drawings. Typically, the architect, the construction project manager and the trade contractors are involved in reviewing the design against the code.

5.3.2. Operation and maintenance efficiency objective

As was explained in Chapter 4, the O&M efficiency project objective, in the context of this research, is directly related to maintenance and operating activities. It addresses the ease and cost of building operation and maintenance. The efficiency of the building's operation and maintenance not only depends on the design, but also on the facility management staff and their maintenance program. Listed below are the aspects identified in this research that affect the efficiency of building operation and maintenance, according to was previously presented in section 4.5:

- Considerations of equipment space, accessibility and ergonomics requirements
- Considerations of space management requirements
- Consideration of documentation that shows the accurate location of the major building systems
- Standardization of the mechanical and electrical equipment
- Considerations for the building energy consumption

The section of the survey questionnaire dealing with the O&M efficiency objective attempted to determine how those aspects are considered in each phase of the building design. The results are presented below and summarized in Table 5-2.

Table 5-2 Considerations of the O&M efficiency objective in the building design

Operation and maintenance considerations during the design process

				Coordination	
Features to consider in the design	100% SD	50% DD	100% DD	50% CD	100 CD
Including the facility management (FM) staff into the design	X	X		X	
Equipment space, accessibility and ergonomics requirements				X	X
Space management requirements	X		X		X
Accurate documentation of the location of the major building systems	X		X		X
Standardization of the mechanical and electrical equipment			Between 26% and 50%		
Building energy consumption	X		X		

- SD phase

In order to have a better understanding of the building operations and performance, CA incorporates the knowledge and views of the facility management staff in the schematic design phase for their institutional projects. However, the information provided by them depends on whether the owner approves or not the inclusion of this information in the design. Sometimes, these requirements are excessive and not always necessary and rather than bringing savings in maintenance, they may cause the design and construction to go over the project budget. In addition, space management requirements, location of the major building systems and building energy consumption are also reviewed and updated in this phase by the architect, MEP consultant, MEP contractor, the FM staff and the owner. There is no particular software used to conduct these reviews except for the energy consumption which uses an energy modeling software and third party audits.

- DD phase

The incorporation and review of the O&M efficiency objective during the DD phase is conducted in two parts. In the first part, the FM staff is still included, while the space management and location of the building systems are reviewed. In the second part the O&M requirements are generally reviewed by the Architect, MEP contractor, MEP coordinator, Owner, Project Manager and Superintendents. The energy consumption of the building, is reviewed by the MEP contractor, MEP coordinator and the FM staff.

- CD phase

As in the DD phase, the FM staff is included at the beginning of the CD phase. The equipment space, accessibility and ergonomics requirements are first reviewed in this phase and during the whole 3D coordination process using Navisworks software by the MEP contractor and MEP coordinator, while the space management requirements and the location of the building systems are reviewed one more time at the end of this phase using both the 3D model and 2D drawings.

5.3.3. Constructability objective

The constructability objective, in the context of this research, refers to the extent by which the design team considers the construction process of the building in the design in order to identify any possible difficulties and errors and omissions in the drawings before construction begins, with the objective to facilitate construction. Listed below are the aspects identified in this research that affect the level of constructability of a given design, according to previously presented in section 4.5:

- The integration of construction knowledge in the design
- The consideration of the major construction methods, including project and procurement schedules
- The consideration of the site layout
- The coordination of the building systems
- The standardization and repetition of elements
- The appropriate design documentation

Table 5-3 Considerations of the constructability objective in the building design

Cutler's considerations of constructability during the design process

Features to consider in the design	100% SD	50% DD	100% DD	Coordination phase 50% CD	100 CD
The integration of construction knowledge in the design	X	X	X	X	X
The consideration of the major construction methods	X	X	X		
The consideration of the site layout					
The coordination of the building systems			X	X	X
The standardization and repetition of elements	Between 50% and 75%				
The appropriate design documentation	X	X	X	X	X

The constructability questionnaire attempted to find how those aspects are considered in the building design. The results are presented below and summarized in Table 5-3

- SD phase

CA includes the construction knowledge in their design of institutional projects, in particular during the schematic design phase, in which the structural and civil consultants, as well as the MEP coordinator are involved. The participation of the first two parties is addressed mostly to design activities, whereas the MEP coordinator participates, together with the lead architect in the following: 1) selecting the construction methods; 2) reviewing the project and procurement schedule; 3) reviewing the construction cost and 4) developing drawings and specifications.

Standardized and prefabricated elements are also considered at some level as a design practice to simplify the design and minimize the construction cost. However, this practice has never been evaluated or assessed. In contrast, the documentation used for construction is started in the schematic design phase by the architect, the project manager, the MEP contractor and the MEP coordinator. Along with this process, the documentation is reviewed for completeness, clarity, accuracy and errors. The site layout and coordination of the building systems are not addressed in this phase.

- DD phase

The project manager, the structural engineer, the civil engineer, the MEP contractor, and the MEP coordinator also participate in the constructability review in the design development phase, however the participation of the structural and civil contractor decreases at the end of this phase. In this phase the documentation is reviewed again for constructability, completeness, clarity, accuracy and other errors by the construction staff of the DB team.

- CD phase

During this phase the activities related with constructability are mostly focused on the coordination of the major building systems and these generally involve the MEP contractor and MEP subcontractor. The other teams (structural, civil, and so on) are only involved in a need-to-know basis. The documentation is reviewed again for constructability, completeness, clarity, accuracy and other errors by construction team and subcontractors.

5.3.4. Execution times

Once the activities for attaining the PVOs at each phase of the design process were identified, it was necessary to determine their typical times of execution, amount of errors (if any), amount of rework and iterations, and the type of resources necessary to perform each activity. This information was obtained in terms of a range of minimum and maximum values, such as the minimum and maximum working hours that it takes to execute each task. This information was later used to populate the simulation model of the DB process using the triangular probability distribution function, with minimum, maximum and most likely values for the duration of each activity. In the absence of real data of the most likely value, this field was populated on the simulation software by using the average time of each activity as estimated by CA staff. The detail data of execution time is presented in Appendix H.

5.4. Simulation of CA design-build process

For the purposes of technical reliability, the CA design processes were simulated. Discrete event process simulation was used as a means to validate the DB process representation and work flow obtained from the observations and interviews conducted with the staff from the DB firm. The software Arena® was used to implement the simulation process. Figures 5-6 and 5-7 show the process corresponding to the schematic design phase of the DB Company, in which the design alternatives are developed and evaluated first, and then, one is selected and further developed.

The design development phase is shown in Figures 5-8 and 5-9, where the systems of the building are developed and the building permits are acquired. The construction documentation phase is shown in Figures 5-10 and 5-11, where the coordination of the major building systems takes place.

For simulation purposes, when an iteration occurred, the time spent to repeat the process or an activity was reduced by 20% of its original time, the reason of this is because it is very unlikely to completely change the design in the case it is not acceptable after a revision. On the contrary, when this happens, the design team makes adjustments to the project. Finally, the models in Arena® were adjusted until they reflected the behavior of the DB process of the company. Then, one thousand repetitions were run to have results more closely to reality as possible. Appendix I shows the results of the simulation of the DB process.

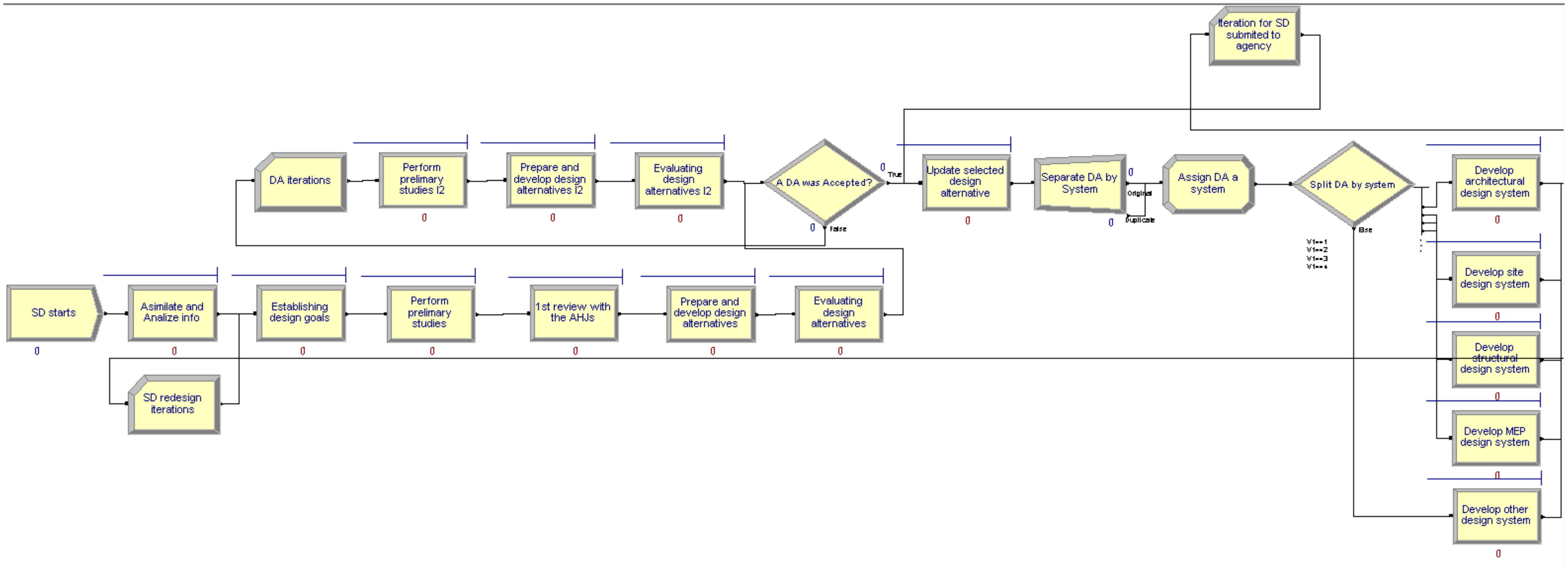


Figure 5-6 Cutler Associates design process at the SD phase modeled in Arena® – First half

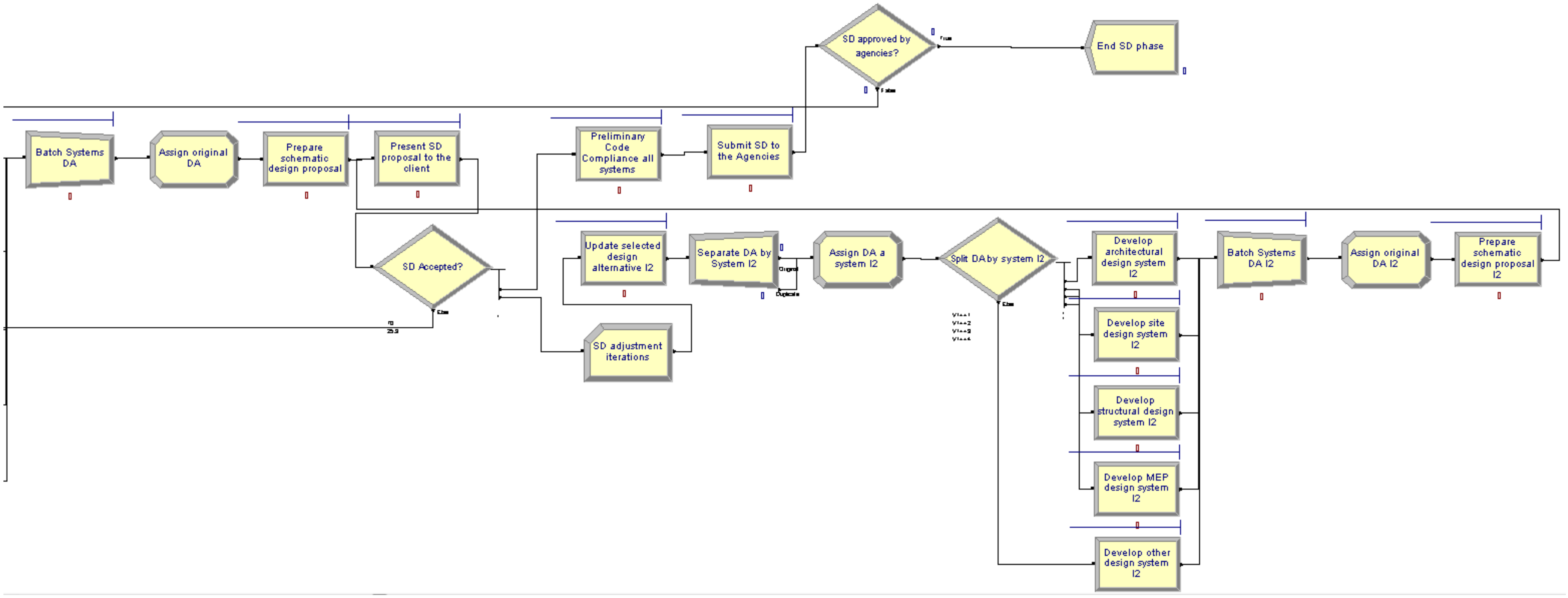


Figure 5-7 Cutler Associates design process at the SD phase modeled in Arena® – Second half

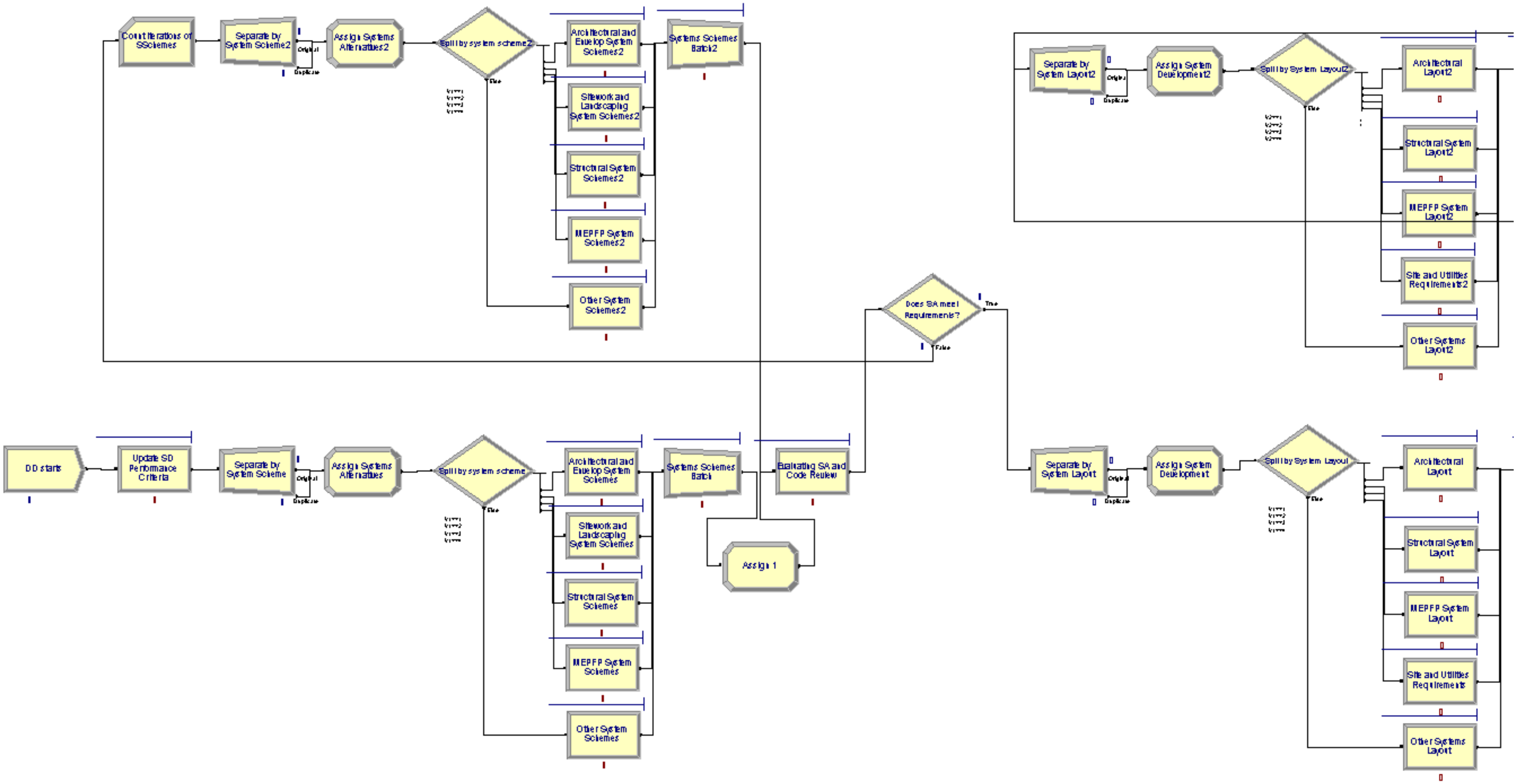


Figure 5-8 Cutler Associates design process at the DD phase modeled in Arena® – First half

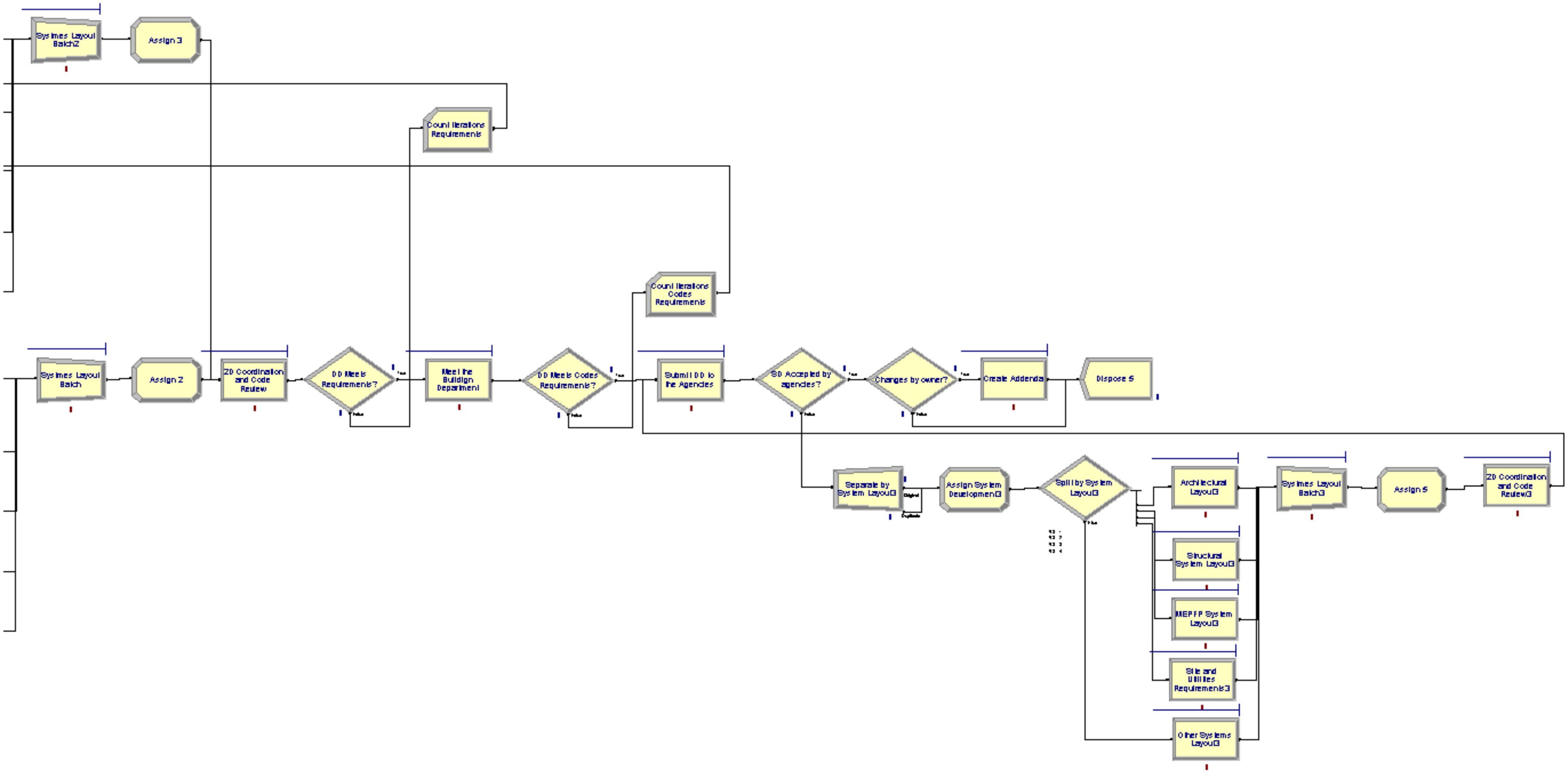


Figure 5-9 Cutler Associates design process at the DD phase modeled in Arena® – Second half

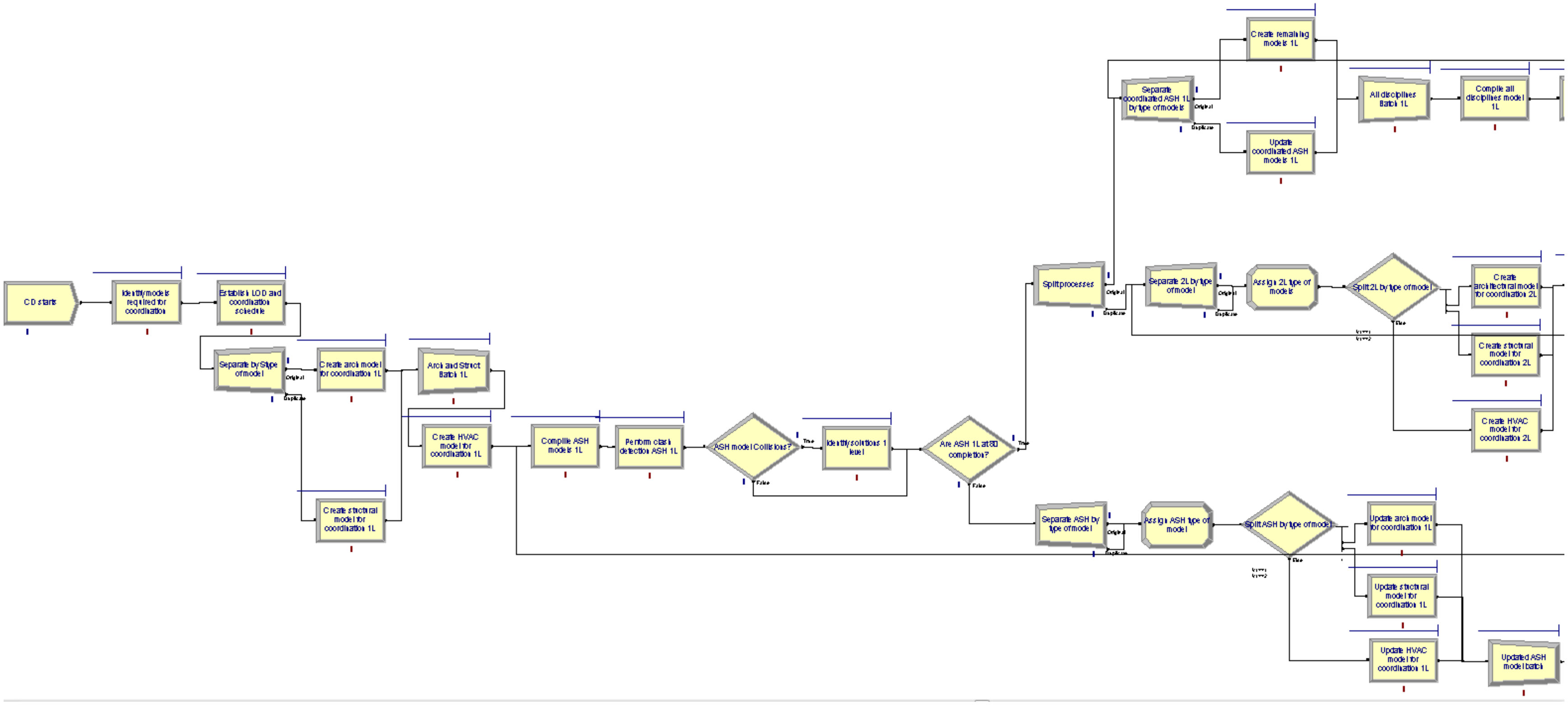


Figure 5-10 Cutler Associates design process at the CD phase modeled in Arena® – First half

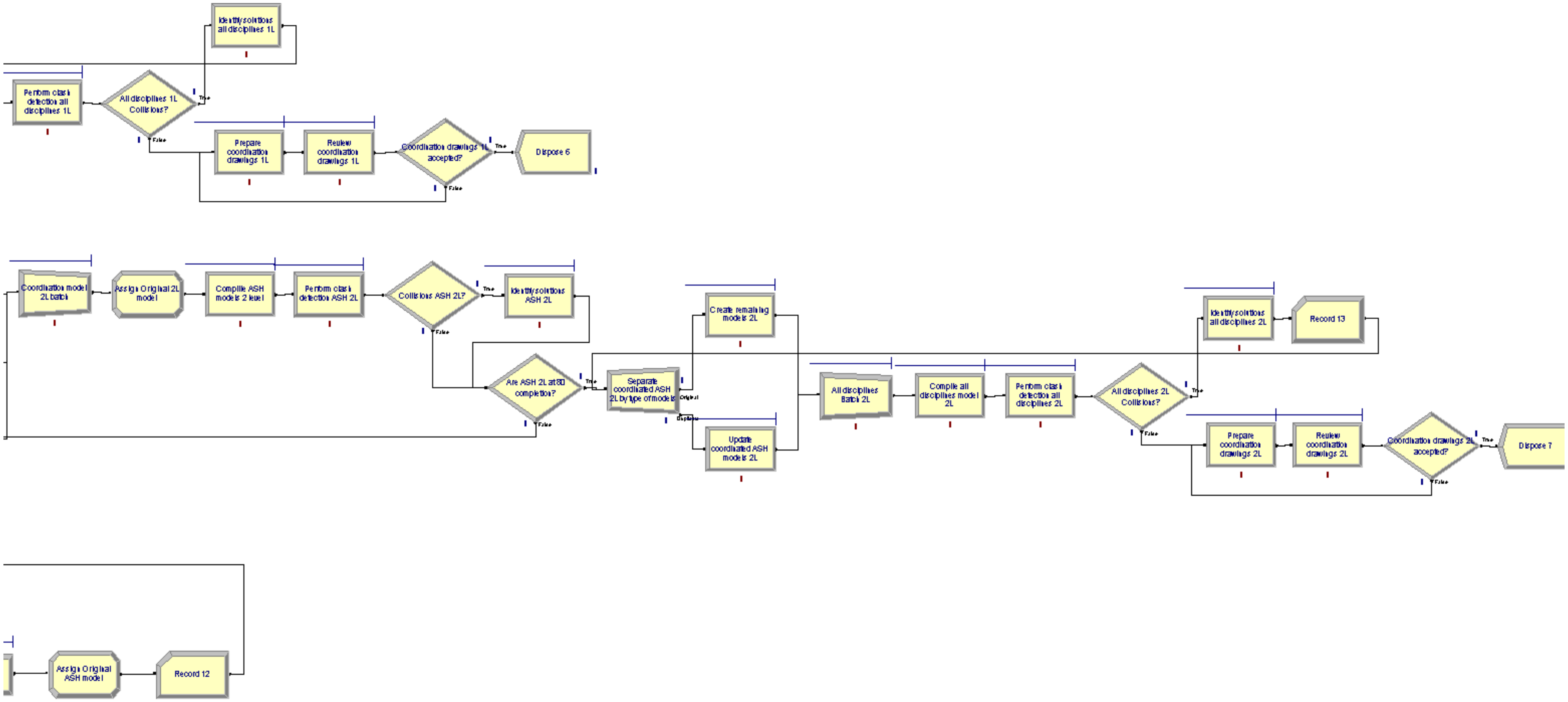


Figure 5-11 Cutler Associates design process at the CD phase modeled in Arena® – Second half

5.5. Summary

This chapter presented and discussed the results of the case study which consisted of reviewing in detail the DB process of a company in Worcester, Ma. The case study was conducted in two parts: interviews with the company personnel, and online questionnaires completed by CA personnel. As a result of these activities, the design process flow and the company's activities performed towards the fulfillment of the three project objectives were mapped and simulate.

The interviews conducted with the company's personnel were a great value for this research since they involved individuals in charge of the design process. The interviews facilitated the mapping of the design process and provided a valuable insight in understanding the complexity and interrelationships of all the activities involved, not only those studied in this research. They also facilitated the understanding of how the BIM technology is used to support the DB process for coordination purposes in CA, substituting the traditional design documentation phase, which essentially consists of drawing production, with a building system coordination process using BIM, allowing for time reductions since the coordinated drawings are used for construction.

During the interviews it was also possible to observe a real-time coordination meeting and decision making process to identify and resolve existing 3D clashes and inconsistencies in the design. Also, the company provided access to detailed documentation of the coordination reports, project meeting, minutes, and coordination models and schedules, among other internal documents.

Figure 5-12 is an example of the documentation created during the coordination reviews. As shown in the figure, during the coordination process everything is reviewed with the 3D model (upper left image), and the 2D drawing is used to record the problem found and its solution, along with a report, which is always accompanied by the 3D image to ensure proper understanding.

One of the challenges that needed to be overcome during the development of the case study was to coordinate the meetings between the researcher and the company staff, who are usually busy working on their current projects. Because of that, the questionnaires served the purpose of facilitating and complementing the collection of information otherwise obtained from the interviews. This was particularly true in the case of obtaining specific information on the execution times for activities and the number of iterations necessary in each review cycle. The questionnaires allowed the staff to provide these information at their convenience.

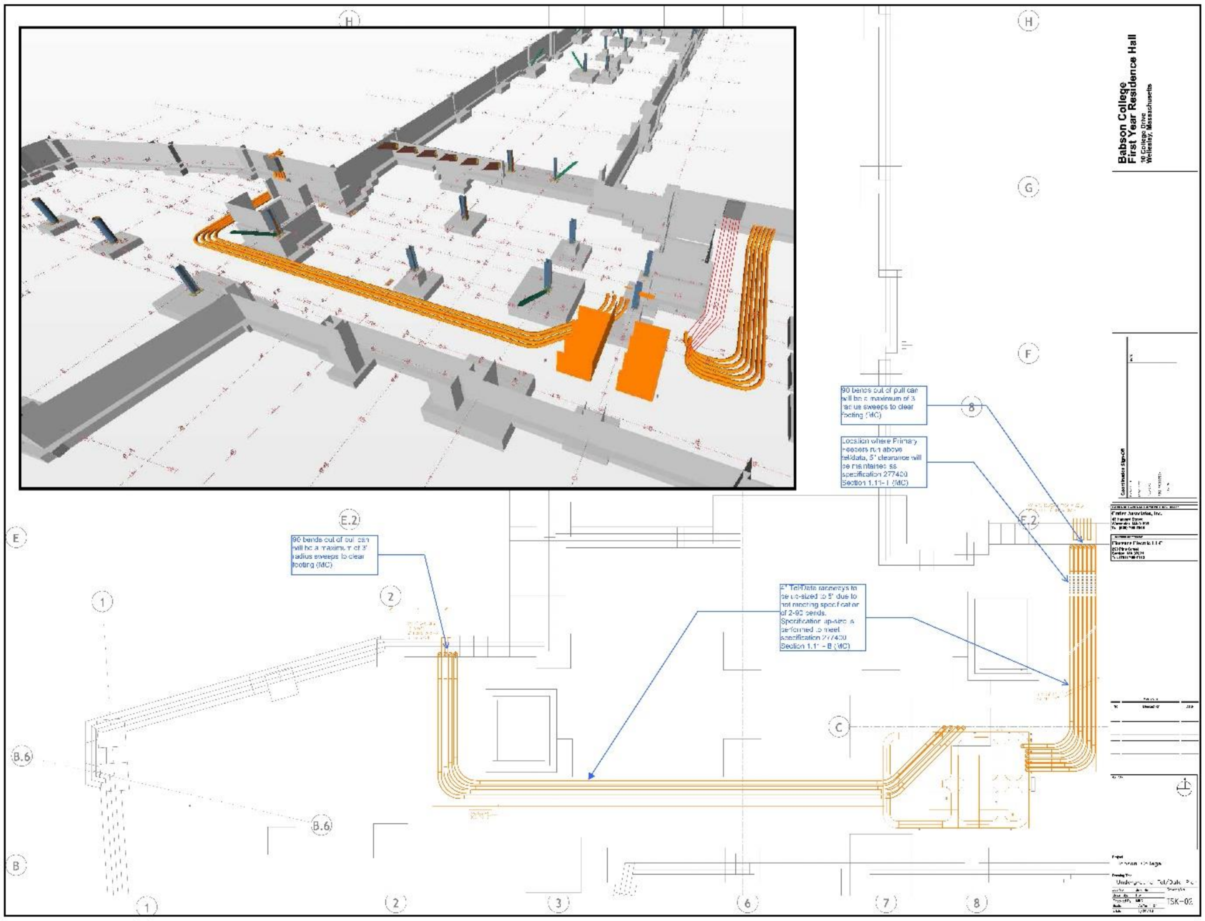


Figure 5-12 Cutler's coordination review documentation – Image provided by Cutler Associates

Finally, the results and the learning obtained from the case study are used to calculate the information content of the DB process in Chapter 7, in order to compare it with the proposed integrated, BIM-based design process.

6. THE INTEGRATED, BIM-BASED DESIGN PROCESS

6.1. Introduction

This chapter proposes an integrated, BIM-based design process based on the results of the AD decomposition presented in Chapter 4 and on the findings of the DB process analysis documented in Chapter 5 following the BIM Project Execution Planning guide (CIC 2010). It is organized in two major sections. The first one discusses the implementation of the BIM uses selected to achieve the desired value-added of the design (the children of DP1.1 through DP1.3), while the second part discusses the implementation of the tools and activities selected to reduce the waste (cost) of producing the design (the children of DP2.1 through DP2.6).

6.2. Implementation of the BIM uses to achieve value

The children of DP1.1 through DP1.3 correspond to the BIM uses and BIM-related activities selected for the fulfillment of the three PVO previously identified in Chapter 4 (see Table 6-1). The BIM execution planning guide (CIC 2010) was used as a reference for their appropriate implementation into the DB process. As was mentioned before, the BIM Project Execution Planning Guide is a set of documents developed and maintained by a research group in Pennsylvania State University (CIC 2010). This document has the objective to guide the project team in successfully creating and implementing a BIM project execution plan that allows them to get the most value out of the use of the BIM technology.

Table 6-1 BIM uses and BIM-related activities resulting from the AD decomposition

Selected BIM uses and BIM-related activities from the AD decomposition

Project objective	BIM Uses	BIM-related activities
Regulatory and Standard Compliance	Code Validatation Process	Process for Creating Permits Drawings
Operation and Maintenance Efficiency	Design Reviews for Space Program	Schedules to Assess Repetition
	Design Reviews for Equipment Accesibility	
	Design Reviews for Physical Location	
	Energy Analysis	
Constructability	4D Modeling / Phase Planning	Schedules to Assess Repetition
	Site Utilization Planning	Process for Creating Construction Drawings
	3D Coordination Process	

The first step in developing a BIM execution plan is to evaluate and decide which BIM uses to implement. For this, a worksheet was created to help the design team or design/construction company to decide which BIM uses are more convenient for them to implement according to the firm's and the project objectives. Since the BIM uses are already selected and shown in Table 6-1 (see Chapter 4, Table 4-20), the worksheet was used in this research to identify the responsible party to include the construction and O&M knowledge necessary for the achievement of the Constructability and O&M efficiency objectives respectively, and other additional information and participants who may be important for the proper implementation of the BIM uses.

The BIM selection worksheet includes columns to identify the value of the BIM use, who is the responsible party, the current BIM capabilities of the firm, additional notes, and the decision from the team on whether or not to implement the BIM Use. Table 6-2 shows the analysis of the BIM uses developed in the context of this research, starting with those related to the operation phase, then construction and lastly the design phase, as suggested by the BIM Execution Planning guide. All BIM uses selected (and resulting from the AD decomposition developed in Chapter 4) were identified with high value and marked with “yes” in the column on whether to proceed or not. Also, the capability rating column was left blank since this column reflects the current ability of the particular company to perform the BIM use and is out of the scope of this research.

Table 6-2 BIM use analysis worksheet – BIM Execution Planning Guide

BIM Use*	Value to Project	Responsible Party	Value to Resp Party	Capability Rating			Additional Resources / Competencies Required to Implement	Notes	Proceed with Use
	High / Med / Low		High / Med / Low	Scale 1-3 (1 = Low)					YES / NO / MAYBE
				Resources	Competency	Experience			
4D Modeling	High	Contractor	High				Design authoring software	Ability to manipulate and assess	**Yes**
		Project Manager	Medium				Software with 4D capabilitites	construction schedule with a 3D model	
		Architect	Low				Scheduling software		
							Construction equipment size		
							Ability to manipulate the 3D model		
							Detailed existing conditions site plan		
							Knowledge on construction methods		
Site Utilization Planning	High	Subcontractor	High				Design authoring software	Knowledge of 4D software	**Yes**
		Contractor	High				Software with 4D capabilitites		
		Project Manager	Medium				Scheduling software		
							Construction equipment size		
							Ability to manipulate de 3D model		
							Knowledge of construction scheduling and general construction process.		
							Strong knowledge of builidng systems and construction methods		
3D Coordination	High	MEP Subcontractor	High				Design authoring software	Knowledge of builidng systems	**Yes**
		MEP Contractor	High				Coordination software	Ability to deal with people and	
		Structural contracto	Medium				Models for coordination	project challenges	
		Architect	Low				Ability to manipulate the 3D model		
Energy Analysis	High	MEP Contractor	High				Design Authoring Tools		**Yes**
		MEP Coordinator	High				Models developed for energy analysis		
		Architect	Medium				Energy analysis software		
		Owner/FM staff	Low				Adequate hardware for running software		
							Knowledge on design standards and codes		
Design Reviews for O&M	High	Contractor	Medium				FM staff knowledge	Reviews using the 3D model	**Yes**
		Architect	High				Building equipment characteristics		
		FM staff	High				Design Review Software		
		Project Manager	Medium				Interactive review space		
							Adequate hardware for running software		
							Ability to manipulate the 3D model		
Design Reviews for Constructabil	High	Contractor	High				Construction Knowledge	Reviews using the 3D model	**Yes**
		Architect	High				Project Schedule	and drawings	
		Project Manager	high				Project cost estimation		
							Design Review Software		
							Interactive review space		
							Adequate hardware for running software		
							Ability to manipulate the 3D model		
							Strong knowledge of builidng systems and construction methods		
Code Validation	High	Architect	High				Applicable code knowledge	BIM use not well adopted	**Yes**
		MEP Engineer	High				Code checking software	Large learning curve	
		Agency	Medium				3D model manipulation		
							Ability to use code validation software		
							Ability to use BIM authoring tool for design and model checking tool		

6.3. Creating the BIM project execution plan for the integrated, BIM-based design process

The second step in the development of a general BIM Execution plan is the creation of a BIM overview map followed by the creation of detail maps for each BIM use in the process. For the purposes of this work, identifying the BIM deliverables and the infrastructure required to support the implementation of the BIM process are more specific to the project and were left out of consideration. The map development process is discussed in the following sections.

6.3.1. BIM overview map

The main objective of the BIM overview process map is to show the relationships among the BIM uses to be implemented in the process. In creating a BIM overview map, the DB process map, as developed in Chapter 5, was modified by replacing the traditional activities that are related to the fulfillment of the three PVO for the BIM processes previously selected.

Figure 6-1 shows the overview BIM process map for the schematic design phase, where the BIM uses for code validation, design reviews for constructability, O&M efficiency, energy analysis, and 4D modeling processes are included. In addition, the authoring of the schematic design models activity was included to show which 3D models are first created and when. It is proposed that in this phase the code validation process should be performed earlier in the schematic design phase instead of at the end of the DD phase (as it is typically done in the DB process), before the documents are submitted to the corresponding agencies for approval. This is because with the use of BIM tools, this activity is expected to be less time consuming, allowing for more repetitions during the design, and therefore, identifying possible errors and getting feedback earlier in the process. It is also proposed that the first energy analysis should be performed at the schematic design phase for the evaluation of the design alternatives because energy consumption might be an important design parameter to consider in the selection of design alternatives. The energy analysis process is repeated one more time after a design alternative is selected by the owner, along with the 4D modeling simulation and constructability design reviews.

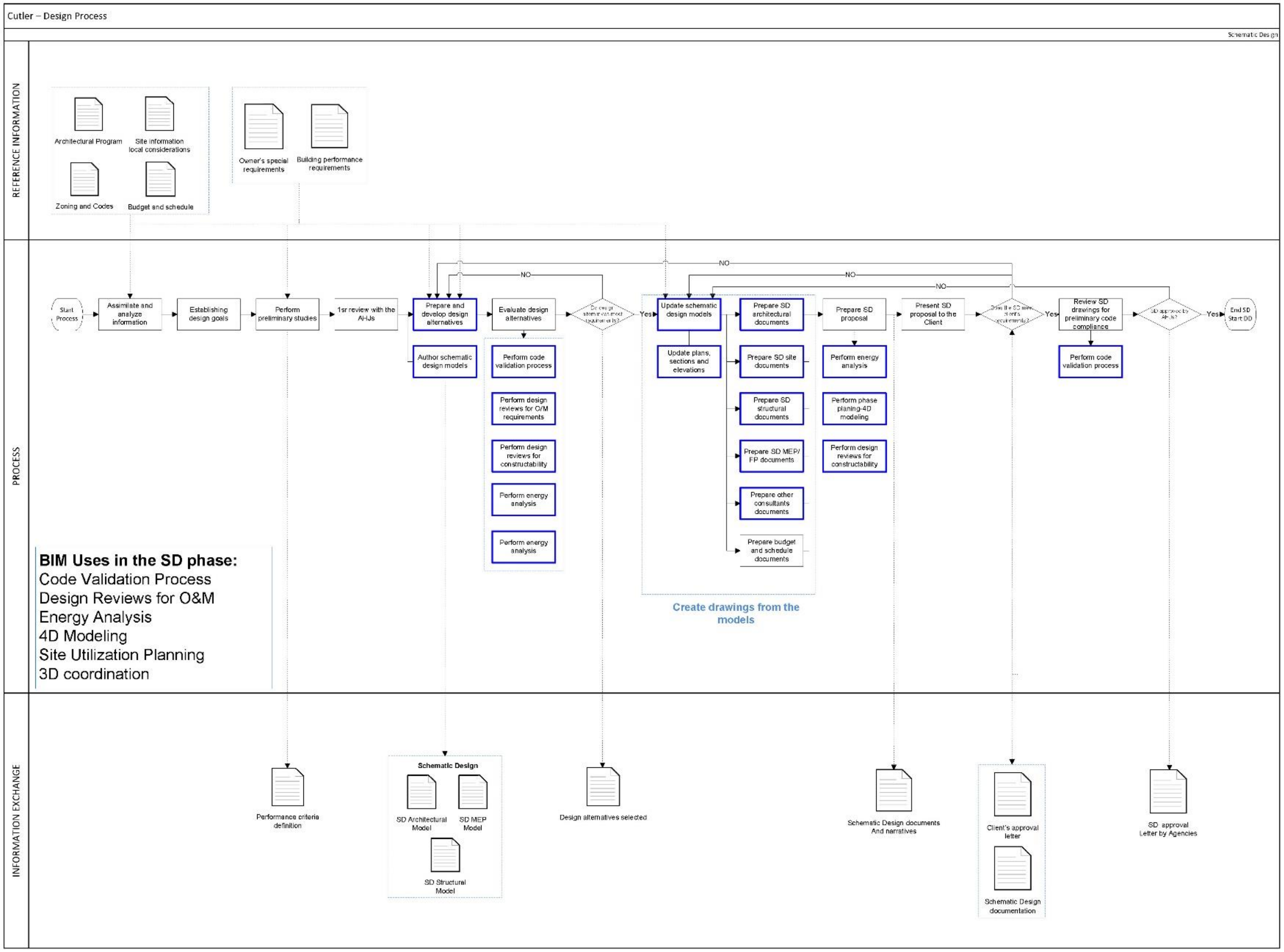


Figure 6-1 BIM overview map of the schematic design phase

Figure 6-2 shows the overview map corresponding to the DD phase. The BIM uses included in this phase are code validation, design reviews for operation and maintenance efficacy, energy analysis, 4D modeling, and 3D coordination process for constructability. In this phase the 3D models first created in the schematic design phase are continued to be developed and updated, adding corresponding information as it becomes available. For example, once the MEP contractor is selected, he is now responsible for developing the MEP model based on the model initially created by the design team. At this point, the model might not have all the desired information and level of development, such as the slope for the pipes, but it can be used to create the MEPFP drawings required for permits, which are also the responsibility of the contractor.

Figure 6-3 shows the overview map corresponding to the construction documentation phase. This phase, as was mentioned before, primarily focuses on the coordination of the major building systems; therefore, the 3D coordination process essentially remains the same as CD phase of the DB process described in Chapter 5. However, other BIM uses are also included in this phase such as the 4D modeling and site utilization planning. Also, it is suggested that during the coordination meetings for the building systems, the model should also be reviewed for constructability, O&M efficiency requirements, and regulatory and standard compliance. The energy analysis is no longer performed at this stage, since it is assumed that the construction of the building starts after the first level of the building systems are successfully coordinated at 80%, making changes in the design due to energy issues difficult and expensive to implement.

6.3.2. Detailed BIM use map

This section presents and discusses in more detail the BIM overview process maps for each one of the selected BIM uses included in this approach. Each of the BIM uses were adapted and mapped to be consistent with the DB process explained in Chapter 5 and based on the information provided by the BIM Execution Planning guide.

6.3.2.1. BIM use of code validation to achieve FR1.1.1

The BIM use of code validation was selected to achieve FR1.1.1 – Achieve a regulatory, code and standard compliant design. "It is the process in which a code validation software is used to check the model against specific codes (CIC, 2010)", The objective of this BIM use is to confirm that the building design complies with the applicable building codes and standards, like the International Building Code (IBC), the Americans with Disabilities Act (ADA) and Leadership in Energy and Environmental Design (LEED), among others.

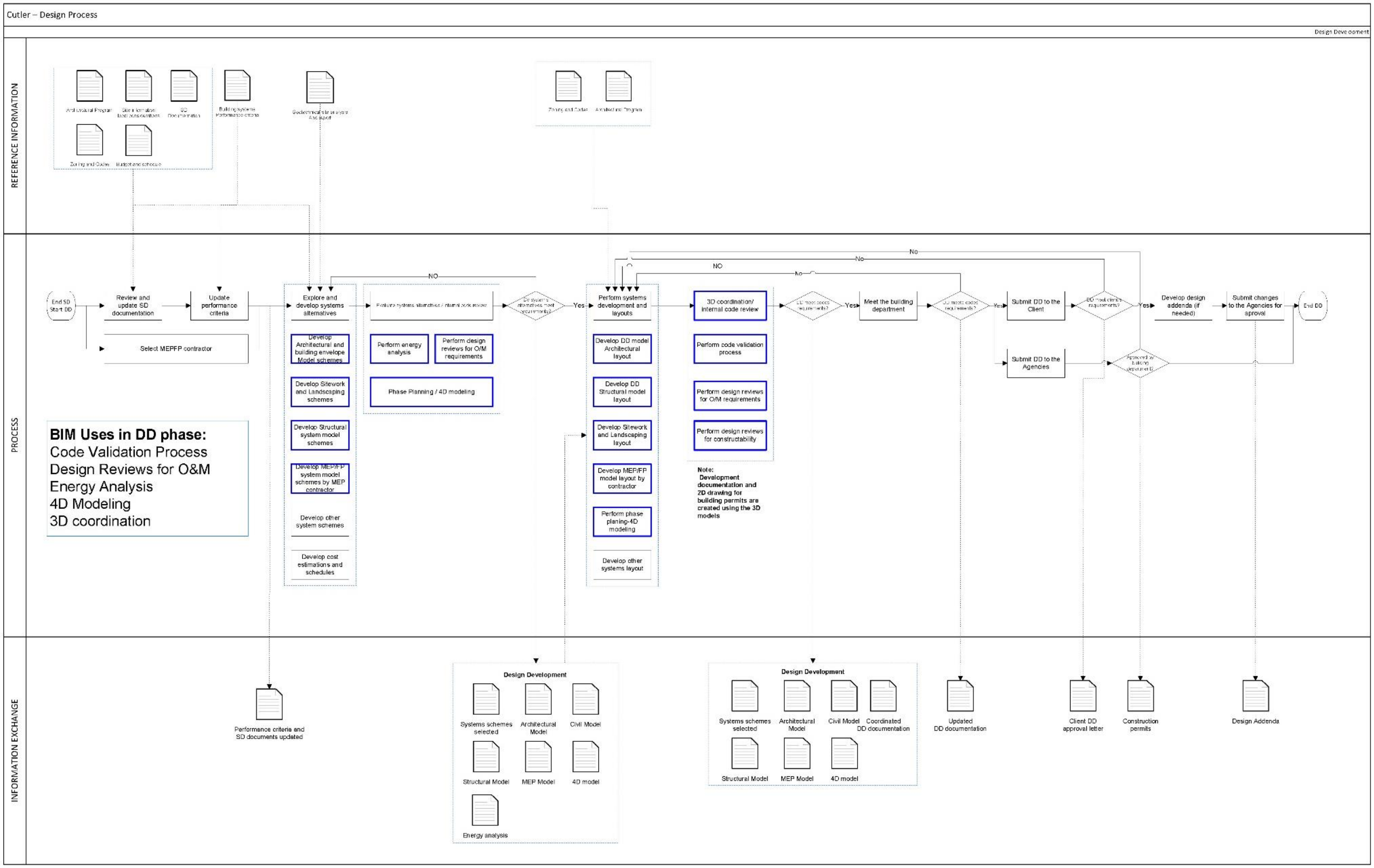


Figure 6-2 BIM overview map of the design development phase

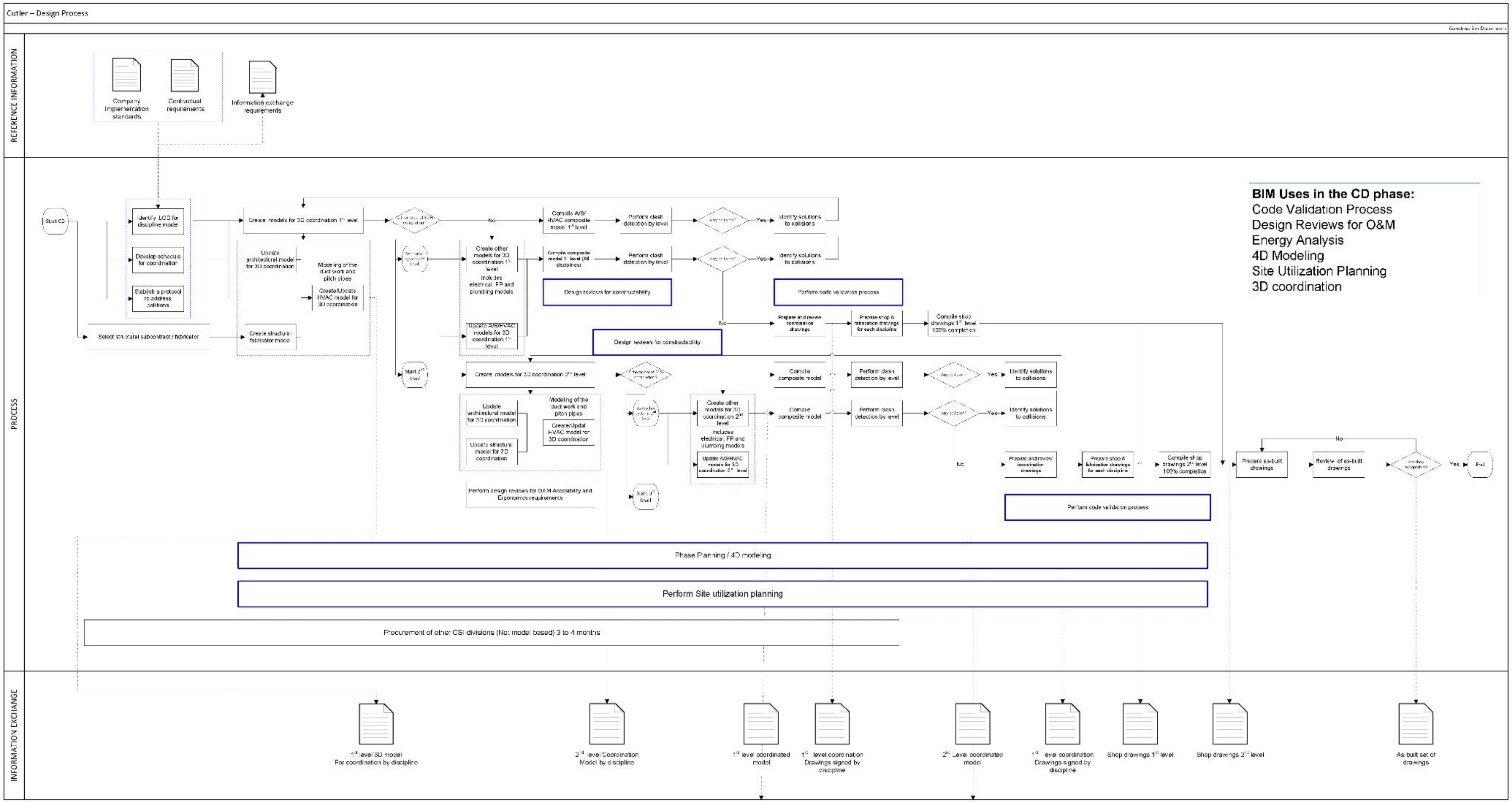


Figure 6-3 BIM overview map of the construction documentation phase

The BIM-based code validation process is currently in its infant stage of development. One reason might be that the translation and interpretation of building codes into a code validation software is very challenging, this along with the continuing innovation and growth in construction buildings and methods. However, there have been several efforts in developing automated code compliance applications since the 1990's, examples include CORENET®, HITOS® project, Solibri®, Fornax®, ED Model Checker®, and SMARTcodes® (Eastman et al. 2009; Dimyadi and Amor 2013), and this type of software is expected to continue in the next few years and become more common within the industry. To date, several benefits have been identified with the use of an automated code validation software (CIC 2010), among which are:

- The model can be checked against any international and/or local code
- Reduces the chance of errors and omissions on the design documentation, which would be more expensive to change or correct later in the design or during construction
- Automated code checking is performed in less time and gives continuous feedback on code compliance, resulting in a more efficient design process.
- Review reports with comments are also available to assist in the review process.

The BIM code validation process proposed in this research is established in general terms through the use of a non-identified, external software that directly checks the 3D model for code compliance in general. Figure 6-4 shows the proposed BIM code validation process map developed in this research for its implementation in the DB process.

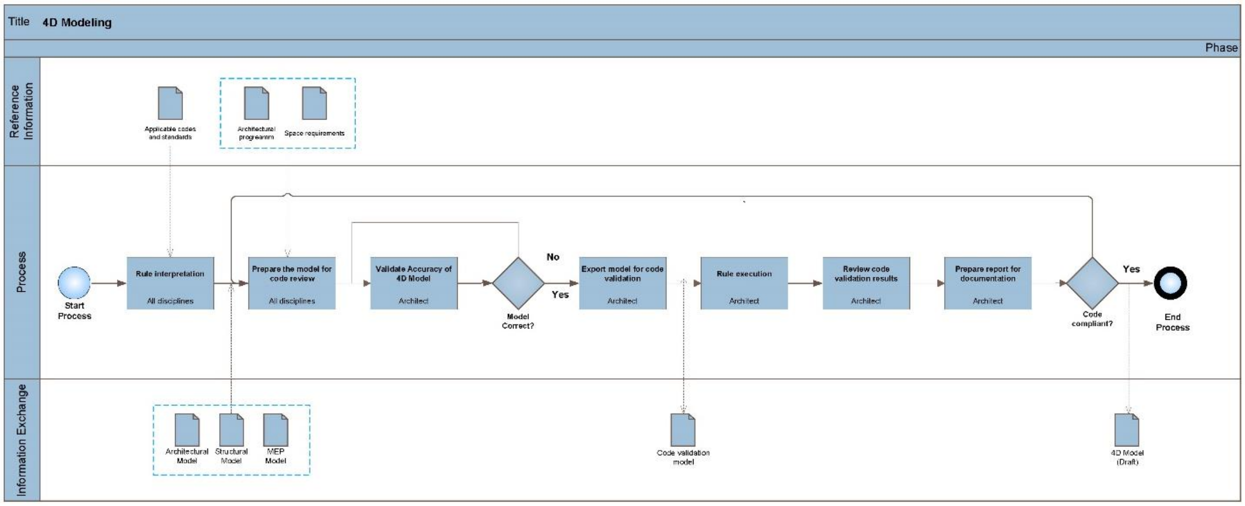


Figure 6-4 Proposed code validation process map

In order to perform the BIM code validation process, the building systems created in the model (architectural, structural, and MEP) must be developed first in a generic level with their geometric properties using a design authoring tool. Then, the model is exported according to the Industry Foundation Classes (IFC) format. IFC is the most common open file format specification used to facilitate information exchange among BIM platforms. It is advisable to review that the IFC file has been properly exported so that the model provides the information necessary to run the analysis. This can be achieved by developing the appropriate delivery manual (IDMs) and model view definitions (MVDs) (Nawari 2012b). Once the IFC model is suitable, the code validation analysis is performed using one of the automated code compliance applications available in the market. At the end of this process, a report with the results of the code validation process can be obtained in HTML, XML, XLS, or PDF format, among others. The report usually provides information of the building elements that are not code compliant, the reason for non-compliance, and the textual reference of code criteria at this issue.

6.3.2.2. BIM use of design reviews to achieve FR1.2.1 through FR1.2.4, and FR1.3.4

The design review has been defined as "a process in which stakeholders use the 3D building model to review and provide their feedbacks to validate multiple design aspects" (CIC 2010). In the context of this research, those aspects include the constructability and maintainability requirements stated in FR1.2.1 through FR1.2.4, and FR1.3.4 which are to achieve a design with accurate space use, achieve a design with clear understanding of the physical location of equipment, achieve a design that facilitates equipment accessibility to perform maintenance operations, achieve a design that enables efficient O&M through standardization/repetition, and achieve a design that promotes standardization and prefabrication to facilitate efficient construction, respectively.

The objective of this process is to better visualize the facility by using the 3D model and support design decision making about the constructability and maintainability aspects of the building. Design reviews that are conducted using only the 3D model can be very powerful and bring several benefits to the project team, among which are:

- Design review meetings are more efficient
- The effectiveness of the design can be evaluated by determining the degree to which constructability and maintainability requirements, as stated in FR1.2.1 through FR1.2.4, and FR1.3.4, are met.
- Design reviews allow to identify design or documentation errors, and to model different solutions that can be changed in real time during the design review meeting with direct assistant from the contractor, the FM staff, and other owner's staff.
- 3D models for design review are a great tool to more effectively communicate and coordinate the design to the owner, the construction team and to the end users.

The BIM design review process map proposed in this research is shown in Figure 6-5. It represents the general flow and steps needed to use the model for reviewing the maintainability and constructability aspects stated in FR1.2.1 through FR1.2.4, and FR1.3.4. The process starts with the adjustment of the architectural, structural and MEP models with the proper pre-agreed level of development (LOD). This can be achieved with the 2013 Level of Development Specification for Building Information Models (BIMForum 2013), which is a guide that can be used for the project team for defining the content and reliability of Building Information Models at various stages in the design. Then, the models are integrated into a 3D-viewer BIM software with all the information required to perform the design review process. During this process, FR1.2.1 through FR1.2.4, and FR1.3.4 are checked for compliance with the BIM model and a feedback report is produced with the results of the review. The process finishes when all of the requirements, FR1.2.1 through FR1.2.4, and FR1.3.4, are met.

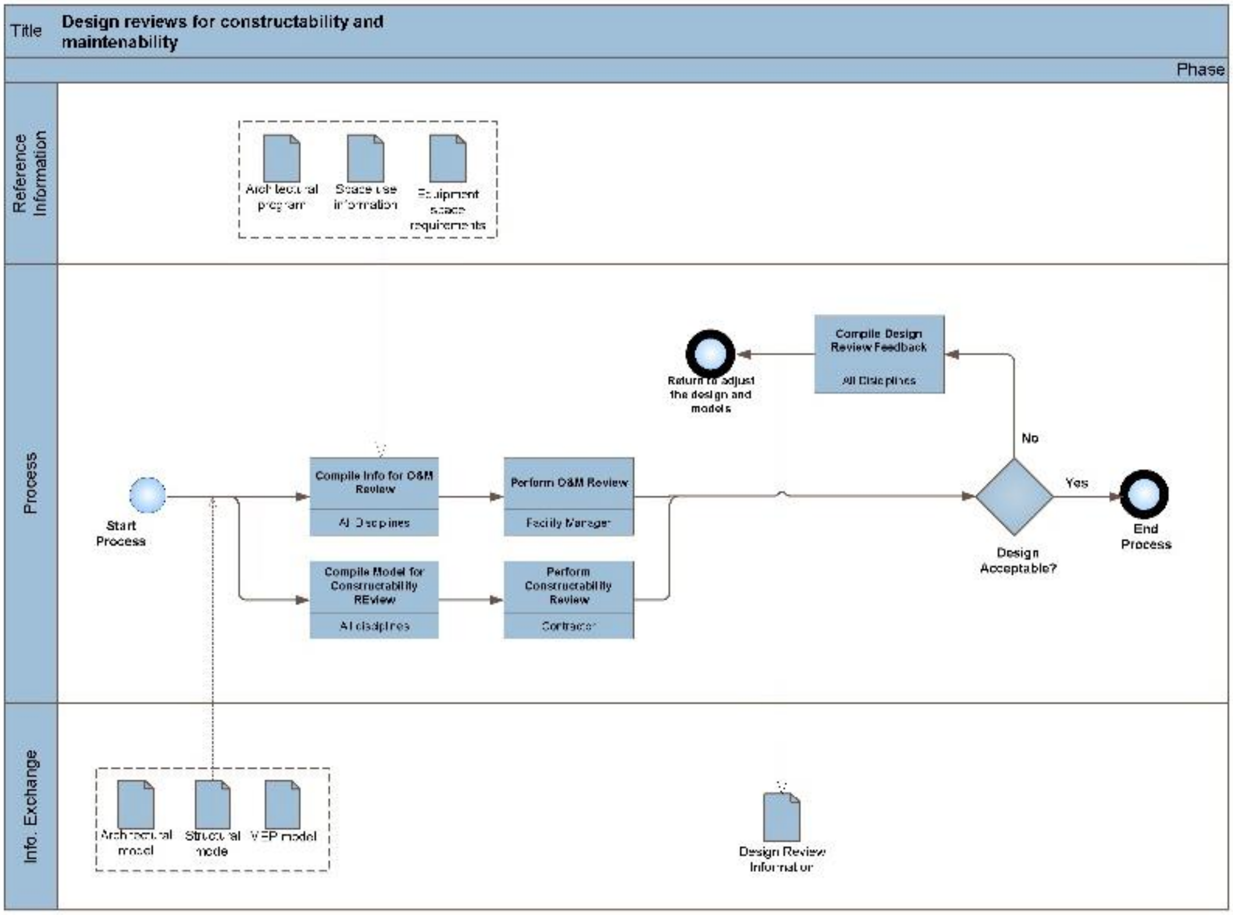


Figure 6-5 Proposed design review process for constructability and maintainability

6.3.2.3. BIM use of energy analysis to achieve FR1.2.5

The energy analysis "is a process in which an energy simulation program is used to conduct energy assessments for the building design" (CIC 2010). The objective of this process is to estimate building energy consumption and to inspect building energy standard compatibility, and thus attain FR1.2.5, achieving an energy efficient design. Based on the results of this analysis further development, refinement and optimization of the design takes place in order to reduce the building's life-cycle costs.

Energy analyses are becoming a common practice due to current sustainability and environmental concerns, and to the efforts of reducing the building operation cost. The use of BIM energy simulation programs at the different phases of the design can:

- Reduce the time spent in calculating the building's energy consumption or inputting data manually
- Help the design team to more accurately estimate the building's energy consumption and to improve the design for better performance and lower life-cycle costs, achieving FR1.2.5
- Get quick feedback on the expected energy consumption of the building
- Compare the performance of design alternatives, at the conceptual phase
- Generate detailed energy analysis reports that can be used to gain more control over the HVAC equipment and operating schedules

This research uses the BIM energy analysis process map as it is suggested in the BIM Execution Planning Guide shown in Figure 6-6, since it represents and is in accordance with the DB process outlined in Chapter 5.

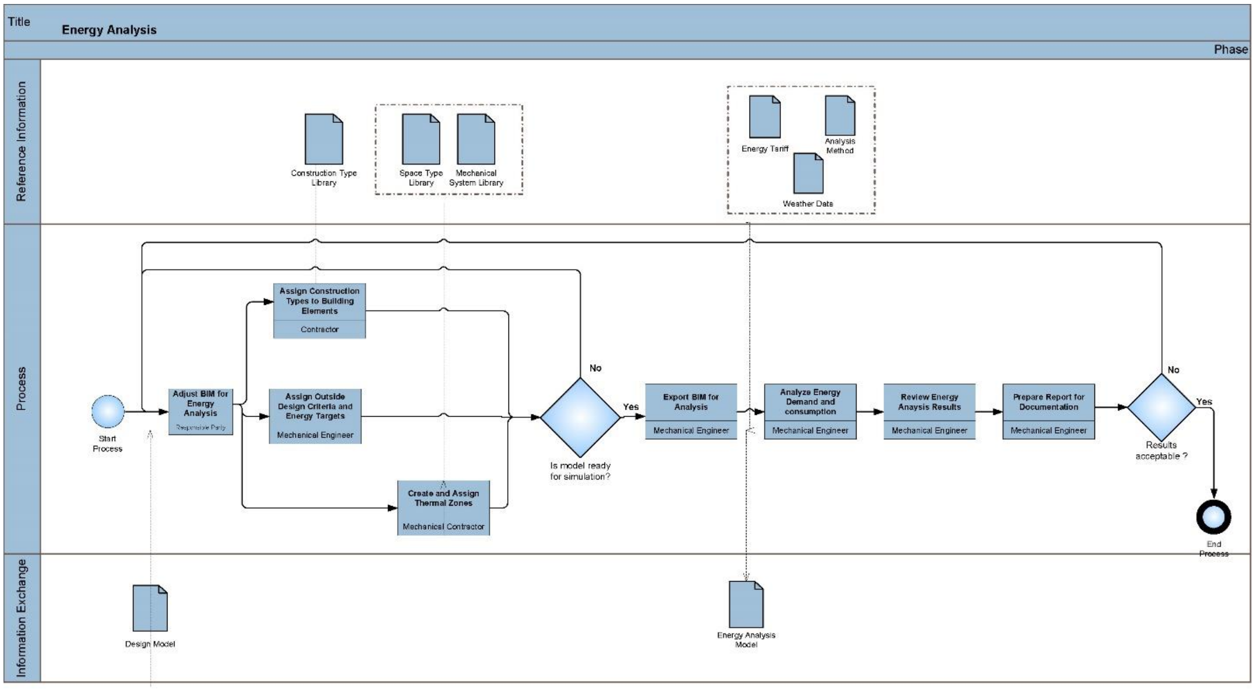


Figure 6-6 Energy analysis process from BIM Execution Planning Guide

In order to perform the energy analysis, the design or architectural model is adjusted specifically to conduct the energy assessment with information, including structural and MEP models and other relevant design information, like materials properties and the HVAC system performance. Some design authoring tools now have the capability of performing energy simulations directly from the architectural model by including the building location and orientation as well as the thermal properties of the building elements. However, these type of tools are recommended to be used at the SD phase. Energy analyses are usually performed during the SD phase to evaluate different HVAC systems alternatives. It is proposed in this research to perform more detailed energy analyses once the design alternative has been selected by the owner at the design development phase to ensure the achievement of FR1.2.5

6.3.2.4. BIM use of phase planning/4D modeling to achieve FR1.3.1

According to the BIM Execution Planning guide, phase planning or 4D modeling is “the process in which a 4D model (3D + time) is utilized to effectively plan the phased occupancy in a renovation, retrofit, addition, or to show the construction sequence and space requirements on a building site” (CIC 2010), This type of BIM modeling is conducted to visualize and analyze the construction sequence in coordination with the procurement schedule to enable efficient construction. This process has several benefits for the design team, such as:

- Provides a powerful visualization and communication tool to better understand project milestones and construction plans
- Allows the design team to analyze and improve the construction sequence by including the major construction methods and identifying and resolving sequencing conflicts before the actual construction starts, therefore, achieving FR1.3.1
- Allows to easily monitor the procurement status of project materials
- Allows the project team to evaluate various alternatives resources over a period of time to optimize the resources and labor accordingly.

Under the proposed approach, 4D modeling is used to analyze the construction sequence and to coordinate it with the procurement schedule. Even though this type of modeling is highly useful to the contractor during the construction phase, its inclusion during design can improve constructability, allowing for more efficient construction.

There are some considerations to be taken into account when creating a 4D model. First, the construction and procurement schedules must match the level of development of the 3D model. Also, it is convenient to include the temporary components that are critical for the sequence of work, like the formwork. Finally, including text information for every component that the contractor must purchase, can make the model useful for procurement. It is important to note that during the construction stage, the contractor will add information to the model required for construction and procurement tracking and control. The 4D modeling process map to be used in the BIM-based integrated design process proposed in this research is shown in Figure 6-7

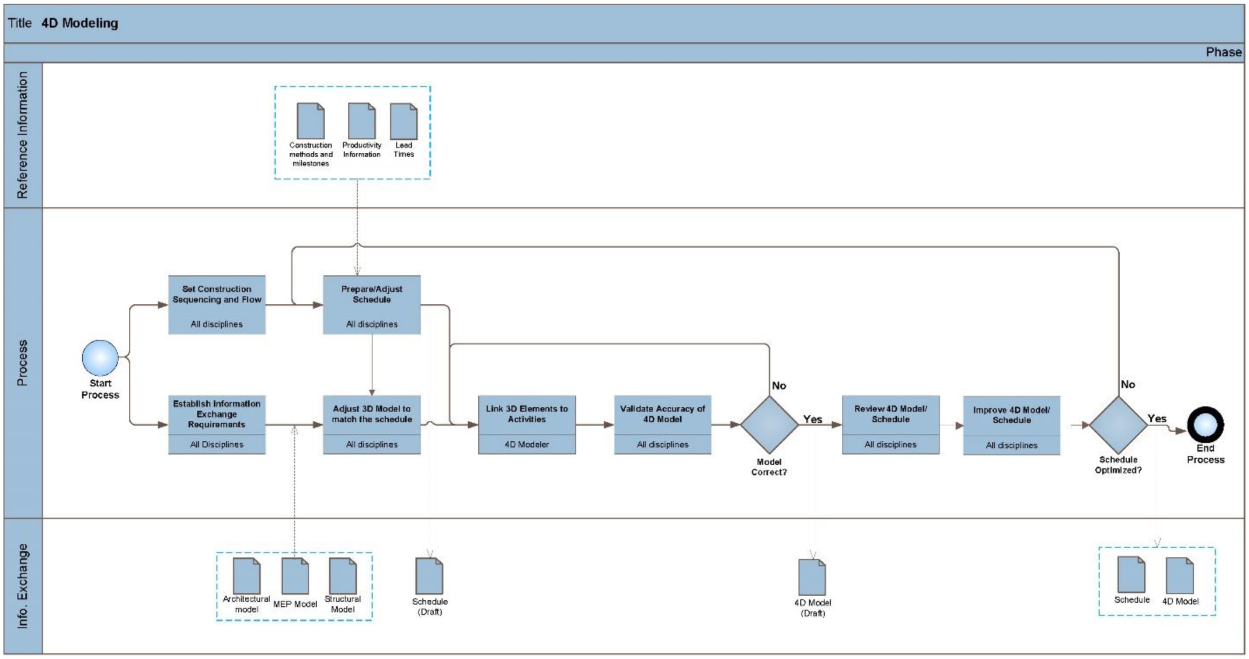


Figure 6-7 Proposed 4D modeling process map

6.3.2.5. BIM use of site utilization planning to achieve FR1.3.2

According to the BIM Execution Planning guide, site utilization BIM use is “the process in which BIM is used to graphically represent both permanent and temporary facilities on site during multiple phases of the construction process” (CIC 2010). Even though this is a BIM use for construction, it is included in the proposed integrated, BIM-based design process to attain FR1.3.2 – achieve a site and building layout that promotes efficient construction by including additional information to the 4D model like temporary construction, storage areas and site accessibility requirements. During the design phase, this information should be defined in terms of the physical arrangement and location of those specific areas within the site, and they can be linked with the construction schedule to convey space and sequencing requirements. During the construction phase, more information can be incorporated by the contractor like material deliveries, equipment location, routes and sizes.

It is proposed that this BIM use is performed along with the 4D modeling process during the construction documentation phase for analyzing the site layout for space and time conflicts, as is shown in Figure 6-8

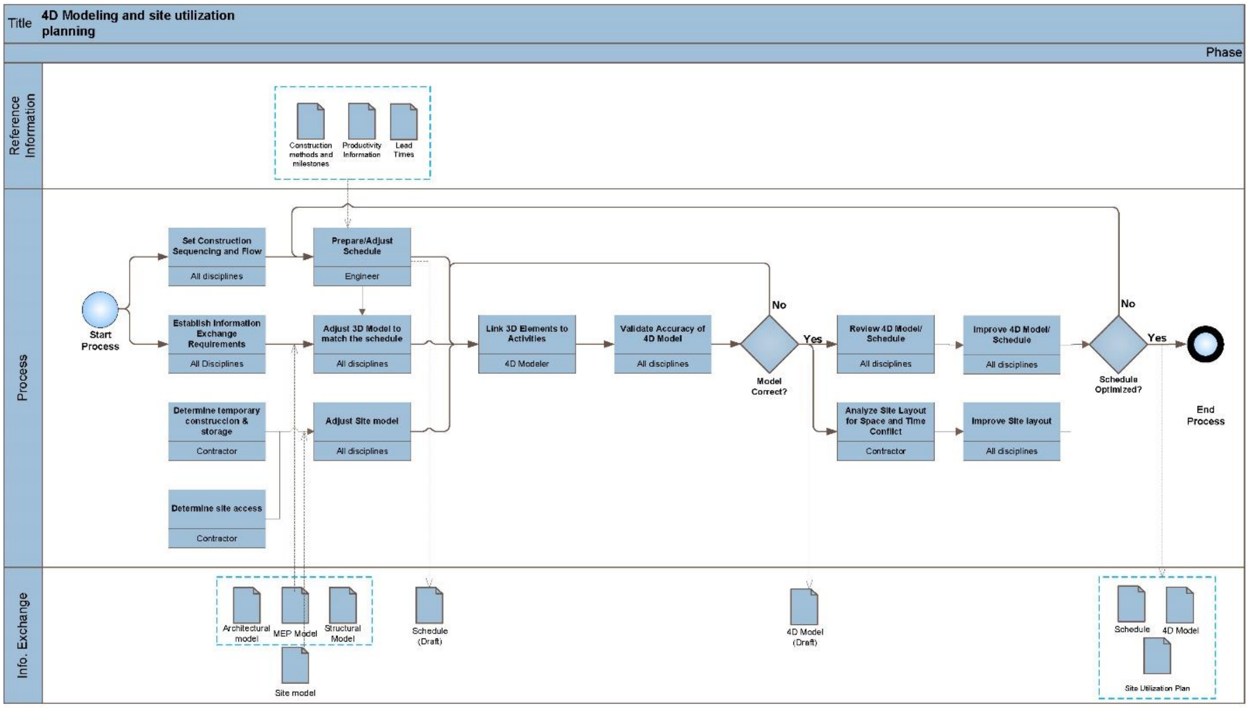


Figure 6-8 Proposed site utilization planning with 4D modeling

6.3.2.6. BIM use of 3D coordination to achieve FR1.3.3

As defined by the BIM Execution Planning guide, 3D coordination is the "process in which Clash Detection software is used during the coordination process to determine field conflicts by comparing 3D models of building systems" (CIC 2010). The BIM process of 3D coordination integrates the 3D models of the major building systems into one model to ensure that they will fit together in the physical three-dimensional space as it is planned in the 3D digital space. 3D coordination is now one of the most widely used applications of BIM in the industry (also known as MEP coordination) because of the many benefits it gives to the project and design team, among which are:

- Spend less time in coordinating the building using the model
- Identify possible field conflicts before construction starts, thus reducing significantly or even eliminating the need for Requests for Information (RFIs) and enhancing the efficiency during construction, therefore achieving FR1.3.3
- Provide powerful visualization tools for constructability reviews
- Create more accurate coordination and as-built drawings and other documentation

As was mentioned before, the 3D coordination process has been widely adopted by the industry and many design and construction firms have made this a well-established practice. This also applies for the DB coordination process previously mapped in Chapter 5 (Figure 5-4). For that reason, it is used (with no modifications) in the integrated, BIM-based design process proposed in this work.

6.4. BIM deliverables (Information exchanges)

The information exchanges define the information and level of detail required for each BIM use to be implemented. In this step, the project team needs to identify and understand the specific information that each BIM use will require and deliver, so that, they can define which elements of the project are valuable and essential and need to be included in the 3D models, together with their corresponding level of development and specific attributes. This information may vary depending on the type of project, location, size, and the firm’s BIM-related capabilities. Therefore, specific aspects of the BIM deliverables are not discussed in detail in this study.

6.5. Infrastructure required to support the BIM implementation

The infrastructure required to support the implementation addresses the hardware, software platforms and licenses, as well as the network infrastructure available and/or necessary to properly implement and execute the BIM uses. Similar to the previous step, the infrastructure requirements should be identified by the design team at the time of the implementation of each BIM use, therefore, this part is not discussed in more detail.

6.6. Implementation of the tools and activities to reduce waste

The children of DP2.1 through DP2.6 correspond to the activities and tools selected for reducing waste (and cost) in producing the building design previously presented in Chapter 4. The complete list of these activities shown in Table 6-3.

Table 6-3 List of selected DP2.1 through 2.6

List of tools and activities selected to reduce waste in the design process
DP2.1.1: Use of virtual meetings during the buidlign design process
DP2.1.2: Use of digital information and prototypes in the building design process
DP2.2.1: List of building's plans required according to the type of project and location
DP2.2.2: Standarization of drawing information content
DP2.2.3: Establishing appropiate level of design detailing for project type
DP2.3.1: Co-location of the design team within the office area
DP2.3.2: Creating design meetings agenda, schedule and minutes
DP2.4.1: Establishing the appropiate IT and software to use during the building design - BIM Exec Planning Guide
DP2.4.2: Establishing the appropiate level of development of the BIM models - LOD document
DP2.5.1: Activity for Inspectioning completness of drawings and specifications
DP2.5.2: Activity for Inspectioning accuracy of drawings and specifications
DP2.5.3: Activity for Inspectioning clarity of drawings and specifications
DP2.6.1: Establishing design milestones and times for checking
DP2.6.2: Data and document management system repository
DP2.6.3: Establishing information and communication mapping workflow in the design process
DP2.6.4: Establish BIM information exchange protocol - BIM Execution Planning Guide

The implementation of these tools and activities is outside of the scope of this research and is not reflected in the BIM processes previously mapped, nor in the integrated, BIM-based design process proposed. Therefore, further work in needed to accurately analyze and measure the process improvement.

6.7. Summary

This chapter discussed in detail the development of the proposed integrated, BIM-based design process, which focuses on the use of specific BIM processes and tools for the fulfillment of the three PVO selected in Chapter 4, which are:

- Regulatory and standard compliance
- Operation and maintenance efficiency, and
- Constructability.

These objectives seem to be the most important for the industry practitioners and encompass the major stakeholders (the owner, the design team and the construction team), and other project goals like building security and safety. For that reason and due to the scope of this research, they meet the CEMEmin rule of AD. If another PVO must to be fulfilled using BIM tools, it must be included in the decomposition as a third level FR and then decomposed and analyzed following the AD method described in Chapter 4.

In addition to the fulfillment of the three PVO, the proposed integrated, BIM-based design process seeks to reduce the waste of the design process, previously identified in the literature review, by the implementation of the tools and activities resulting from the AD decomposition presented in Chapter 4. The waste of the design process was categorized based on the seven lean wastes, which are:

- Transportation
- Inventory
- Motion
- Waiting time
- Over-processing
- Over production
- Defects

The activities and tools selected to reduce waste seek to support and facilitate the use of the BIM uses and technology implemented, thereby, increasing process efficiency. Further simulation of the proposed BIM-based integrated design process is needed to analyze the results of the implementation in order to know the benefits of using the BIM technology (if any) during the design process compared to the DB process presented in Chapter 5.

7. THE INFORMATION AXIOM

7.1. Introduction

According to the Axiomatic Design (AD) method, axiom one, the independence axiom, seeks to seeks to maintain the design adjustable and controllable. The complete deployment of the design decomposition is discussed in Chapter 4. This chapter discusses the calculation of the information content of both processes: the DB process and the proposed integrated, BIM-based design process by the application of the axiom two, the information axiom, which states that among all designs that satisfies axiom one, the design with less information content has higher probability of success and therefore, is the best design (Albano 1993; Suh 1999, 2001; Brown 2011a; Towner 2013)

Calculating the information content allows the designer to objectively compare the level of complexity and the probability of success of two or more solutions. Therefore, in this research, the information content is used to compare the DB process discussed in Chapter 5 and the integrated, BIM-based design process proposed in Chapter 6.

7.2. Metrics for the functional requirements

Following the method of AD, each FR should be independently and objectively evaluated. This chapter also presents appropriate metrics to quantitatively evaluate the degree of success achieved by the design process to meet each FR and therefore, the whole system. These metrics also allow the designer to compare results over time or to compare values from one design process against benchmarks (Towner 2013) with the purpose of objectively control and improve the system.

Twelve metrics were proposed for the first, second and third levels of FRs. The development of the third level of FRs metrics was not included in this work. The proposed metrics are the result of a literature review of construction performance metrics, where two types of metrics where found: at company level and at project level. The proposed metrics in this work focuses at the project level, since at the company level include factors like managerial practices that are only indirectly related to the project. The most common project performance indicators found in the literature review are those related with the cost, time, safety and quality. Some others include productivity, efficiency, effectiveness, customer satisfaction, defects, claims, changes and rework. Invariably all of these indicators are translated into time and money.

7.2.1. Metric for FR0 – Produce a design of a building (effectively and efficiently)

The proposed metric of producing a design is to measure the cost efficiency ratio of the design process shown in the Equation 7.1:

$$Design\ project\ cost\ efficiency\ ratio\ \% = \frac{Cost\ of\ the\ overall\ achievement\ of\ the\ PVO}{Expenses\ for\ producing\ the\ design}$$

Equation 7-1 Metric for FR0 – Design efficiency ratio

This metric measures the efficiency of the design project by determining the overall level of fulfilment of the Project Value Objectives (PVO) and the total resources spent in producing the design of the building. The efficiency of the design project can increase if the achievement of the PVOs are higher than the expenses, decrease if they are less or remain constant

7.2.2. Metric for FR1 – Achieve the desired value-added of the design

The value in the design of a building is directly related to the satisfaction of the customer needs expressed in terms of the PVO's. Therefore, the value-added by the design is measured by the degree to which the built facility ultimately meets or exceeds customer stated performance expectations with a survey properly defined to measure customer satisfaction.

7.2.3. Metric for FR1.1 – Achieve a regulatory and standard compliance objective

By law, all buildings must be code compliant, otherwise the government agencies won't issue the design and building permits. Since codes and regulations must be completely addressed during the design, the measurement for the achievement of this FR can be expressed as the percentage of the time spent in reviewing and adjusting the design to meet the code requirements as shown in the following equation:

$$\%\ of\ time\ spent\ in\ code\ reviews = \frac{Total\ duration\ spent\ in\ code\ reviews}{Total\ duration\ of\ the\ design\ phase}$$

Equation 7-2 Metric for FR1.1.1 – Time spent in code reviews

7.2.4. Metric for FR1.2 – Achieve a design that meets the desired level of O&M efficiency

The efficiency of the building's operation and maintenance can be affected by other factors outside the design stage, like developing and following a good operation and maintenance program and having the required facility management skills. Therefore, a metric that shows how well the design facilitated and supported the building's operation and maintenance efficiency should be defined as relating the repair and maintenance time of the equipment (maintenance costs) and the building's energy consumption (operation costs). This is expressed in the following equation:

$$\%\ of\ cost\ of\ the\ time\ of\ maintenability = \frac{Cost\ of\ maintenability + cost\ of\ EC}{Total\ cost\ of\ O\&M}$$

Equation 7-3 Metric for FR1.2 – Cost of maintainability

Where the planned cost of O&M only includes the cost of the building energy performance and the cost of the maintenance activities estimated during the design phase. The actual cost of the O&M refers to the real cost of the building energy consumption and on the time spent on maintenance activities. This metric assumes that the O&M staff have and follow the O&M program of the building in accordance with the design and equipment specifications.

7.2.5. Metric for FR1.3 – Achieve a design that meets the desired level of constructability

Constructability is defined as to how well the design promotes efficient construction. A design with high level of constructability prevents or reduces changes, errors, and delays during the construction phase, and therefore cost overruns. In the construction industry, the quality of the construction documentation is reflected in part by the number of Requests for Information (RFI) that are issued by the builder during the construction phase. RFIs are originated because the builder: 1) needs additional or to clarification of information on the construction drawings; 2) requests for a modification in the construction method; 3) finds a deficiency in the construction document. In any case, the designer should review the RFI request and respond it. When the designer’s reply involves a change in the original scope of work, then, the contractor reviews the schedule and cost impact of that change. If this change is authorized by the client, then the RFI becomes a Change Order (CO) that ultimately affects time and cost for the project. Not all RFIs result in change orders, however, the work associated with the RFI can’t continue until the issue is resolved.

The equation shown below measures the percentage factor of the cost incurred by request for information (RFI) and change orders (CO) due to lack of constructability of the design over the total construction cost. This equation leaves out of consideration the cost of RFI and CO that are not related to poor constructability as described in FR1.3.1 through FR1.3.5 in Chapter 4.

$$\%\ of\ cost\ of\ constructability = \frac{Cost\ of\ construtability\ related\ RFI + CO}{Total\ construction\ cost}$$

Equation 7-4 Metric for FR1.3 – Cost of constructability

7.2.6. Metric for FR2 – Reducing the waste in producing the design

Waste is commonly defined as anything that does not add value to the customer. Reducing the waste in the design process increases the company profitability throughout the elimination of time and cost associated with that waste. The equation shown below measures the waste reduction as the percentage ratio of the time of the value-added activities in the design process over the total duration of the design process.

$$\%\ of\ value-added\ time = \frac{Total\ value\ added\ activities\ time}{Total\ duration\ of\ the\ design\ phase}$$

Equation 7-5 Metric for FR2 – Value-added time

7.2.7. Metric for FR2.1 – Reduce overproduction waste of drawings and specifications

Overproduction waste of drawings and specifications refers to unnecessary time spent in the creation of redundant information (duplication of content and unnecessary detail on drawings and specifications) as it can be observed by the production of more design documentation than is actually needed for clear and precise communication of the design intent. The waste of overproduction is calculated by how much added time the design team spent on the creation of redundant information over the total time spent in producing the building plans, as shown in the equation below:

$$\%\ Time\ spent\ in\ drawings = \frac{Total\ value\ added\ time\ in\ producing\ building's\ plans}{Total\ time\ in\ producing\ the\ building\ plans}$$

Equation 7-6 Metric for FR2.1 – Time spent in producing drawings

7.2.8. Metric for FR2.2 – Reduce unnecessary transportation waste of the design meetings

Transportation waste in the result of the designer are not always in the same space, therefore, it is common that during the design phase the architect meets several times with the design team in a collaborative session to discuss a solution for a particular design problem. In addition to this meetings, the design team also meets with the owner to review the progress of the design. At the beginning of the design, the meetings with the owner are not as frequent as the end of the design.

Transportation waste can be reduced by using more digital information (like PDF plans, 3D models and virtual mock-ups) and by attending virtual meetings when face to face meeting is not necessary, as shown in the equation below:

$$\%VA\ meetings = \frac{Total\ duration\ of\ the\ design\ meetings}{Total\ duration\ of\ the\ design\ meetings + transportation\ time}$$

Equation 7-7 Metric for FR2.2 – Value-added meetings time

7.2.9. Metric for FR2.3 – Reduce non-value-added processing waste from using BIM

Over-processing waste from using Building Information Modeling (BIM) tools occurs when unnecessary or more complex tools are used to develop the BIM model, and when the model is developed in more detail than the needed. To reduce this waste, it is necessary to properly identify the purposes of the model and tools and level of development that matches its purpose. The none-value-added processing waste can be measured as the ratio resulting from the total value-added time spent in developing a BIM model over the total duration of this activity, as shown in the equation below:

$$\%\ VA\ time\ of\ BIM\ models = \frac{Total\ value\ added\ time\ in\ developing\ BIM\ models}{Total\ duration\ in\ developing\ the\ BIM\ models}$$

Equation 7-8 Metric for FR2.3 – Value-added time of creating BIM models

7.2.10. Metric for FR2.4 – Reduce the waste due to non-value-added queues

Waiting waste in the design process is mainly because the information needed to start an activity is not available or properly transferred to all the design team. Also, waiting waste occurs when the information is not properly exchange among the team members resulting in an extra time to adjusting the format of the information so it can be use by other team members. Finally, waiting waste also occurs due to unnecessary checking activities. The waiting waste queues can be measured as the ratio of the total waiting time for information over the total duration of the design phase

$$\%\ Waiting\ time = \frac{Total\ waiting\ time\ for\ information}{Total\ duration\ of\ the\ design\ phase}$$

Equation 7-9 Metric for FR2.4 – Waiting time

7.2.11. Metric for FR2.5 – Reduce unnecessary motion waste

Motion waste in the design process is the result of the excessive walking of the design team because they are working in separate areas within the office building, as well as the result of incomplete internal design reviews, as shown in the equation below:

$$\% \, Motion = \frac{Co\ location\ \ factor + Complete\ design\ reviews\ factor}{2}$$

Equation 7-10 Metric for FR2.5 – Motion waste

Where:
Co-location factor is the result of the number of project participants co-located within the office divided by the total number of project participants in the office involved in the project.

Complete design reviews factor is the result of the total number of design reviews that were successfully completed (all items in the agenda were reviewed and discussed in the meeting) divided by the total design reviews.

7.2.12. Metric for FR2.6 – Reduce defects waste in the design documentation

Defects waste in the design documentation is the result of incomplete, inaccurate and ambiguous building's plans. In order to reduce this defects an inspection activity is proposed during the production of the drawings to allow the design team if the accomplished progress is defective or not. The equation below shows the defect ratio as:

$$\% \, First\ time\ drawings = \frac{Number\ of\ plans\ pass\ at\ first\ time}{Total\ number\ of\ drawings}$$

Equation 7-11 Metric for FR 2.6 – Defects on drawings

7.3. Calculation of information content

The information content is defined by the probability of successfully fulfilling the FRs, as it is shown in equation 1, where "I" is the information content of a given system in units of nats (when the natural logarithm is used) and "P" is the probability of satisfy the FRs. The units of information is bits when the logarithm based on 2 is used (Suh 1998)

$$I = Log\left(\frac{1}{P}\right)$$

Equation 7-12 Information content

The probability of success of can be computed using the probability density function (Frey et al. 2000, Suh 2003, Shin et al. 2004, Towner 2013), where the value of "P" can be determined by defining the system range as the range of values on a given metric that a given design process is capable to deliver and by defining the design range as range of values on a given metric that a given FR needs to achieve to be satisfied. The overlap area between these values is defined as the common range and it represents the region where the FRs are satisfied. Figure 7.1 illustrates these concepts when the uncertainty on these ranges is captured by a uniformly distributed probability density function.

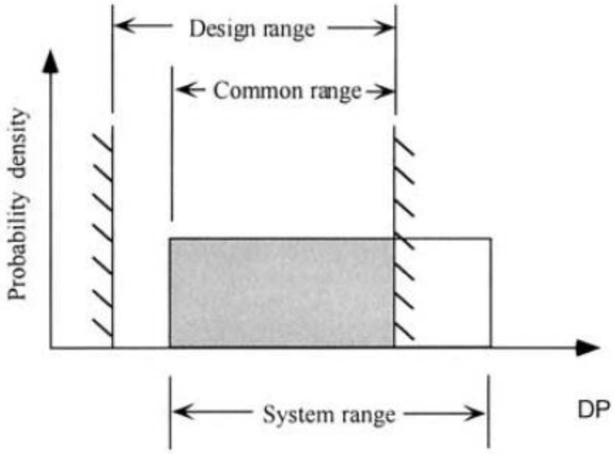


Figure 7-1. The probability density function – Figure taken from Frey, et al. 2000

The probability of success (P) of achieving the specified goal or FR can be defined as the ratio between the common range and the system range as shown in equation 7-13.

$$P_{FR1} = \frac{common\ range}{System\ range}$$

Equation 7-13 Probability of success

By substituting equation 7-12 into equation 7-13, then, the information content of a given FR is calculated using equation 7-14

$$I_{FR1} = Log\ \left(\frac{System\ Range}{Common\ Range}\right)$$

Equation 7-14 Information content for each FR

According with the AD method, if each FR is statistically independent of other FRs, in other words, if they form a diagonal matrix (uncoupled design), then the probability of satisfying the highest level FR0 is given by the product of all probabilities associated with satisfying the lowest level FRs (leaves[11]) in the system. Therefore, the information of the total system (FR0) is expressed in the equation below, where P(leaves) is the joint probability of satisfying all the lowest level FRs.

$$I_{sys} = Log\left(\frac{1}{P_{(leaves)}}\right)$$

Equation 7-15 Information content of the total system for uncoupled designs

For events that are not statistically independent, as may be the case for a decoupled designs or triangular matrices, proper conditional probabilities need to be used (Suh 1990, Frey et al. 2000, Suh 2003, Shin et al. 2004, Towner 2013)[12]. As was mentioned before, for triangular design matrices, the independence of the FRs is satisfied by the sequence of the process, therefore the probability of success of the later process depends on the probability of success of the previous one. Conditional probability measures the probability of an event given that (by assumption or evidence) another event has occurred. The notation of conditional probability is P(B|A) which is read as the probability of B given A has occurred. So that, the information content of FR2, given FR1 has successfully occurred is expressed as

$$I_{FR2} = Log\left(\frac{1}{P_{(FR1|FR2)}}\right)$$

Equation 7-16 Information content of the total system for decoupled designs

Either in the case of a diagonal or triangular matrix, where the integration of the lowest level of FRs and DPs does not introduce a new element of uncertainty, the information content of the total systems is the sum of the information contents associated with all lowest-level FRs, as is expressed in the equation below, since the probability of satisfying the higher levels is related to the probability of satisfying the lowest levels FRs. Otherwise, if the integrations of FRs and DP introduces new elements of uncertainty, the calculation of the total information content must take into account the additional probability (and information) associated with that uncertainty.

$$I_{sys} = \sum I_{Of\ FR\ lowest\ level-leaves} = \sum\ [Log\left(\frac{1}{P_{leaf}}\right)]$$

Equation 7-17 Sum of Information of the lowest level FRs

---

[11] Leaf refers to each FR of the lowest level for each branch that does not require further decomposition

[12] Theorem 7 (Path Dependency of Coupled and Decoupled Design). The information content of coupled and decoupled designs depend on the sequence by which the DPs are changed to satisfy the given set of FRs.

The design matrix developed in Chapter 4 shows a decoupled design at the four levels, with some FRs that are uncoupled or independent (Figure 4-2, Chapter 4). Even though conditional probabilities are expected to be used for calculating the information content, in the case of the proposed integrated, BIM-based design process, the information content was calculated assuming the condition of independence for the FRs This assumption was made because of in the building design process, the probability of success of the later PVOs does not fully depend on the probability of success of the previous one as it is the case of the FR1.1 (Achieve Regulatory & Standard Compliance objective) and FR1.2 (Achieve a Design that Meets the Desired Level of O&M Efficiency objective). The building codes and standards provide the minimum standards for constructed facilities, with the purpose of protecting public health, safety and general welfare. Even though these minimum standards may include some aspects considered within the building O&M Efficiency objective, the achievement of FR1.1 does not necessarily guarantee the success of the achievement of FR1.2 and vice versa. In other words, FR1.1 can be achieved and yet don't meet FR1.2. The coupling condition between FR1.1 and FR1.2 is that codes and regulations should be reviewed and met at early stages to acquire design and construction permits and continue with the design process.

According with the above and following equation 7-14, the probabilities of success were calculated by using the probability density function and using the natural logarithm. For the DB process, the system range values were provided by CA through a questionnaire developed for this specific purpose, therefore, it is assumed they reflect the real project outcomes. The values under the design range, represent the design tolerances, and were established by the designer, based on a desired percentage of improvement (between the 30 to 40% of improvement).

The following is an example of the process followed to calculate the information content of FR1.1 Achieve Regulatory & Standard Compliance objective with its corresponding metric (Equation 7-2): %Time spent in reviewing the code = Total duration of codes reviews / Total duration of the design phase.

To determine the system range:

- Total hours spent in reviewing the design against the code = 10 hours min; and 40 hours min.
- Total duration in weeks since the design starts until the construction permits are obtained = 160 hours min; 480 hours max.

Therefore, the system range in percentage terms is (10/160)* (100) min, and (40/480)*(100) max. These are equal to 6.25% minimum to 8.33% maximum. Assuming the time until the building permits remains the same, the design range is defined as a

20% of improvement of the system range.
To determine the design range:
(10)*(.8)/160 hours min; and (40)*(.78)/480 hours max, resulting in 5.00% to 6.67%.

The design range is determined using the probability density function, assuming that all FRs have a uniform distribution, as shown in figure 7-2. Therefore, the common range is 42% and the probability of success of FR1.1 is 20% and the information content is 1.61 nats using natural logarithm. Note that if logarithm base two is used, it should be also used to calculate the IC of the remaining FR to be consistent with the units of bits.

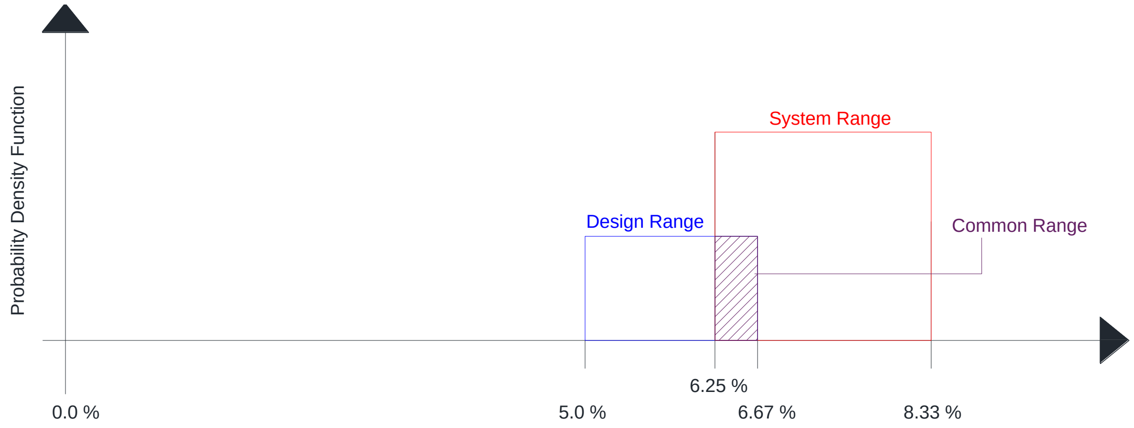


Figure 7-2 Graphic of the System range, Design range and Common range

Table 7-1 Calculation of the information content of the design-build process

Calculation of the Information Content for the DB process

FR	Description	Metric	System Range	Design Range	Probability of success: Comon range/System range	(1/P)	Information Content: Log Nat (1/P)
FR0	Produce a design of a building (effectively and efficiently)	% = Overall achievement of the PVO / expenses for producing the design					**12.98**
FR1	Achieve the desired value added of the design (3 objectives)	Customer satisfaction by predetermine survey					**3.53**
FR1.1	Achieve Regulatory & Standard Compliance objective	% = Total duration of codes reviews / Total duration of the design phase	6.25% to 8.33%	5.0% to 6.67%	20%	5.00	1.61
FR1.2	Achieve a design that meets the desired level of O&M efficiency objective	% = Cost of maintenability+cost of EC / Total cost of O&M	55% to 75%	50% to 65%	50%	2.00	0.69
FR1.3	Achieve a design that meets the desired level of constructability objective	% = Cost for Constructability RFI + change orders / Total Construction cost	23% to 47%	15% to 30%	29%	3.43	1.23
FR2	Reduce the cost (waste) in producing the design	% = Total value-added activities time / Total duration of the design process					**9.44**
FR2.1	Reduce unncessary transportation waste in the design process	% = Total duration of transpotation time / Total duration of the design meeting + transpotation time	17% to 80%	10% to 40%	37%	2.71	1.00
FR2.2	Reduce overproduction waste of drawings and specifications in the design process	% = Total value added time in producing builidng plans / Total time in producing builidng plans	75% to 83%	80% to 100%	40%	2.50	0.92
FR2.3	Reduce unnecessary motion waste in the design process	% = (# employees co-located / # total employees same office)+(% = # Complete rev / # Total rev)	0% to 25%	20% to 60%	20%	5.00	1.61
FR2.4	Reduce non-value added processing waste from using BIM in the design process	% = Total duration for developing BIM models / Total duration of the design phase	63% to 100%	44% to 70%	20%	5.00	1.61
FR2.5	Reduce defects waste of the design documentation in the design process	% = Number of plans pass first time / Total number of drawings	5% to 4%	4.9% to 15%	8%	11.90	2.48
FR2.6	Reduce waiting waste due to non-value added queues in the design process	% = Total waiting time for information / Total duration of the design phase	25% to 17%	9% to 18%	16%	6.25	1.83
					Information Content		**12.98**

Table 7-1 shows the twelve FRs used to calculate the information content of the DB process and their associated metrics. Some the numbers used in these calculations were based on assumptions since data was not directly provided by CA, mainly because the company does not keep track of all the metrics proposed in this research. The assumed data is highlighted in blue and was estimated based on the knowledge and learning of the DB process so that the information content could be calculated.

Table 7-2 Information content of the proposed integrated, BIM-based design process

Calculation of the Information Content for the integrated, BIM-based design process

FR	Description	Metric	System Range	Design Range	Probability of success: Comon range/System range	(1/P)	Information Content: Log Nat(1/P)
FR0	Produce a design of a building (effectively and efficiently)	% = Overall achievement of the PVO / expenses for producing the design					**2.93**
FR1	Achieve the desired value added of the design (3 objectives)	Customer satisfaction by predetermine survey					**1.68**
FR1.1	Achieve Regulatory & Standard Compliance objective	% = Total duration of codes reviews / Total duration of the design phase	5.81% to 7.75%	5% to 7%	44%	2.27	0.82
FR1.2	Achieve a design that meets the desired level of O&M efficiency objective	% = Cost of maintenability+cost of EC / Total cost of O&M	45.0% to 60.0%	50% to 65%	67%	1.50	0.41
FR1.3	Achieve a design that meets the desired level of constructability objective	% = Cost for Constructability RFI + change orders / Total Construction cost	18.0% to 37.0%	15% to 30%	63%	1.58	0.46
FR2	Reduce the cost (waste) in producing the design	% = Total value-added activities time / Total duration of the design process					**1.24**
FR2.1	Reduce unncessary transportation waste in the design process	% = Total duration of the desing meetings / Total duration of the design meeting + transpotation time	15.5% to 50.0%	10% to 40%	71%	1.41	0.34
FR2.2	Reduce overproduction waste of drawings and specifications in the design process	% = Total value added time in producing builidng plans / Total time in producing builidng plans	90% to 100%	80% to 100%	100%	1.00	0.00
FR2.3	Reduce unnecessary motion waste in the design process	(% = # employees co-located / # total employees same office)+(% = # Complete rev / # Total rev)	15% to 50%	20% to 60%	86%	1.17	0.15
FR2.4	Reduce non-value added processing waste from using BIM in the design process	% = Total duration for developing BIM models / Total duration of the design phase	50% to 80%	44% to 70%	67%	1.50	0.41
FR2.5	Reduce defects waste of the design documentation in the design process	% = Number of plans pass first time / Total number of drawings	8% to 10%	4.9% to 15%	100%	1.00	0.00
FR2.6	Reduce waiting waste due to non-value added queues in the design process	% = Total waiting time for information / Total duration of the design phase	13% to 10%	9% to 18%	71%	1.41	0.34
					Information Content		**2.93**

Table 7-2 shows the information content calculated for the proposed integrated, BIM-based design process. The design range values are the same as specified in the Table 7-1 for the DB process, this is to have a point of comparison. The values under the system range design are theoretical and are based on miscellaneous information obtained from a variety of sources published in the literature related to BIM performance statistical data using case studies where the value resulting from BIM applications is estimated in terms of percent of improvements for a specific project. Among these documents are the SMART Market Report, the AIA Integrated Project Delivery: Case Studies, BIM Handbook and the NBS National BIM Report 2015 and 2016.

7.4. Summary

In this chapter, AD's axiom two was presented leading to the evaluation of the information content of the DB process and the proposed integrated, BIM-based design process. Specific metrics were developed to quantitatively determine a range of values that the design process needs to achieve to satisfy a given FR. These metrics defined the system range (provided by the output of the system) and the design range (established by the designer as a percentage of improvement). The level of information content was calculated for FR1.1 through FR1.3 and for FR2.1 through FR2.6. The information of FR1 and FR2 is the sum the information content calculated for each of the corresponding FRs decomposed at the next level down. The information content of the total system or FR0 is the sum of the information content of FR1 and FR2.

The information content required to satisfy the PVOs (or FR0s) by the proposed integrated, BIM-based design process is lower than the information content that is needed by the DB process. An important note is that the values used in the calculation of the information content for the integrated, BIM-based design are approximate at this stage and need to be further refined through future research. However, a formal framework to evaluate the potential benefits of the proposed design approach has been established in this study through the use of AD. The set of values obtained in this study can be used as a benchmark to compare the proposed process against its benchmarks since a common range of values for each metric and its corresponding probability of success to achieve the desired goals or FRs have been established. This offers the possibility to continue monitoring the system over time, leading to a continuous process improvement

The metrics developed in this research are project based. Other metrics could be developed to determine the fulfillment of the FRs

8. CONCLUSIONS AND FUTURE WORK

8.1. Conclusions

It has been established that the decisions made at early stages of the design process have the highest impact on the project lifecycle cost and facility performance. For that reason, new project delivery systems, software tools and lean principles have emerged in the industry enhancing collaboration among project participants and reducing the existing gap between the design and construction phases. The increased use of Building Information Modeling (BIM) allows project participants to generate, manage and share information through a 3D digital model to better collaborate, communicate and understand the design intent. Still, design and construction professionals do not necessarily share their models and collaborate in an integrated fashion to accrue the benefits of an early involvement during design.

The design process is the most important stage of the building's life cycle because is in this stage where thousands of decisions are made which can greatly influence, positively or negatively, the subsequent processes and the quality of the final building. Several studies have pointed out that faulty designs or poor designs result in higher construction costs and buildings more expensive to operate and maintain, focusing on the improvement of the design process through the implementation of tools like lean, BIM and integrated practices.

This research uses the Axiomatic Design (AD) method to analyze some essential aspects of the design process integrating lean principles, BIM tools and the BIM Project Execution Plan in order to propose an improved process that seeks to produce better designs by adding value and reducing waste. The proposed approach is a BIM-based design integrated approach seeking compliance of the two AD axioms in order to achieve a more efficient and effective process that benefits not only the owner but also the design and construction professionals involved with the project. By seeking attainment of three major Project Value Objectives (PVO): 1) Regulatory and Standards Compliance Objective 2) Operation and Maintenance Efficiency Objective; and 3) Design and Construction Quality Objective, which in this document is referred as Constructability, the proposed approach increases value to the project and construction teams while reduces the waste in the design process.

AD is a systems design methodology that uses matrix methods to systematically analyze the transformation of customer needs into functional requirements, design parameters, and process variables. AD uses design principles or design axioms governing the analysis and decision making process in developing high quality product or system designs. More specifically, the use of AD in this research yields the following methodological benefits:

- To develop a better understanding of the requirements that affect the fulfillment of the project objectives and need to be explicitly considered in the design
- To treat BIM uses, design activities and waste in work flows in an explicit and systematic fashion through the use of design decomposition matrixes that relate project requirements with design parameters
- To clearly identify the degree of dependency between functional requirements and to eliminate these dependencies to the extent possible in a systematic fashion, thus reducing complexity in the design process and streamlining the order of execution of design activities.
- To provide a formal quantitative and reliable approach for the assessment of design process benefits by minimizing information content in the process.
- To use process information content as an index that relates the probability of success of meeting the main project objectives. This index can then be used to create benchmarks establish meaningful comparisons between alternative design processes, as well as to monitor the performance of the process and make adjustments or improvements.

In addition to the use of AD, this research conducted an extensive literature review and a case study of a Design-Build (DB) company in Worcester, Ma This work allowed the research to examine in-depth the current design process for institutional buildings and then, use this understanding to propose an integrated, BIM-based design process. As a result of the case study, the DB process was mapped and its information content was also calculated.

The proposed integrated, BIM-based design process, explicitly identifies uses of BIM and other practices as tools that assist the design process in the fulfillment of the main PVO and for reducing waste. More specifically these uses and practices are:

- BIM code validation process
- BIM process for creating drawings for building permits
- BIM project execution planning guide for identifying project participants
- BIM design reviews process for evaluating the space program
- BIM design reviews process for understanding the physical location of the equipment
- BIM design reviews process for evaluating the space and ergonomics requirements
- BIM design reviews process to create schedules to assess the degree of repetition/modularity of equipment
- BIM energy analysis process to assess the building energy operation costs
- BIM project execution planning guide for identifying project participants

- BIM phase planning (4D modeling)
- BIM Site utilization planning process
- BIM 3D coordination process
- BIM design reviews process to create schedules to assess the degree of repetition /modularity
- BIM process for creating drawings and specifications
- Use of virtual meetings during the building design process
- Use of digital information and prototypes in the building design process
- List of building's plans required according to the type of project and location
- Standardization of drawing information content
- Establishment of the appropriate level of design detailing for project type
- Co-location of the design team within the office area
- Creation design meeting’s agenda, schedule and minutes
- Establishment of the appropriate IT and software to use during the building design
- Establishment of the appropriate level of development of the BIM models - LOD document
- Inspection for completeness of drawings and specifications
- Inspection for accuracy of drawings and specifications
- Inspection for clarity of drawings and specifications
- Establishment of design milestones and times for checking
- Creation of data and document management system repository
- Establishment of information and communication mapping workflow in the design process
- Establishment of BIM information exchange protocol - BIM Execution Planning Guide

The Business Process Mapping Notation (BPMN) was used to make a graphic representation of the design processes work flow (the DB and the proposed BIM-based design process). This notation is proposed by the BIM Project Execution Planning Guide (CIC 2010), which was taken as the basis for the development of the proposal and allows to identify the parties responsible and involved in each BIM use, and to facilitate its future implementation.

Finally, twelve metrics are proposed to keep track on the process and assess performance eventually used to calculate the design process information content. The results of the calculation of the information content show that the BIM-based integrated design process yields a higher probability of success compared with the design-build process resulted from the case of study.

8.2. Future work

This research main contribution is to demonstrate how the use of BIM technology can produce better designs and therefore, deliver more value to the owner, design and construction teams, while allowing them to work more collaboratively and integrated. However, it has some limitations.

Although the assessment of the integrated, BIM-based design process was conducted through the calculation of the information content, it was done using theoretical (assumed) values. Therefore, to extend the current scope of the results of this research, the next step would be to complete the simulation of the proposed integrated, BIM-based design process, for validation of the execution times and number of iterations and assuring technical reliability of the process, so it can be compared against the DB process documented in Chapter 5 and other benchmarks.

The simulation consists in two parts. The first part is the mapping of the five BIM uses/processes in Arena®. The BIM processes are: code validation, design reviews for constructability and maintainability, 4D modeling, energy analysis, 3D coordination and site utilization planning. This part was successfully completed and the maps are included in Appendix J. The second part consists in collecting and determining data regarding the typical times of execution, amount of errors (if any), amount of rework and iterations, and the type of resources necessary to perform each of the BIM uses/processes. The execution times should considerate the use of other improvement tools and activities selected for reducing the waste (cost). All that data is then used to populate the simulation software.

The following steps are suggested for the simulation of the proposed integrated, BIM-based design process:

1. Gathering data of the execution times of the BIM processes implemented in this work (see list above)
2. Gathering data of the time reduced by the implementation of the activities that focus on reducing waste (see list above)
3. Populate the BIM processes in Arena® with the data obtain in the step 1 and 2 (if apply)
4. Replace the execution times of the DB process in Arena® for the new BIM execution times (resulted from step 3), as indicated in the process maps developed in Chapter 4
5. Replace the execution times in the corresponding boxes of the DB process in Arena® for the times resulted from the step 2
6. Once the DB process map in Arena® has the new execution times, the next step is to simulate the whole design process (SD, DD and CD maps)

7. Compare the results of the simulation with the results of the DB process

As a result of this work, the design team can get the benefits of implementing the selected BIM uses and other applications, as well as to easily improve the design process and measure the improvement by using the metrics proposed for the calculation of the information content. In addition, the project team can include another PVO by following the steps of the AD method used in this research and checking for CEME rule.

BIBLIOGRAPHY

Albano, L, (1992). An axiomatic Approach to Performance – Based Design, PhD Thesis, Massachusetts Institute of Technology (MIT), 1992

Alvarez S. (2014). Use of Building Information Modeling Technology in the Integration of the Handover Process and Facilities Management, PhD Thesis, Worcester Polytechnic Institute (WPI), 2014

Alvarez S. and Gomez M. (2012). Building Information Modeling during the Construction Phase, conducted as Independent Study at WPI, Fall 2012

Arditi D., and Nawakorawit M. (1999). Designing Buildings for Maintenance: Designers' Perspective. Journal of Architectural Engineering, Vol. 5, No. 4, December, 1999. ASCE, ISSN 1076-0431/99/0004-0107–0116

Ballard G. (2011). Target Value Design: Current Becnhmark. Lean Construction Journal 2011. Pp. 79-84. Retrieved from http://www.leanconstruction.org

BIMForum. (2013). Level of Development Specification.

Boecker J., Horst S., Keiter T., Lau A., Sheffer., Toevs B., R. B. (2009). The integrative Design guide to Green Building, Redefining the Practice of Sustainability. (I. John Wiley & Sons, Ed.). Hoboken, NJ, USA: John Wiley & Sons, Inc.

Brown C. (2006), Elements of Axiomatic Design: A Simple and Practical Approach to Engineering Design, Book Draft Chapter retrieved from http://www.axiomaticdesign.org/2008/ElementsofAxiomaticDesign.pdf

Brown C. (2011a). Approaching Design as a Scientific Discipline. In M. K. Thompson (Ed.), First International Workshop on Design in Civil and Environmental Engineering. Korea Advanced Institute of Science and Technology, KAIST.

Brown C. (2011b). Axiomatic Design for Understanding Manufacturing Engineering as a Science. Proceedings of the 21st CIRP Design Conference, Korea 2011 Interdisciplinary Design / Thompson, Mary Kathryn (Editor). KAIST, 2011. 239 p.

Brunsgaard C, Dvorakova P, Wyckmans A, Stutterecker W, Laskari M, Almeida M, Kabele K, Magyar Z, Bartkiewicz P. (2013). Integrated Energy Design – Education and Training in Cross-Disciplinary Teams Implementing Energy Performance of Buildings Directive (EPBD). Journal of Building and Environment, 72 (Octuber).

Burr K. (2011). What happened to the Master Builder? Implications for the Build Environment. International Journal of the Constructed Environment. 1(1), 1–14.

Chew M., Tan S., and kang K. (2004) Building Maintainability—Review of State of the Art. Journal of Architectural Engineering © ASCE / September 2004 10:80-87.

Computer Integrated Construction (CIC) Research Group (2010), BIM Project Execution Planning Guide 2.0, Department of Architectural Engineering. The Pennsylvania State University, July 2010.

Construction Industry Institute (CII). Constructability Concepts File, retrieved from https://www.construction-institute.org/scriptcontent/more/sp3_3_more.cfm, December 2015

Dimyadi J. and Amor R. (2013). Automated building Code Compliance Checking – Where is it at? 19th International CIB World Building Congress Conference Paper

Eastman C, Jae-min Lee, Yeon-suk Jeong, J. L. (2009). Automatic rule-based checking of building designs. ELSEVIER, July (18), 23.

Eastman C., Teicholz P, Sacks R, Liston K. (2011). BIM Handbook, a Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors. (John Wiley & Sons, Inc.) Second edition, Hoboken, New Jersey.

Faniran O., Lovel P., Treloar G., Anumba C., (2001). Methodological Issues in Design-Construction Integration. Journal in Logistics Information Management; 2001; 14, 5/6; pg. 421.

Flavell, E. (2011). The Master Builder: Historical Icon, Leadership and Management in Engineering, 11, 78–79.

Forbes, L., and Ahmed, S. (2011). Modern Construction: Lean Project Delivery and Integrated Practices. (L. Taylor and Francis Group, Ed.) (Second.). Boca Raton, FL: CRC Press.

Freire, L, and Alarcon, L. (2002). Achieving Lean Design Process: An Improvement Methodology. Journal of Construction Engineering and Management, ASCE, 128(3).

Frey D., Jahangir E., and Engelhardt F. (2000) Computing the Information Content of Decoupled Designs. Research in Engineering Design 12:90-102 Springer-Verlag London Limited, 2000

Green S, and May S., (2005). Lean Construction: Arenas of Enactment, Models of Diffusion, and the Meaning of Leanness. Journal of Building Research and Information, Vol. 33, No. 6, Taylor and Francis Group.

Group, C. R. (2010). BIM Project Execution Planning Guide 2.0. (Department of Architectural Engineering, Ed.) (July.). Pennsylvania State University.

Gyung-Jin Park (2007). Analytic Methods for Design Practice, Springer

Howard, H., Levitt R. E., Paulson B.C., Pohl J. G., and Tatum C. B., (1989). Computer Integration: Reducing Fragmentation in AEC Industry. Journal of Computing in Civil Engineering, 3(1).

Howell G and Ballard, G. (1998), Implementing Lean Construction: Understanding and Action, Proceedings of the International Group of Lean Construction (IGLC) 1998, Guajura, Brazil

Hungu C (2013). Utilization of BIM from early design stage to facilitate efficient FM operations M.S. thesis, Chalmers University of Technology, Goteborg, Sweden, 2013, http://publications.lib.chalmers.se/records/fulltext/183268/183268.pdf

Jergeas G., and Van der Put J. (2001). Benefits of Constructability on Construction Projects. Journal of Construction Engineering and Management, Vol. 127, No. 4, July/August, 2001. ASCE, ISSN 0733-9634/01/0004-0281–0290

Johannes Dimyadi; Robert Amor. (2013). Automated Building Code Compliance Checking - Where is it at? In 19th International CIB World Building Congress (p. 14). Australia.

Jorgensen B. (2006). Integrating Lean Design and Lean Construction: Processes and Methods. PhD Thesis submitted to the Technical University of Denmark. May 2006

Jorgensen B., and Emmitt S., (2007). Investigating the Integration of Design and Construction from a Lean Perspective. Construction Innovation. Emerald Publishing, 9(2).

Jorgensen B., Nielsen M., Stromann-Andersen J. (2011). Integrated Design – A Paradigm for the Design of Low-Wnwrgy Office buildings. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (www ashrae.org). Published in ASHRAE Transactions, Volume 117, Part 1.

Karna, S. (2004). Analyzing Customer Satisfaction and Quality in Construction – The Case of Public and Private Customers. Construction Economics and Management, Helsinki University of Technology, Finland.

Kent D, Becerik-Gerber B., (2010). Understanding Construction Industry Experience and Attitudes toward Integrated Project Delivery. Construction Engineering and Management ASCE, 136(8).

Ko C., and Chung N. (2014). Lean Design Process. Journal of Construction Engineering and Management, 06/2014, Volume 140, Issue 6 ASCE, 11. doi:10.1061/(ASCE)CO.1943-7862 .0000824

Koskela, L. (1992). Application of the New Production Philosophy to Construction. CIFE.

Kreider, Ralph G.; Messner, J. I. (2013). The Uses of BIM: Classifying and Selecting BIM Uses. Retrieved January 1, 2013, from http://bim.psu.edu

Kulak O., Cebi S., and Kahraman C. Applications of axiomatic design principles: A literature review. Expert Systems With Applications, 2010, Volume 37, Issue 9

Lawrence and Lorch 1967. "Differentiation and Integration in Complex Organizations", Administrative Science Quarterly, 12 (1).

Lean Construction Institute. (2004). What Is Lean Construction. Retrieved from http://www.leanconstruction.org/about-us/what-is-lean-construction

Maloney William F. (2002). Construction Product / Service and Customer Satisfaction. Journal of Construction Engineering and Management, ASCE, November /. doi:10.1061/~ASCE!0733-9364~2002!128:6~522

Mitropoulos M. (1994). Management-Driven Integration. Center for Integrated Facility Engineering (CIFE), Technical Report Number 96, July 1994, Stanford University.

Mitropoulos M.; and Tatum B. (2000). Management-Driven Integration. Journal of Management in Engineering. January/February 2000 16:48-58

Marzouk M., Bakry I., and El-Said M., (2011). Application of Lean Principles to Design Processes in Construction Consultancy Firms. International Journal of Construction Supply Chain Management, 1(1), 13.

Marzouk M., Bakry I., and El-Said M., (2012). Assessing Design Process in Engineering Consultancy Firms Using Lean Principles. Simulation: Transactions of the Society for Modeling and Simulation International. 88 (12) 1522-1536

Meng X. (2013). Involvement of Facilities Management Specialists in Building Design: United Kingdom Experience. Journal of Performance of Constructed Facilities © ASCE / September/October 2013

Moreno E. (2012). Advanced engineering design – An integrated approach. Philadelphia, PA.

Mounir E. A., Awad S. H.., Loh. W. (2013). Quantifying Performance for the Integrated Project Delivery System as Compared to Established Delivery Systems. Journal of Construction Engineering and Management, ASCE, 139(11).

Nam C.H., and Tatum F. (1992). Noncontractual Methods of Integration on Construction Projects. Journal of Construction Engineering and Management, Vol. 118, No. 2, June, 1992ASCE

Nawari, O. (2012a). The Challenge of Computerizing Buildings codes in BIM Environment. ASCE, 11(November), 8.

Nawari O. (2012b). Automated Code Checking in BIM Environment. In 14th International Conference on computing in Civil and Building Engineering (p. 8).

Nawari O. (2012c). Automating Codes Conformance. ASCE, 18(December), 9. doi:10.1061/(ASCE)

NBS National BIM Report 2015, RIBA Enterprises Ltd © 2015

NBS National BIM Report 2016, RIBA Enterprises Ltd © 2016

Nguyen, T.-H., and Kim, J-L. (2011). Building Code Compliance Checking Using BIM Technology. Proceedings of the 2011 Winter Simulation Conference (WSC), 2011, p. 3395 – 3400

O'Connor J., O'Brien W., Jarrah R., and Wallner B., (2007). Planning for, Facilitating, and Evaualting Design Effectiveness. Research Report 233-11 to Construction Industry Institute (CII) and the University of Texas at Austin, December 2007

Osman Kulak, Selcuk Cebi, C. K. (2010). Applications of axiomatic design principles: A literature review. ELSEVIER, 13.

Per Anker J. (2009) Design Integration of Facilities Management: A Challenge of Knowledge Transfer, Architectural Engineering and Design Management, 5:3, 124-135

Pietroforte R., and Miller. J. (2002). Procurement Methods for US Infrastructure: Historical Perspectives and Recent Trends. Building Research & Information, 30(6), 425–434.

Prentice, J. (2004). Spearin Doctrine's Effect on the A/E Construction Process. AACE International Transactions, 1(1), CD61.

Raposo A., Magalhaes L., Ricarte I., and F. H. (2001). Coordination of Collaborative Activities: A Framework for the Definition of Tasks Interdependencies. In Seventh International Workshop on Groupware, IEEE. IEEE.

Rauch E., Dallasega P., and Matt D. (2015). Axiomatic Design based Guidelines for the Design of a Lean Product Development Process. 9th International Conference on Axiomatic Design – ICAD 2015, Published by Elsevier

Reed W., and Gordon E. (2000). Integrated Design and Building Process: What research and Methodologies are needed? Building Research & Information, 28 (5-6). Taylor & Francis Ltd.

Sangwon Han, Sang-Hyun Lee, Pena-Mora F. (2012). Identification and Quantification of Non-Value-Adding Effort from Errors and Changes in Design and Construction Projects. Journal of Construction Engineering and Management © ASCE, (January). doi:10.1061/(ASCE) CO.1943-7862.0000406

Sanvido, V, Norton, V. (1994). Integrated Design Process Model. Journal of Management in Engineering ASCE, 10(5), 55–62.

Sayer N., and Anderson J., (2012). Status of Lean in the Construction Industry, Ryder Levett Buknall, July 2012

Senescu R., Haymaker, J., Meža, S., Fischer, M. (2013). Design Process Communication Methodology: Improving the Effectiveness and Efficiency of Collaboration, Sharing, and understanding. Journal of Architectural Engineering ASCE, 20(12), 1522–1536.

Shaikh Hafizur Rahman. (2015). A guideline to utilize automatic code checking capabilities of building information modelling applications simultaneously in the design cycle of building construction.

Shin G-B., Yi J-W., Yi S-I., Kwon Y-D., and Park G-J (2004). Calculation of Information Content in Axiomatic Design. Proceedings of ICAD2004 The Third International Conference on Axiomatic Design Seoul – June 21-24, ICAD-2004-22

Smart Market Report. (2012a). The Business Value of BIM in North America. McGraw Hill Construction, 72.

Smart Market Report. (2012b). The Business Value of BIM for Construction in Major Global Markets. McGraw Hill Construction.

Suh N. P. (1990). The Principles of Design (Oxford Series on Advanced Manufacturing). (O. U. P. USA, Ed.). New York, NY.

Suh N. P. (1998). Axiomatic Design Theory for Systems Research in Engineering Design (1998) Springer-Verlag London Limited

Suh N. P. (2001) Axiomatic Design: Advances and Applications. Oxford University Press, New York

Suh N. P. (2003) Complexity: Theory and Applications. Oxford University Press, MIT-Pappalardo series in mechanical engineering, 2005

The American Institute of Architects. (2007). Integrated Project Delivery: A Guide. California: The American Institute of Architects.

The American Institute of Architects. (2010). Integrated Project Delivery: Case Studies. Copyright 2010 AIA/AIA California Council, 1303 J Street, Suite 200, Sacramento, CA 95814

The American Institute of Architects. (2011). IPD Case Studies, AIA Minnesota, School of Architecture – University of Minnesota, February 2011

The American Institute of Architects. (2013). Emerging Professional's Companion, retrieved from http://www.aia.org

Thompson, M. (2013a). Challenges and Opportunities for Establishing Design as a Research Discipline in Civil and Environmental Engineering. Second International Workshop on Design in Civil and Environmental Engineering, June 28-29, 2013, WPI, Worcester, MA.

Thompson, M. (2013b). A Classification of Procedural Errors in the Definition of Functional Requirements in Axiomatic Design Theory. In ICAD 2013. The Seventh International Conference on Axiomatic Design. Worcester, MA.

Thompson, M. (2013c). Improving the Requirements Process in Axiomatic Design Theory. CIRP Annals-Manufacturing Technology 62 (1), 115-118, 2013

Tiwari S, Odelson J, Watt A, Khanzode A. (2009). Model Based Estimating to Inform Target Value Design. Building the Future, (August). Retrieved from Online Article by AECbytes

Towner, W. (2013). The Design of Engineering Education as a Manufacturing System. PhD Thesis, Worcester Polytechnic Institute (WPI).

Wilson L. (2010), How to Implement Lean Manufacturing, Book, McGraw Hill, United States

Yates, J., & Battersby, L. (2003). Master Builder Project Delivery System and Designer Construction Knowledge. Journal of Construction Engineering and Management, ASCE, 129(6).

Zimina D, Ballard G, Pasquire C. (2012). Target Value Design: Using Collaboration and a Lean Approach to Reduce Construction Cost. Construction Management and Economics 30:5, 383 – 398. DOI: 10.1080/01446193.2012.676658

Appendix A. Axiomatic Design (AD)

Axiomatic Design (AD) is a design methodology developed in the field of mechanical engineering by Suh in 1970, which was well-established in 1990 and has been gaining popularity in other areas since then. Currently, AD has been widely applied and adopted in the field of mechanical engineering, as well as in manufacturing industry, and product design. According with Thompson (Thompson 2013b) in the construction industry, AD is still considered to be in a more theoretical level, although it has been used for architectural and structural design, urban planning, transportation, and water resource management. An example in the area of structural design is the research work developed by Albano in 1992 (Albano, 1992), in which AD approach is used for developing a performed-based design process for the design of structural systems. Then, the proposed process was theoretically applied to a case study.

The methodology of AD has three important elements: the axioms, the structure, and the zigzagging decomposition process. Axioms are statements that are so evident that are accepted and considered true until otherwise is proven. AD methodology is based two axioms, and all good design is consistent with these two axioms (Suh 1990, Brown 2011):

- Axiom 1 – the Independence Axiom, which seeks to maintain the independence of the Functional Requirements (FRs), and the design adjustable and controllable.
- Axiom 2 – The Information Axiom, which seeks to minimize information content of the design, and to identify the best design as the one that satisfies axiom 1 with the highest probability of success.

The second important element in AD method is the structure. The structure is made up by the domains or lateral decomposition and the hierarchy or vertical decomposition (Brown 2011). The lateral decomposition lies between four domains: customer, functional, physical, and process domains. Figure A-1 below shows the four domains of AD which are related according to this established order: if one domain represents what needs to be achieved, the next one represents how to achieve it. The customer domain is characterized by the identification of Customer Needs or CN (what adds value to the project), the functional domain is characterized by Functional Requirements or FRs, which are the minimum set of independent requirements that completely characterize the functions needed to attain value for the owner, the physical domain represents the Design Parameters or DPs which provide the physical solution that meet the FRs, and the process domain represents the Process Variables or PVs which are the process solution, which establish the steps or requirements of the process that can generate the specified DPs.

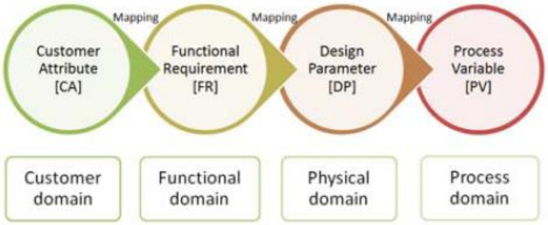


Figure A-1. Domains of Axiomatic Design (Gilbert et al. 2013)

The second element of the AD structure is the vertical decomposition. Vertical decomposition is hierarchical, and is used to solve problems by breaking it down into parts that are easier to understand and to solve. Essentially, in AD, the vertical decomposition is the development of the FRs in levels that go from general to specifics, like a building that can be decomposed into public and private area, the public areas can be decomposed in exterior and interior public areas, which can be decomposed into the specific spaces like gardens, parking, and so on. In this sense, a good definition of the FRs is very important, since they are a reformulation of the CNs, they must represent the desired functions that the design should accomplish and explicitly define the problem to be solved and guide its solution (Brown, 2006; Thompson, 2013).

A decimal notation is used to name the FRs at each level, so that, the top (highest) FR is FR0. When FR0 is decomposed into FR1 and FR2 at the upper level, then it becomes the parent and the FR1 and FR2 become the children of FR0. The same apply if FR1 is decomposed into FR1.1, FR1.2 and FR1.3, the latest become children of FR1. In addition, the decomposition of FRs at each level should be Collectively Exhaustive and Mutually Exclusive (CEME). The first refers that the sum[13] of the children must be equal to the parent and assures that everything is included in the decomposition. The second refers that each children is different and independent assuring there is no overlapping between them.

Finally, the third important element in this methodology is the zigzagging decomposition shown in figure A-2, which is the process of defining the FRs on one level and selecting DPs to satisfy these FRs, then, going back to define the FRs at the next lower level. This process continues down each of the braches until the solution is obvious. This process is important because the DPs selected at one level provide constraints on the design at a lower levels (Brown 2006)

---

[13] Sum in AD methodology refers to the addition, all children together are equal to the parent – Elements of Axiomatic Design, Brown 2006

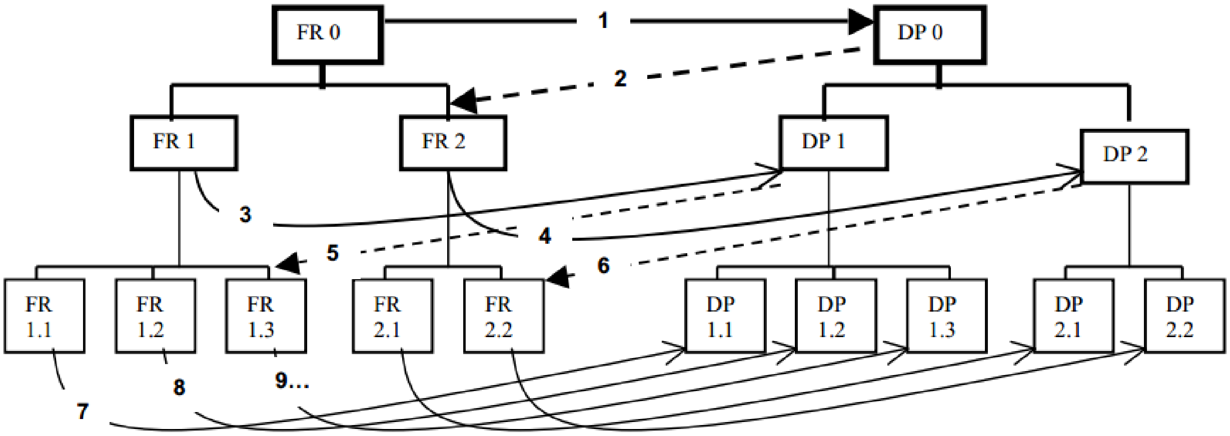
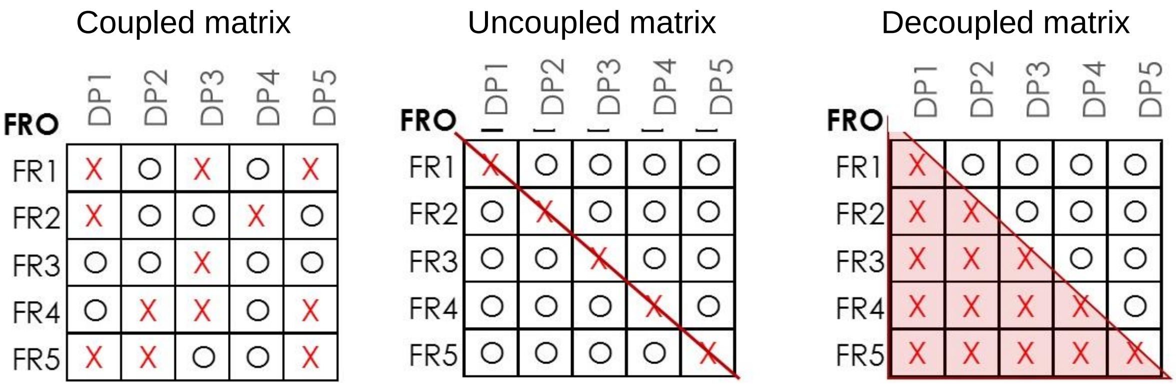


Figure A-2. AD Zigzagging Process (Brown 2006)

Axiom one, the independence axiom

Once the DPs are selected at one level, the AD method suggests to use a matrix method to analyze the decomposition and the relationship between the FRs and their corresponding DPs. This process allows for the evaluation of the possible solutions while maintaining the independence of the FRs, and therefore, axiom 1 compliance. There are three different kinds of design matrices, shown in figure A-3, which represent the degree of dependency between DPs and FRs and the level of complexity of design:

- **The coupled matrix**, which is when one or more DPs affect one or more FRs, making the design dependent. This solution doesn't comply with axiom 1, therefore is considered an unacceptable solution and further iteration of DPs or the selection of other DPs are needed.
- **The uncoupled matrix**, which is distinguished by having a diagonal solution where each DP affects only one FR. The diagonal matrix is considered to be the best solution because represents a design solution that is independent, adjustable and controllable, therefore, complies with axiom 1.
- **The decoupled matrix**, which is distinguish by a triangular solution, when one or more DP might affect one or more FR, but still allows to solve the problem without further iterations by adjusting the FRs in the right order. This is considered to be an acceptable solution by following the right implementation sequence.



Coupled matrix

FRO	DP1	DP2	DP3	DP4	DP5
FR1	X	O	X	O	X
FR2	X	O	O	X	O
FR3	O	O	X	O	O
FR4	O	X	X	O	X
FR5	X	X	O	O	X

Uncoupled matrix

FRO	DP1	DP2	DP3	DP4	DP5
FR1	X	O	O	O	O
FR2	O	X	O	O	O
FR3	O	O	X	O	O
FR4	O	O	O	X	O
FR5	O	O	O	O	X

Decoupled matrix

FRO	DP1	DP2	DP3	DP4	DP5
FR1	X	O	O	O	O
FR2	X	X	O	O	O
FR3	X	X	X	O	O
FR4	X	X	X	X	O
FR5	X	X	X	X	X

Figure A-3 Types of design matrices

Axiom two, the information axiom

During the decomposition process decisions are made to select a DP that satisfy its corresponding FR. These decisions are then evaluated using the matrix method in order to comply with axiom 1 or the independence axiom. However, the design effort may produce several solutions that satisfy axiom 1. When this happens, the information axiom or axiom 2 can be used to select the best design, since it provides a quantitative measure of the merits of a given design. Once the best design solution is selected, axiom 2 can also be used for design optimization and robust design (Suh, 2003).

The information axiom states that the design with less information content has the highest probability of success of achieving the goals expressed by the FRs, and therefore, is the best design. The information content is expressed in equation A-1, where "I" is the information content of a given FR and "P" is the probability of satisfy that FR:

$$I_{FR1} = \log \frac{1}{P_{FR1}}$$

Then, the information content for the entire system with *m* FRs is represented in the equation below:

$$I_{SYS} = \log \frac{1}{P_{FRm}}$$

The system probability density function (PDF) is used to determine the probability of success of a given FR, since the probability of success is governed by the intersection of the design range defined by the designer to satisfy the FRs and the ability of the system to produce the part within the specified range or system range (Suh 2003). If they don't intersect each other, then the probability of success will be cero or close to cero, and the information content will be infinite. This means that the design solution is complex. Therefore, the probability of success can be computed by specifying the design range or tolerances for each FR and by determining the system range that the proposed DPs can provide to satisfy their corresponding FRs. Tolerances are characteristics of the functional requirements that can influence the quality and cost of the final solution and are needed to calculate the information content.

Appendix B. First Approach to AD Decomposition

This section discusses the first results of the application of axiomatic design method to the development of a building design process. This design decomposition evolved until reach the final decomposition presented in this document in Chapter 4.

For the first decomposition, this study proposed the development of an integrated design process for building projects that identifies and delivers the best value design solution, among all possible solutions. The best value design solution would be the one that delivers more customer satisfaction using least amount of resources[14]. Following the statement above, the top level functional requirements proposed are:

- FR0 = Deliver the Best Design Value Solution
    - FR1 = Maximize the Customer Satisfaction
    - FR2 = Minimize Resource Consumption

To further decompose FR1, the eleven project value objectives (PVO) identified by the Construction Industry Institute (CII) in the Design Effectiveness (DE) research work were used as starting point, since they serve as the major categories of all project outcome parameters. Therefore, as higher these objectives are met, the higher will be the customer satisfaction. Regarding FR2, the most common design issues found in the literature review were used as a starting point.

Figures B-1 and B-2 show the first decomposition developed at the beginning of this study. This decomposition changed over the time as the methodology of axiomatic design was learned. Several principles of the AD methodology were violated in this first decomposition, among which are that the major stakeholders were not identified. In the construction industry, it is common to identify the owner of the project and the buyer as the main customers, however, in a wider perspective, as the customers of the building design process are designers, contractors, subcontractors, owner, final users and society.

Another principle of AD that was not met in this decomposition was the mutually exclusively and collectively exhaustive rule, since the eleven PVO are not completely independent and they overlap. In addition, the waste identified for FR2 are not collectively exhaustive since it doesn't cover the full range of waste in the building design process.

Finally, it was concluded and advised to reduce the amount of PVO to include in this research, to reduce the complexity of the decomposition and the design matrix and due

---

[14] Value, in the context of this research, is defined as the measure of satisfaction of the customer per unit of resources consumed.

to time constraints.

	Functional Requirements
FR0	Produce a project design solution with the highes value
FR1	Maximize customer satisfaction (based on project objectives)
FR1.1	Provide conditions of security
FR1.2	Provide Operation and Maintenance Safety Conditions
FR1.3	Provide Construction Safety Conditions
FR1.4	Provide Regulatory and Standar Compiance
FR1.5	Provide Capital Cost Efficiency
FR1.6	Provide OM efficiency
FR1.7	Provide Product/Plant/Service Quality
FR1.8	Provide Design and Construction Quality
FR 1.8.1	Provide accurate, clarity and complete drawings and information
FR 1.8.2	Provide Constructability
FR1.8.2	Address physical interferences between systems
FR1.8.2	Address interferences in the construction sequence
FR1.8.2	Address site logistics (material, equipment, and personel access)
FR1.8.2	Address site analysis
FR1.8.2	Address site impact
FR 1.8.3	Facilitare Procurabiliy
FR 1.8.4	Provide Accurate Existing Conditions
FR 1.8.5	Provide Packaging of Construction Contract and Subcontracts
FR1.9	Provide Conditions for Schedule Reduction
FR1.10	Provide Enviromental Stewardship
FR1.11	Provide Conditions for Flexibility for Future Use
FR2	Minimize cost of producing the project design
FR2.1	Reduce Waiting waste in design
FR2.2	Reduce Rework caused by errors and changes
FR2.3	Reduce Amount of Design Revisions

Figure B-1 Functional requirements of the first approach to the AD decomposition

Design Parameters

DP0	System for producing a design project
DP1	System that maximizes value to the project through project's objectives
DP1.1	System for providing Conditions of Security
DP1.2	System for providing OM conditions
DP1.3	System for provide construction safety conditions
DP1.4	System for provide Regulatory and Standar Compliance
DP1.5	System for provide Capital Cost Efficiency
DP1.6	System for provide OM efficiency
DP1.7	System for provide product/plant/service quality
DP1.8	System for provide design and construction quality
DP1.8.1	System for providing accurate, clarity and complete drawings and information
DP1.8.2	System for addressing/facilitationg constructability
DP1.8.2.	System for addressing physical interferences between systems (3D coordination process)
DP1.8.2.	System for addressing interferences in the construction sequence (Phase Planning / 4D modeling)
DP1.8.2.	System for addressing interferences in the construction site (Site Utilization Planning)
DP1.8.2.	System for addressing the availability of site utilities (Site Analysis)
DP1.8.2.	System for addressing impact of adjacent constructions (Existing Conditions Modeling)
DP1.8.3	System for addressing/facilitating procurability
DP1.8.4	System for providing accurate existing conditions
DP1.8.5	System for providing packaging of construction contract and subcontracts
DP1.9	System for provide conditions for schedule reduction
DP1.10	System for provide enviromental stewardship
DP1.11	System for provide conditions for flexibility for future use
DP2	System that minimizes cost of producing the project design
DP2.1	System for reducing waiting waste in design due to non-value added activities
DP2.2	System for reducing rework caused by erros and changes
DP2.3	System for reducing the amount of design revisions

Figure B-2 Design parameters of the first approach to the AD decomposition

Appendix C.
Project Value Objectives (PVO) Definitions and BIM Forum surveys

This section presents a short definition developed in this work to define and describe the eleven Project Value Objectives (PVO) proposed by the Construction Industry Institute (CII, 2009). These definitions were given to the responders for the PVO selection process.

Project value objectives (PVO) definitions

The project objectives are those identified as the specific benefits the owner wants from the project (desired benefits). Those are usually prioritized depending on what the customer wants, what the team project is capable of delivering, and on the project characteristics.

- Security (for building occupants and assets, and security during construction)

Security is the degree of resistance to, or protection from, harm. Effective secure building design involves implementing countermeasures to deter, detect, delay, and respond to attacks from human aggressors or natural hazards. It also provides for mitigating measures to limit hazards to prevent catastrophic damage and provide resiliency should an attack occur.

Security during construction implies that plans and specifications have information about perimeter fencing, gates and locks, signage, Site lighting, office trailers and temporary buildings, storage containers, and motorized equipment.

- Operation and Maintenance Safety

Building design reflects or encourages safety for the worker, the public, and the environment. For example workers must be trained to follow some basic steps and avoid dangerous activities, because in all of their jobs, the workers are exposed to potentially deadly hazards.

- Construction Safety

Construction site safety is an area of concern for employers of construction workers. It has often been regarded the sole responsibility of the construction contractor, however the safety performance on a project may well be dictated to a large extent by decisions made by the designer. The objective is to avoid construction site injuries.

- Regulatory and Standards Compliance

Codes that regulate the design and construction of buildings by law. A Building code is a set of rules that specify the minimum standards for constructing buildings.

- Capital Cost Reduction

Cost to produce a building effectively with a minimum amount expense/cost, or unnecessary effort.

- Operation and Maintenance Efficiency

How the building design consider or includes features to reduce costs of operation and maintenance for the building to be profitable/economically viable, by optimizing the use of the space, including high efficiency features and materials.

- Product/Plant/Service Quality

Quality is defined as "conformance to established requirements." The quality of the elements directly related to the physical building itself. It refers to achieving quality in the materials, equipment, and technology that go into the building of a structure, and it also refers to the customer satisfaction and how the end product and service satisfies the customer requirements.

- Design and Construction Quality

Quality is defined as "conformance to established requirements." Quality of design refers how the design is constructible. Constructability is the optimum use of construction knowledge and experience in planning, engineering, procurement, and field operations to achieve overall objectives". The concepts promote construction-driven schedules, simplified design configurations, standardization of elements, and module/preassembly designs which facilitate fabrication, transport, and installation. Concepts also address the accessibility of manpower, materials, and equipment; design modifications to facilitate construction in adverse weather; and specification improvement. The input of construction knowledge and experience into the planning and design of a project can result in reduced install cost and improve safety during construction.

Quality of construction mainly refers to quality, accuracy and completeness of design drawings, the frequency of design changes and request for information (RFI) during construction, as well as inspecting the quality of the materials (testing).

- Schedule Reduction

Reduce time for project development.

- Environmental Stewardship

This is when owners want to achieve LEED (Leadership for Energy and Environmental Design) certification or environmentally friendly buildings, by minimizing the use of resources, waste, emission, etc.; maximizing the use of recycled materials, re-use, and use of environmentally friendly features; improve/minimize the harm made to the environment; uses alternative energies (solar panels, wind energy, etc.).

- Flexibility for future use

Flexibility for future use is the flexibility/ability of the building to change the use of a space over the time, thereby increasing building longevity and reducing waste. It also includes having savings of low renovations costs or by reducing the number of renovations. The concept of Flexibility includes modularity, adaptive re-use, renovation, dual use, and churn.

References:

Principles of Construction Safety by Allan St John Holt
Facilities Management: Managing Maintenance for Buildings and Facilities by Joel Levitt

First Question

The BIMForum is conducting research to develop solid metrics to compare and contrast process performance in the design and construction industry.

Our October Conference discusses the concept of Construction Optimization and we would like to collect your views and thoughts with regards to this concept before the conference takes place. Therefore we are asking you to respond to this short survey. It may take you no more than 10 minutes. The results of the survey will be presented at the conference.

This research is supported by students and faculty from Worcester Polytechnic Institute and Norwich University.

Which one of the following best describes your company?

○ Architect
○ Engineer
○ General Contractor/Construction Manager
○ Specialty Contractor / Fabricator
○ Owner/Developer/Property Manager
○ Other (Please Specify)

Block 2

Among companies of your type, what size is your company? (select one)

○ Small (professional fees under 500K)
○ Medium (professional fees $500K to $5M)
○ Large (professional fees over $5M)

Block 5

How frequently do you specifically attempt to enable or optimize construction in your designs?

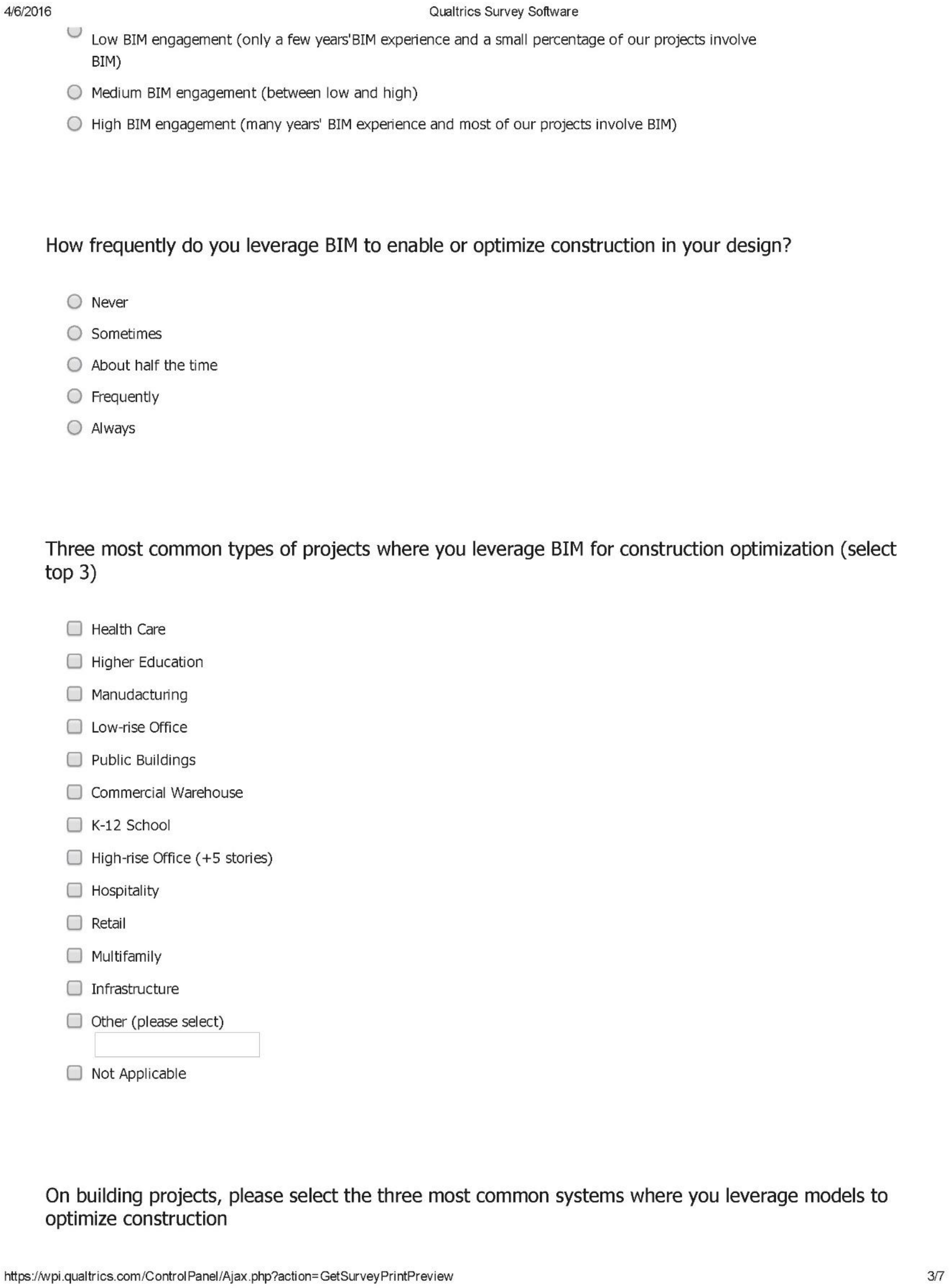
○ Never
○ Sometimes
○ About half the time
○ Frequently
○ Always

Top three reasons for your company engaging in construction optimization (select top three reasons)

☐ Improve Safety
☐ Improved Productivity
☐ Competitive Advantage
☐ Customer Driven Needs
☐ Improve Supply Chain Management
☐ Supports Principles of Sustainability
☐ Schedule Conformance
☐ Cost Reduction
☐ Enhance Decision Making Process
☐ Improve Resource Management (People/Material)
☐ Other (please specify)
☐ Not Applicable

How engaged is your company with BIM? (select one)

○ My company is not involved with BIM



○ Low BIM engagement (only a few years'BIM experience and a small percentage of our projects involve BIM)

○ Medium BIM engagement (between low and high)

○ High BIM engagement (many years' BIM experience and most of our projects involve BIM)

How frequently do you leverage BIM to enable or optimize construction in your design?

○ Never

○ Sometimes

○ About half the time

○ Frequently

○ Always

Three most common types of projects where you leverage BIM for construction optimization (select top 3)

☐ Health Care

☐ Higher Education

☐ Manudacturing

☐ Low-rise Office

☐ Public Buildings

☐ Commercial Warehouse

☐ K-12 School

☐ High-rise Office (+5 stories)

☐ Hospitality

☐ Retail

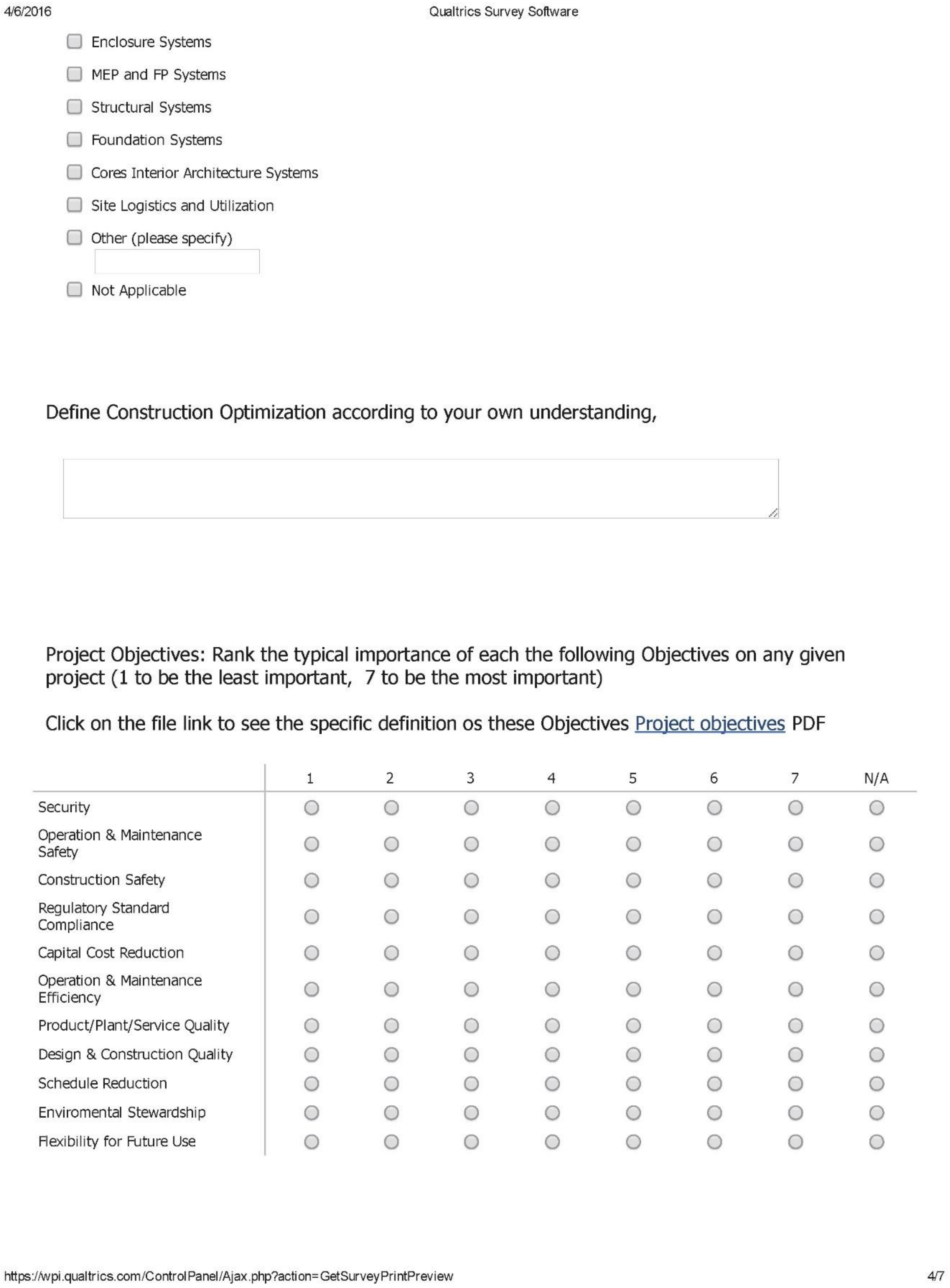
☐ Multifamily

☐ Infrastructure

☐ Other (please select)

☐ Not Applicable

On building projects, please select the three most common systems where you leverage models to optimize construction



☐ Enclosure Systems

☐ MEP and FP Systems

☐ Structural Systems

☐ Foundation Systems

☐ Cores Interior Architecture Systems

☐ Site Logistics and Utilization

☐ Other (please specify)

☐ Not Applicable

Define Construction Optimization according to your own understanding,

Project Objectives: Rank the typical importance of each the following Objectives on any given project (1 to be the least important, 7 to be the most important)

Click on the file link to see the specific definition os these Objectives [Project objectives] PDF

	1	2	3	4	5	6	7	N/A
Security	○	○	○	○	○	○	○	○
Operation & Maintenance Safety	○	○	○	○	○	○	○	○
Construction Safety	○	○	○	○	○	○	○	○
Regulatory Standard Compliance	○	○	○	○	○	○	○	○
Capital Cost Reduction	○	○	○	○	○	○	○	○
Operation & Maintenance Efficiency	○	○	○	○	○	○	○	○
Product/Plant/Service Quality	○	○	○	○	○	○	○	○
Design & Construction Quality	○	○	○	○	○	○	○	○
Schedule Reduction	○	○	○	○	○	○	○	○
Enviromental Stewardship	○	○	○	○	○	○	○	○
Flexibility for Future Use	○	○	○	○	○	○	○	○

The following practices have been identified by the CII as processes that, when executed effectively, lead to enhanced project performance.

Rank the importance of each of the following practices in improving project performance (1 to be the least important, 7 to be the most important).

Click on the file to see a more detailed definition of these practices CII processes to enhance PP

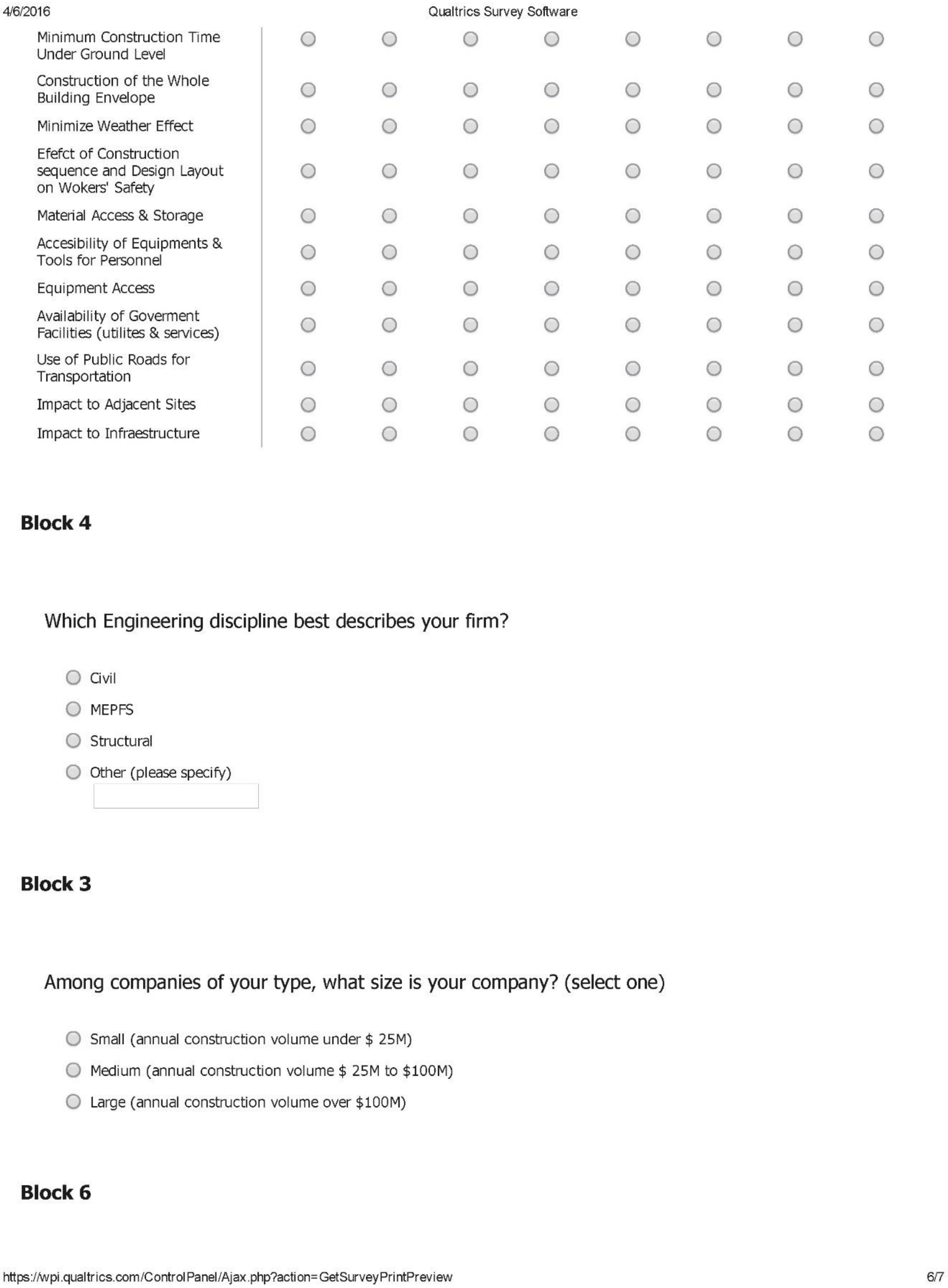
	1	2	3	4	5	6	7	N/A
Alignment	○	○	○	○	○	○	○	○
Benchmarking and Metrics	○	○	○	○	○	○	○	○
Change Management	○	○	○	○	○	○	○	○
Constructability	○	○	○	○	○	○	○	○
Disputes Prevention and Resolution	○	○	○	○	○	○	○	○
Front End Planning	○	○	○	○	○	○	○	○
Lessons Learned	○	○	○	○	○	○	○	○
Materials Management	○	○	○	○	○	○	○	○
Partnering	○	○	○	○	○	○	○	○
Planning for Startup	○	○	○	○	○	○	○	○
Project Risk Assessment	○	○	○	○	○	○	○	○
Quality Management	○	○	○	○	○	○	○	○
Team Building	○	○	○	○	○	○	○	○
Zero Accidents Techniques	○	○	○	○	○	○	○	○

The following factors have been identified as those that affect/impact constructability.

Rank the importance of each the following factors in improving project constructability (1 to be the least important, 7 to be the most important).

click on the file link to see a more detailed definition of these practices Factors that affects constructability

	1	2	3	4	5	6	7	N/A
Prefabrication	○	○	○	○	○	○	○	○
Grid Layout	○	○	○	○	○	○	○	○
Standard Dimensions	○	○	○	○	○	○	○	○
Resource Availability	○	○	○	○	○	○	○	○
Components' Flexibility	○	○	○	○	○	○	○	○
Availability of Special Labor Skills	○	○	○	○	○	○	○	○
Construction Sequence	○	○	○	○	○	○	○	○



Minimum Construction Time Under Ground Level	○	○	○	○	○	○	○	○
Construction of the Whole Building Envelope	○	○	○	○	○	○	○	○
Minimize Weather Effect	○	○	○	○	○	○	○	○
Efefct of Construction sequence and Design Layout on Wokers' Safety	○	○	○	○	○	○	○	○
Material Access & Storage	○	○	○	○	○	○	○	○
Accesibility of Equipments & Tools for Personnel	○	○	○	○	○	○	○	○
Equipment Access	○	○	○	○	○	○	○	○
Availability of Goverment Facilities (utilites & services)	○	○	○	○	○	○	○	○
Use of Public Roads for Transportation	○	○	○	○	○	○	○	○
Impact to Adjacent Sites	○	○	○	○	○	○	○	○
Impact to Infraestructure	○	○	○	○	○	○	○	○

Block 4

Which Engineering discipline best describes your firm?

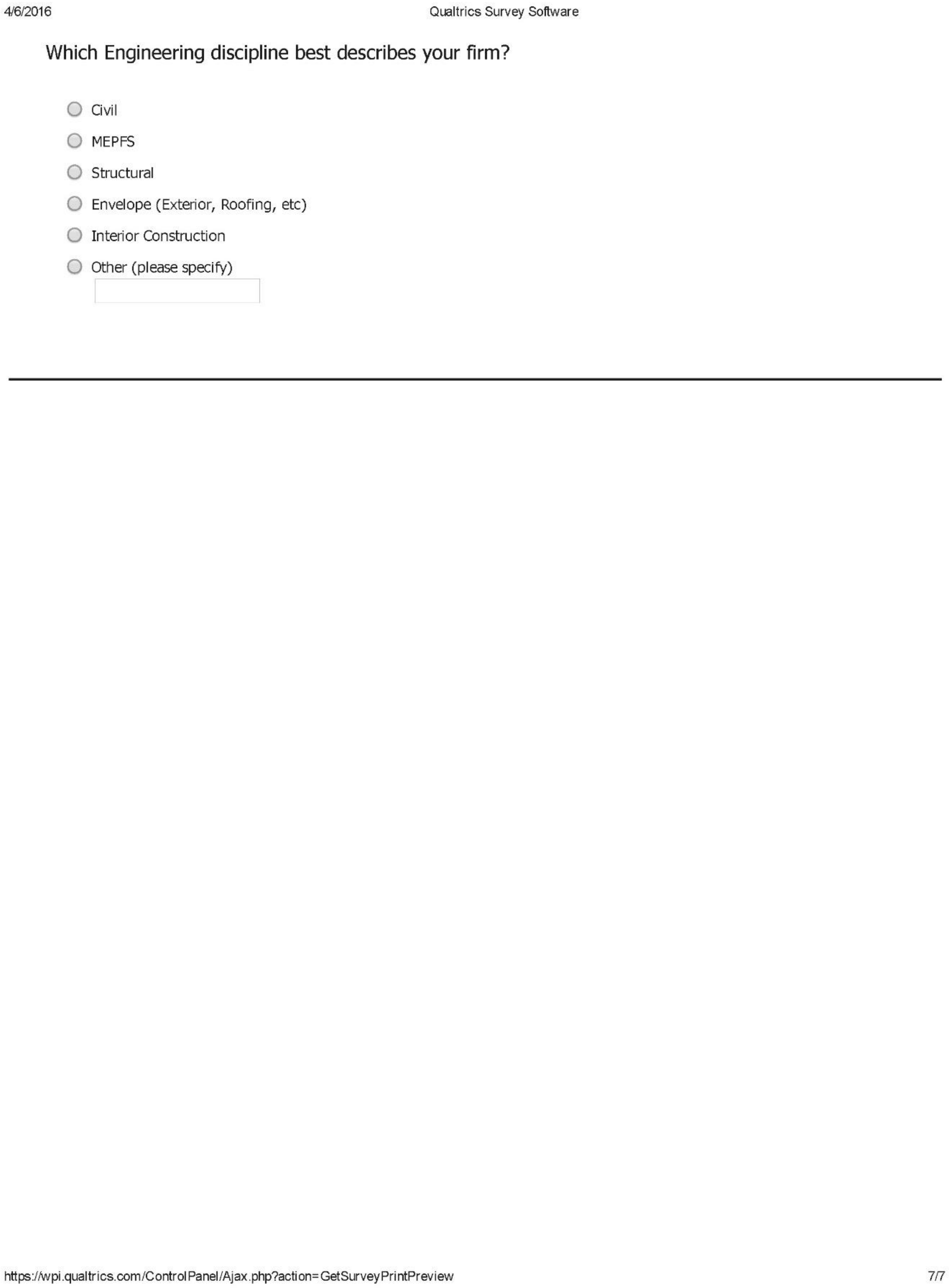
- ○ Civil
- ○ MEPFS
- ○ Structural
- ○ Other (please specify)

Block 3

Among companies of your type, what size is your company? (select one)

- ○ Small (annual construction volume under $ 25M)
- ○ Medium (annual construction volume $ 25M to $100M)
- ○ Large (annual construction volume over $100M)

Block 6

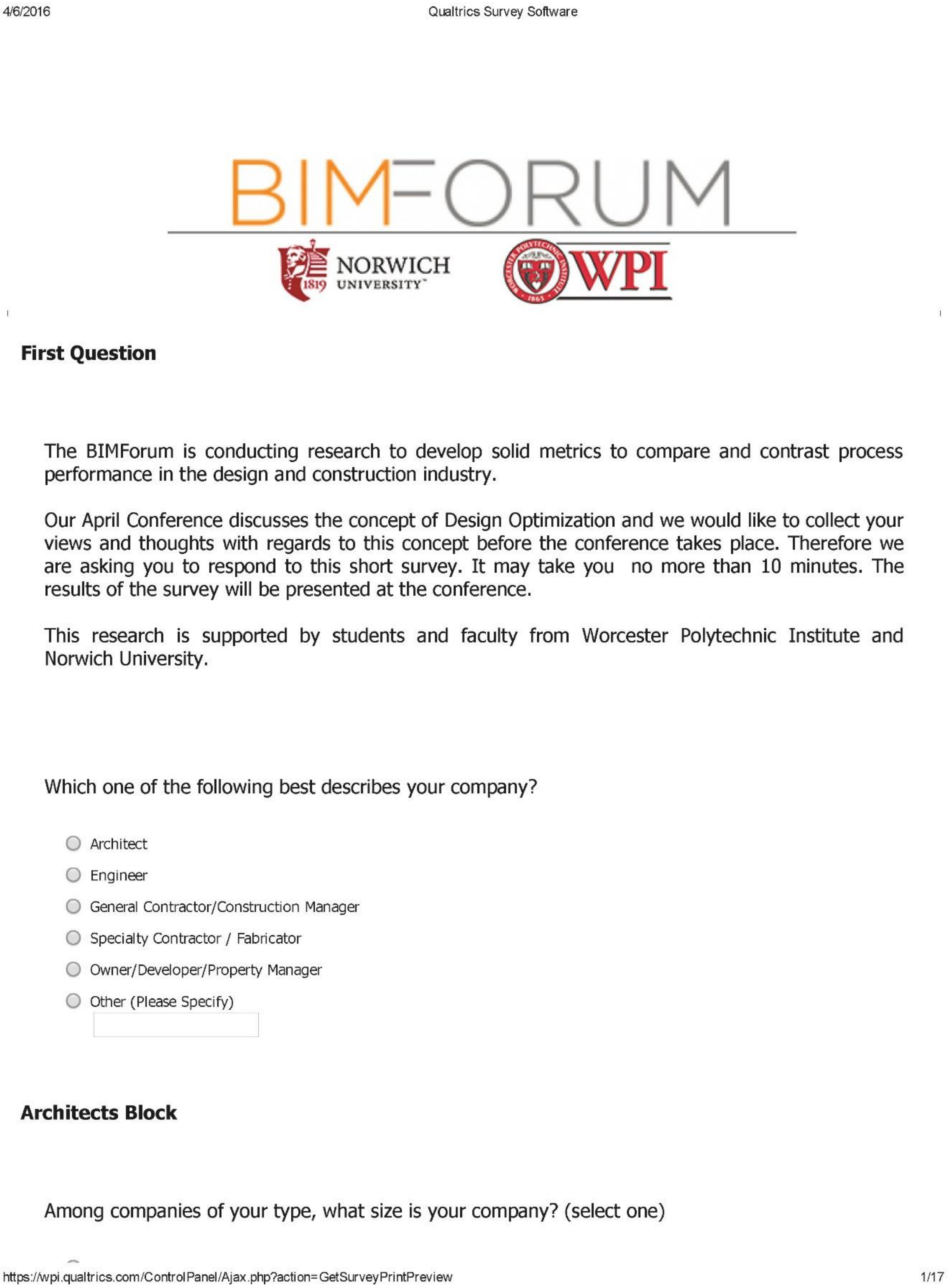


4/6/2016 Qualtrics Survey Software

Which Engineering discipline best describes your firm?

- ○ Civil
- ○ MEPFS
- ○ Structural
- ○ Envelope (Exterior, Roofing, etc)
- ○ Interior Construction
- ○ Other (please specify)

https://wpi.qualtrics.com/ControlPanel/Ajax.php?action=GetSurveyPrintPreview 7/7



BIMFORUM

NORWICH UNIVERSITY 1819

WPI

First Question

The BIMForum is conducting research to develop solid metrics to compare and contrast process performance in the design and construction industry.

Our April Conference discusses the concept of Design Optimization and we would like to collect your views and thoughts with regards to this concept before the conference takes place. Therefore we are asking you to respond to this short survey. It may take you no more than 10 minutes. The results of the survey will be presented at the conference.

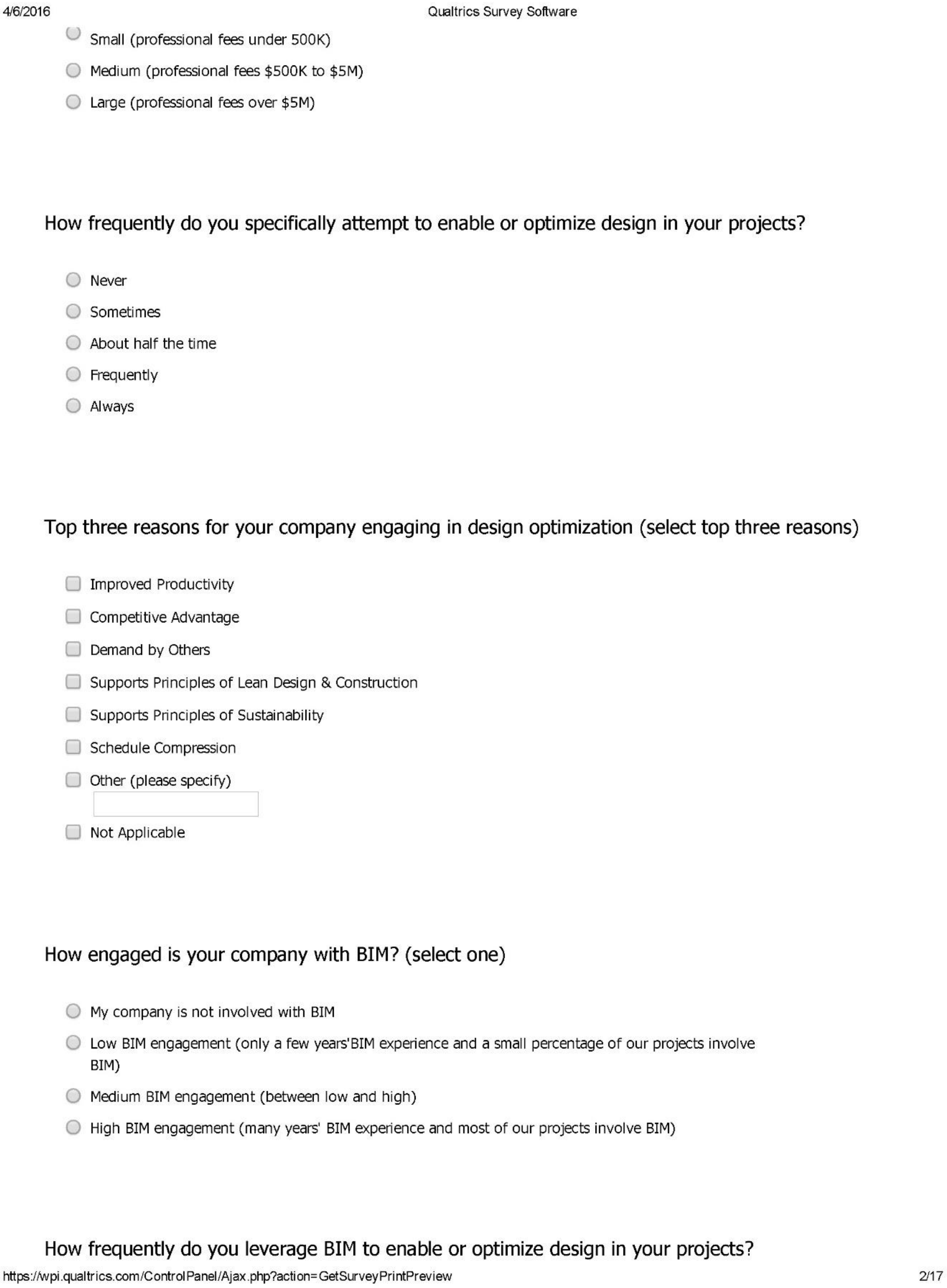
This research is supported by students and faculty from Worcester Polytechnic Institute and Norwich University.

Which one of the following best describes your company?

- ○ Architect
- ○ Engineer
- ○ General Contractor/Construction Manager
- ○ Specialty Contractor / Fabricator
- ○ Owner/Developer/Property Manager
- ○ Other (Please Specify) ☐

Architects Block

Among companies of your type, what size is your company? (select one)



○ Small (professional fees under 500K)
○ Medium (professional fees $500K to $5M)
○ Large (professional fees over $5M)

How frequently do you specifically attempt to enable or optimize design in your projects?

○ Never
○ Sometimes
○ About half the time
○ Frequently
○ Always

Top three reasons for your company engaging in design optimization (select top three reasons)

☐ Improved Productivity
☐ Competitive Advantage
☐ Demand by Others
☐ Supports Principles of Lean Design & Construction
☐ Supports Principles of Sustainability
☐ Schedule Compression
☐ Other (please specify)
☐ Not Applicable

How engaged is your company with BIM? (select one)

○ My company is not involved with BIM
○ Low BIM engagement (only a few years'BIM experience and a small percentage of our projects involve BIM)
○ Medium BIM engagement (between low and high)
○ High BIM engagement (many years' BIM experience and most of our projects involve BIM)

How frequently do you leverage BIM to enable or optimize design in your projects?

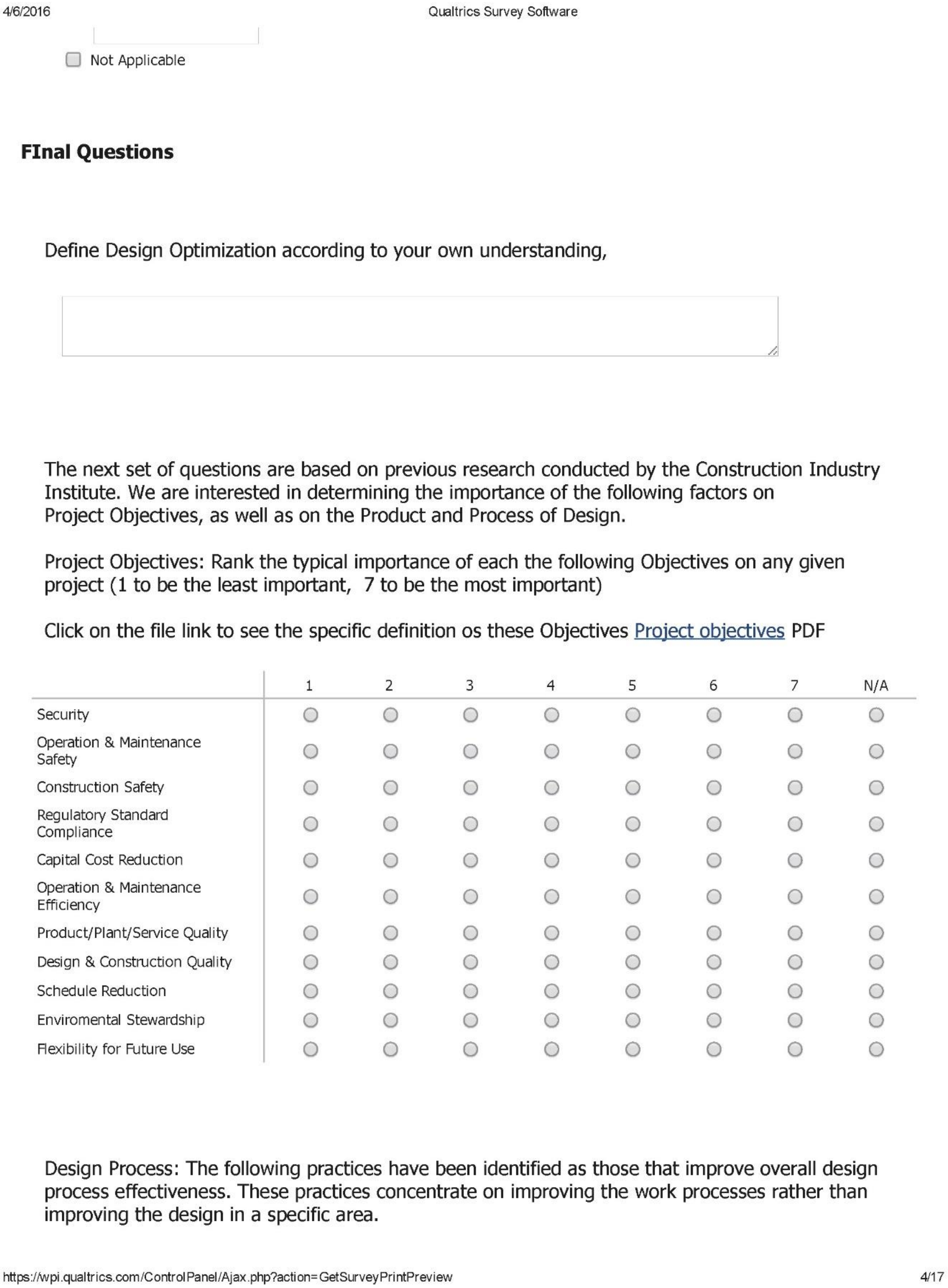
○ Never
○ Sometimes
○ About half the time
○ Frequently
○ Always

On building projects, please select the three most common elements where you leverage models to optimize design

☐ Exterior Walls
☐ MEP Building Systems
☐ Building Structure
☐ Roof Construction
☐ Floor Construction
☐ Interior Room Modules
☐ Other (please specify)
☐ Not Applicable

Three most common types of projects where you leverage BIM for design optimization (select top 3)

☐ Health care
☐ Higher Education
☐ Manudacturing
☐ Low-rise Office
☐ Public Buildings
☐ Commercial Warehouse
☐ K-12 school
☐ High-rise Office (+5 stories)
☐ Hospitality
☐ Retail
☐ Multifamily
☐ Infrastructure
☐ Other (please select)



☐ Not Applicable

FInal Questions

Define Design Optimization according to your own understanding,

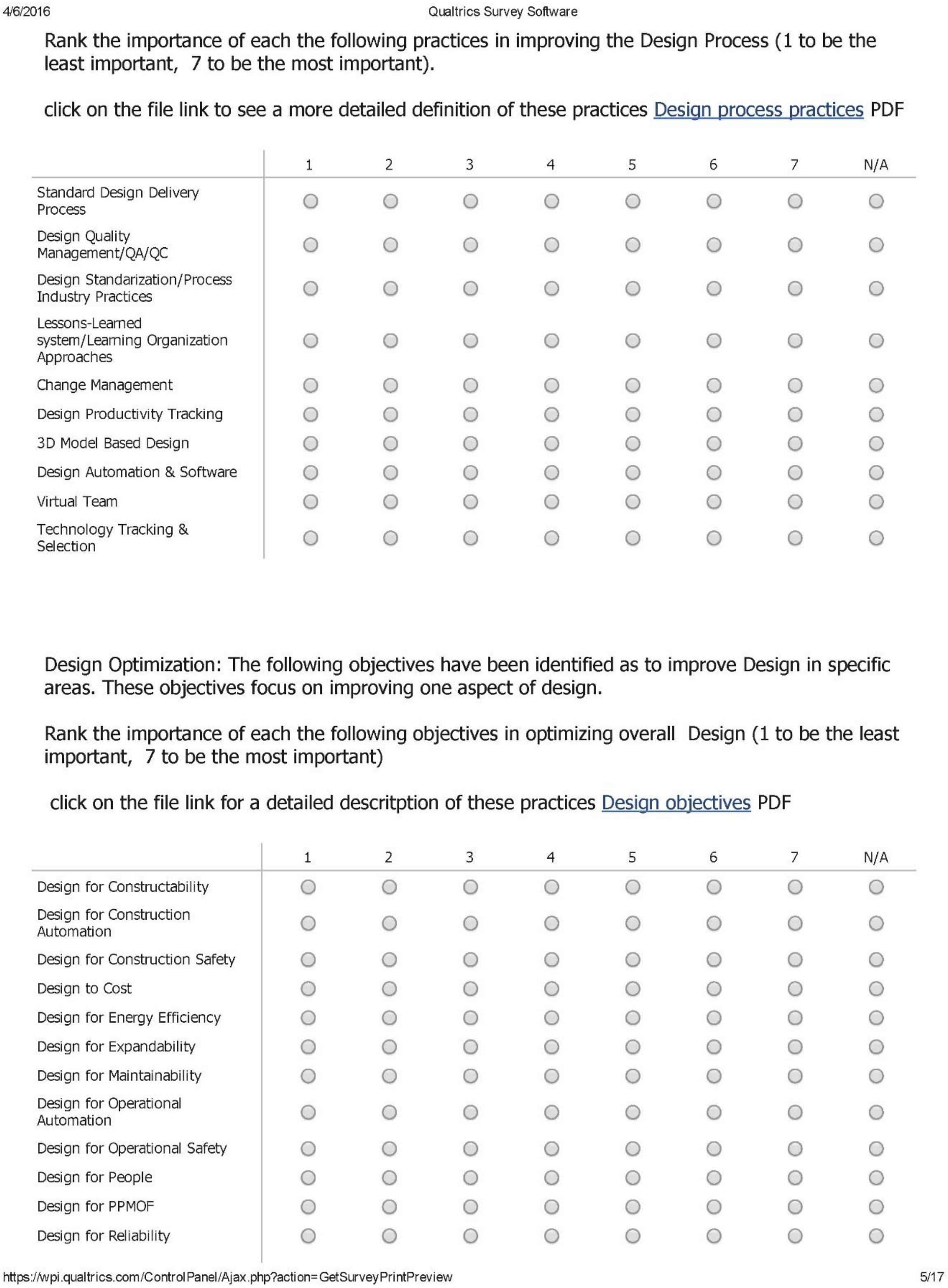
The next set of questions are based on previous research conducted by the Construction Industry Institute. We are interested in determining the importance of the following factors on Project Objectives, as well as on the Product and Process of Design.

Project Objectives: Rank the typical importance of each the following Objectives on any given project (1 to be the least important, 7 to be the most important)

Click on the file link to see the specific definition os these Objectives Project objectives PDF

	1	2	3	4	5	6	7	N/A
Security	○	○	○	○	○	○	○	○
Operation & Maintenance Safety	○	○	○	○	○	○	○	○
Construction Safety	○	○	○	○	○	○	○	○
Regulatory Standard Compliance	○	○	○	○	○	○	○	○
Capital Cost Reduction	○	○	○	○	○	○	○	○
Operation & Maintenance Efficiency	○	○	○	○	○	○	○	○
Product/Plant/Service Quality	○	○	○	○	○	○	○	○
Design & Construction Quality	○	○	○	○	○	○	○	○
Schedule Reduction	○	○	○	○	○	○	○	○
Enviromental Stewardship	○	○	○	○	○	○	○	○
Flexibility for Future Use	○	○	○	○	○	○	○	○

Design Process: The following practices have been identified as those that improve overall design process effectiveness. These practices concentrate on improving the work processes rather than improving the design in a specific area.



Rank the importance of each the following practices in improving the Design Process (1 to be the least important, 7 to be the most important).

click on the file link to see a more detailed definition of these practices Design process practices PDF

	1	2	3	4	5	6	7	N/A
Standard Design Delivery Process	○	○	○	○	○	○	○	○
Design Quality Management/QA/QC	○	○	○	○	○	○	○	○
Design Standarization/Process Industry Practices	○	○	○	○	○	○	○	○
Lessons-Learned system/Learning Organization Approaches	○	○	○	○	○	○	○	○
Change Management	○	○	○	○	○	○	○	○
Design Productivity Tracking	○	○	○	○	○	○	○	○
3D Model Based Design	○	○	○	○	○	○	○	○
Design Automation & Software	○	○	○	○	○	○	○	○
Virtual Team	○	○	○	○	○	○	○	○
Technology Tracking & Selection	○	○	○	○	○	○	○	○

Design Optimization: The following objectives have been identified as to improve Design in specific areas. These objectives focus on improving one aspect of design.

Rank the importance of each the following objectives in optimizing overall Design (1 to be the least important, 7 to be the most important)

click on the file link for a detailed descritption of these practices Design objectives PDF

	1	2	3	4	5	6	7	N/A
Design for Constructability	○	○	○	○	○	○	○	○
Design for Construction Automation	○	○	○	○	○	○	○	○
Design for Construction Safety	○	○	○	○	○	○	○	○
Design to Cost	○	○	○	○	○	○	○	○
Design for Energy Efficiency	○	○	○	○	○	○	○	○
Design for Expandability	○	○	○	○	○	○	○	○
Design for Maintainability	○	○	○	○	○	○	○	○
Design for Operational Automation	○	○	○	○	○	○	○	○
Design for Operational Safety	○	○	○	○	○	○	○	○
Design for People	○	○	○	○	○	○	○	○
Design for PPMOF	○	○	○	○	○	○	○	○
Design for Reliability	○	○	○	○	○	○	○	○

Design for Schedule Performance	○	○	○	○	○	○	○	○
Design for Security	○	○	○	○	○	○	○	○
Design for Startup	○	○	○	○	○	○	○	○
Design for Sustainability	○	○	○	○	○	○	○	○
Design to Capacity	○	○	○	○	○	○	○	○
Risk-Based Design	○	○	○	○	○	○	○	○
Value Engineering in Design	○	○	○	○	○	○	○	○
Vendor Integration & Design for Supply Chain	○	○	○	○	○	○	○	○

Engineers Block

Which Engineering discipline best describes your firm?

○ Civil
○ MEPFS
○ Structural
○ Other (please specify)

Among companies of your type, what size is your company? (select one)

○ Small (professional fees under $500K)
○ Medium (professional fees $500K to $5M)
○ Large (professional fees over $5M)

How frequently do you specifically attempt to enable or optimize design in your projects?

○ Never
○ Sometimes
○ About half the time
○ Frequently
○ Always

Top three reasons for your company engaging in design optimization (select top three reasons)

☐ Improved Productivity
☐ Competitive Advantage
☐ Demand by Others
☐ Supports Principles of Lean Construction
☐ Supports Principles of Sustainability
☐ Schedule Compression
☐ Other (please specify)

How engaged is your company with BIM? (select one)

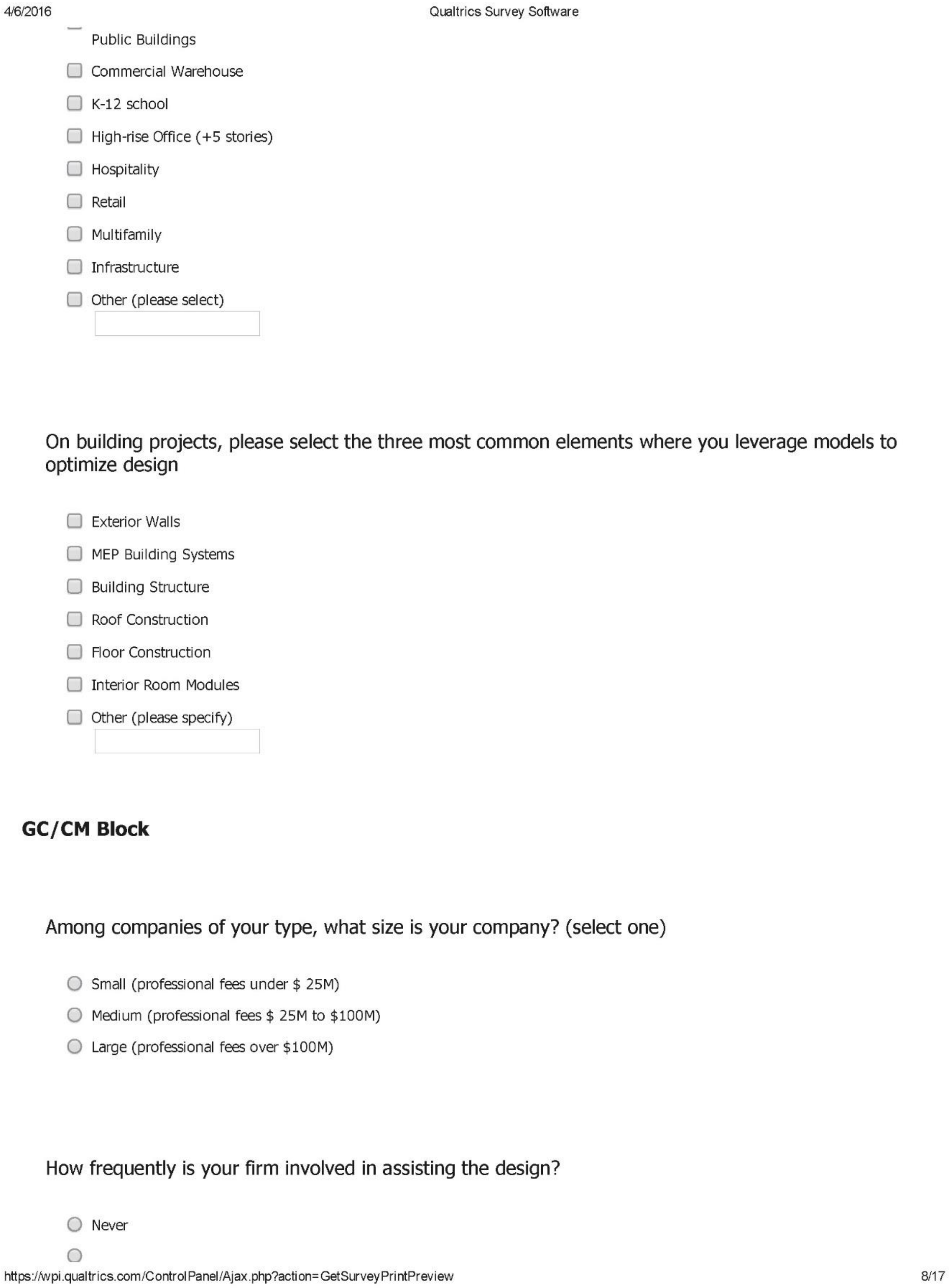
○ My company is not involved with BIM
○ Low BIM engagement (only a few years'BIM experience and a small percentage of our projects involve BIM)
○ Medium BIM engagement (between low and high)
○ High BIM engagement (many years' BIM experience and most of our projects involve BIM)

How frequently do you leverage BIM to enable or optimize design in your projects?

○ Never
○ Sometimes
○ About half the time
○ Frequently
○ Always

Three most common types of projects where you leverage BIM for design optimization (select top 3)

☐ Health Care
☐ Higher Education
☐ Manudacturing
☐ Low-rise office
☐



☐ Public Buildings

☐ Commercial Warehouse

☐ K-12 school

☐ High-rise Office (+5 stories)

☐ Hospitality

☐ Retail

☐ Multifamily

☐ Infrastructure

☐ Other (please select)

On building projects, please select the three most common elements where you leverage models to optimize design

☐ Exterior Walls

☐ MEP Building Systems

☐ Building Structure

☐ Roof Construction

☐ Floor Construction

☐ Interior Room Modules

☐ Other (please specify)

GC/CM Block

Among companies of your type, what size is your company? (select one)

○ Small (professional fees under $ 25M)

○ Medium (professional fees $ 25M to $100M)

○ Large (professional fees over $100M)

How frequently is your firm involved in assisting the design?

○ Never

○

○ Sometimes

○ About half the time

○ Frequently

○ Always

Top three reasons for your company engaging in assisting the design (select top three reasons)

☐ Improved Productivity

☐ Competitive Advantage

☐ Demand by Others

☐ Supports Principles of Lean Construction

☐ Supports Principles of Sustainability

☐ Schedule Compression

☐ Other (please specify)

How engaged is your company with BIM? (select one)

○ My company is not involved with BIM

○ Low BIM engagement (only a few years'BIM experience and a small percentage of our projects involve BIM)

○ Medium BIM engagement (between low and high)

○ High BIM engagement (many years' BIM experience and most of our projects involve BIM)

How frequently do you leverage models and model data to assist the design?

○ Never

○ Sometimes

○ About half the time

○ Frequently

○ Always

Three most common types of projects where you leverage BIM for assisting the design (select top

3)

- ☐ Health care
- ☐ Higher Education
- ☐ Manudacturing
- ☐ Low-rise Office
- ☐ Public Buildings
- ☐ Commercial Warehouse
- ☐ K-12 school
- ☐ High-rise Office (+5 stories)
- ☐ Hospitality
- ☐ Retail
- ☐ Multifamily
- ☐ Infrastructure
- ☐ Other (please select)

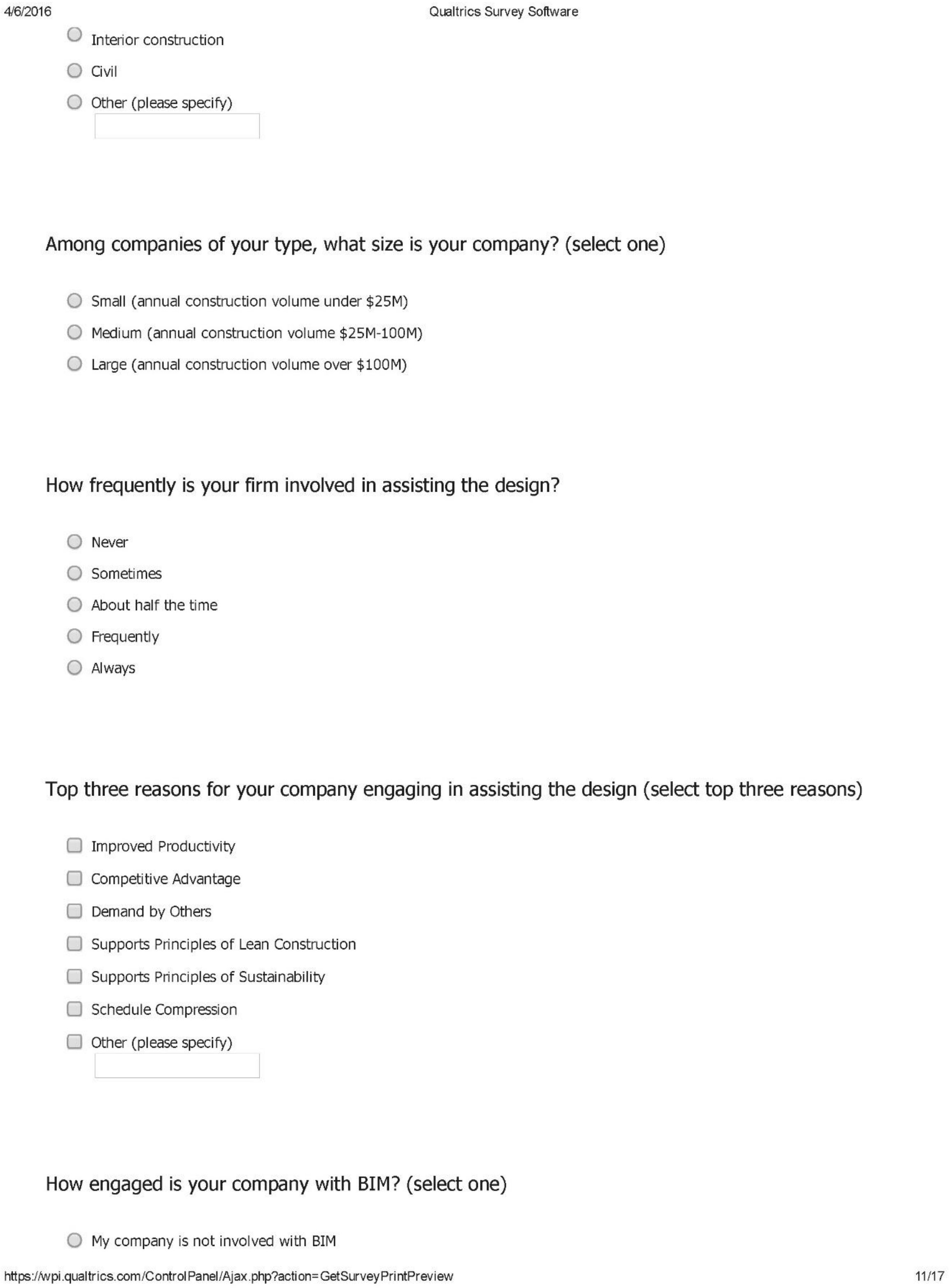
On building projects, please select the three most common elements where you leverage models to assist the design

- ☐ Exterior Walls
- ☐ MEP Building Systems
- ☐ Building Structure
- ☐ Roof Construction
- ☐ Floor Construction
- ☐ Interior Room Modules
- ☐ Other (please specify)

Specialty Contractors/Fabricators Block

Which best decribes your companiy's specialty? (select one)

- ○ MEPFS
- ○ Envelope (exterior, roofing, etc)
- ○ Structural (concrete, steel, etc)



○ Interior construction

○ Civil

○ Other (please specify)

Among companies of your type, what size is your company? (select one)

○ Small (annual construction volume under $25M)

○ Medium (annual construction volume $25M-100M)

○ Large (annual construction volume over $100M)

How frequently is your firm involved in assisting the design?

○ Never

○ Sometimes

○ About half the time

○ Frequently

○ Always

Top three reasons for your company engaging in assisting the design (select top three reasons)

☐ Improved Productivity

☐ Competitive Advantage

☐ Demand by Others

☐ Supports Principles of Lean Construction

☐ Supports Principles of Sustainability

☐ Schedule Compression

☐ Other (please specify)

How engaged is your company with BIM? (select one)

○ My company is not involved with BIM

○ Low BIM engagement (only a few years'BIM experience and a small percentage of our projects involve BIM)
○ Medium BIM engagement (between low and high)
○ High BIM engagement (many years' BIM experience and most of our projects involve BIM)

How frequently do you leverage models and model data to assist the design?

○ Never
○ Sometimes
○ About half the time
○ Frequently
○ Always

On building projects, please select the three most common elements where you leverage models to assist the design

☐ Exterior Walls
☐ MEP Building Systems
☐ Building Structure
☐ Roof Construction
☐ Floor Construction
☐ Interior Room Modules
☐ Other (please specify)

Three most common types of projects where you leverage BIM for assistng the design (select top 3)

☐ Health care
☐ Higher Education
☐ Manudacturing
☐ Low-rise Office
☐ Public Buildings
☐ Commercial Warehouse
☐ K-12 school
☐

High-rise Office (+5 stories)

☐ Hospitality

☐ Retail

☐ Multifamily

☐ Infrastructure

☐ Other (please select)

Others Block

Among companies of your type, what size is your company? (select one)

○ Small (professional fees under 500K)

○ Medium (professional fees $500K to $5M)

○ Large (professional fees over $5M)

How frequently is your firm involved in assisting the design?

○ Never

○ Sometimes

○ About half the time

○ Frequently

○ Always

Top three reasons for your company engaging in assisting the design (select top three reasons)

☐ Improved Productivity

☐ Competitive Advantage

☐ Demand by Others

☐ Supports Principles of Lean Construction

☐ Supports Principles of Sustainability

☐ Schedule Compression

☐ Other (please specify)

How engaged is your company with BIM? (select one)

○ My company is not involved with BIM
○ Low BIM engagement (only a few years'BIM experience and a small percentage of our projects involve BIM)
○ Medium BIM engagement (between low and high)
○ High BIM engagement (many years' BIM experience and most of our projects involve BIM)

How frequently do you leverage BIM to assist the design?

○ Never
○ Sometimes
○ About half the time
○ Frequently
○ Always

On building projects, please select the three most common elements where you leverage models to assist the design

☐ Exterior Walls
☐ MEP Building Systems
☐ Building Structure
☐ Roof Construction
☐ Floor Construction
☐ Interior Room Modules
☐ Other (please specify)

Three most common types of projects where you leverage BIM for assisting the design (select top 3)

☐ Health care
☐ Higher education

☐ Manudacturing

☐ Low-rise Office

☐ Public Buildings

☐ Commercial Warehouse

☐ K-12 school

☐ High-rise Office (+5 stories)

☐ Hospitality

☐ Retail

☐ Multifamily

☐ Infrastructure

☐ Other (please select)

Owners block

Among companies of your type, what size is your company? (select one)

○ Small (annual construction volume under $25M)

○ Medium (annual construction volume $25M-100M)

○ Large (annual construction volume over $100M)

How frequently do you specifically attempt to enable or optimize design in your projects?

○ Never

○ Sometimes

○ About half the time

○ Frequently

○ Always

Top three reasons for your company engaging in design optmization (select top three reasons)

☐ Improved Productivity

☐ Competitive Advantage

☐ Demand by Others

☐ Supports Principles of Lean Construction

☐ Supports Principles of Sustainability

☐ Schedule Compression

☐ Other (please specify)

How engaged is your company with BIM? (select one)

○ My company is not involved with BIM

○ Low BIM engagement (only a few years'BIM experience and a small percentage of our projects involve BIM)

○ Medium BIM engagement (between low and high)

○ High BIM engagement (many years' BIM experience and most of our projects involve BIM)

How frequently do you leverage BIM to enable or optimize design in your projects?

○ Never

○ Sometimes

○ About half the time

○ Frequently

○ Always

On building projects, please select the three most common elements where you leverage models to optimize design

☐ Exterior Walls

☐ MEP Building Systems

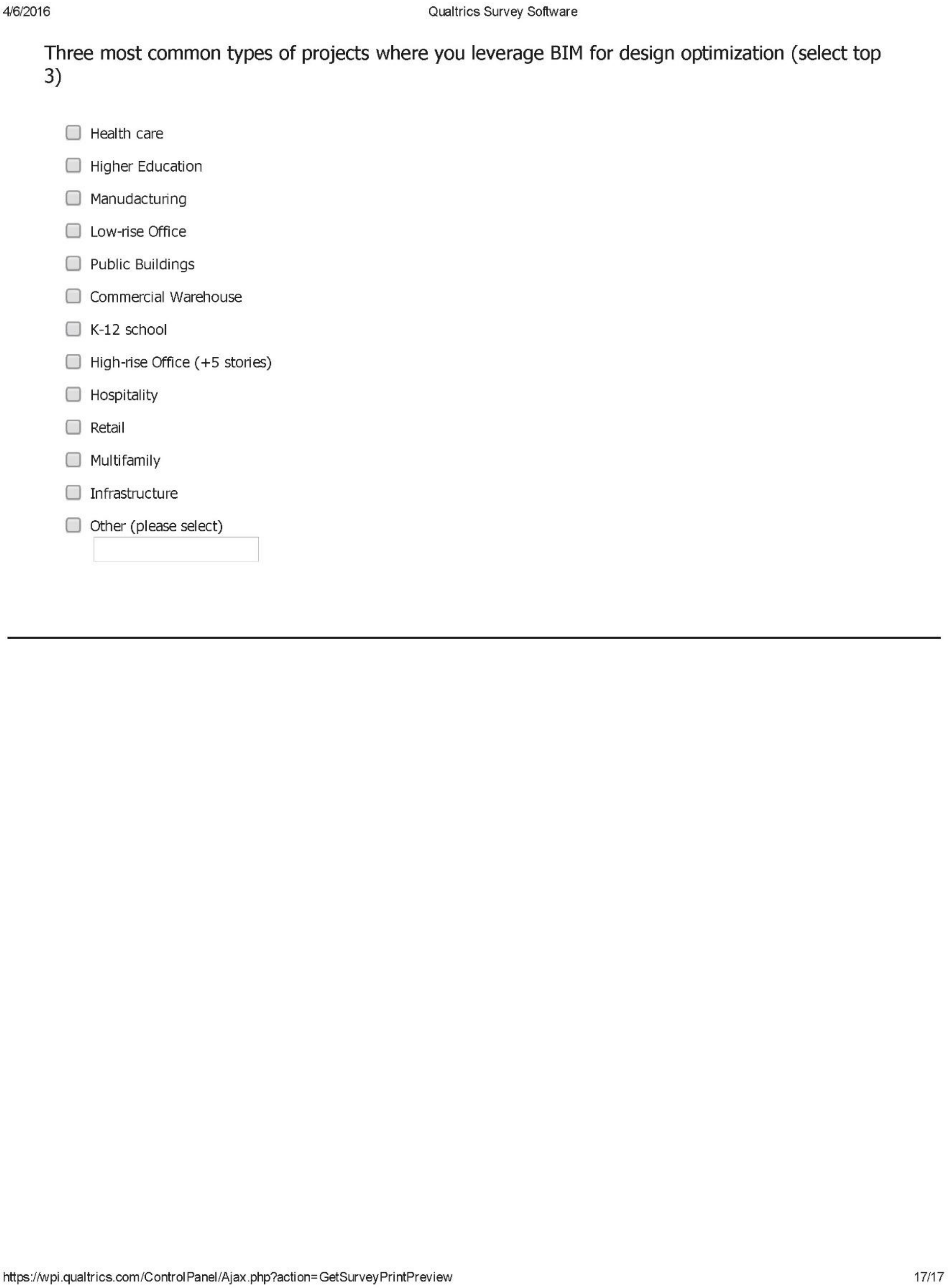
☐ Building Structure

☐ Roof Construction

☐ Floor Construction

☐ Interior Room Modules

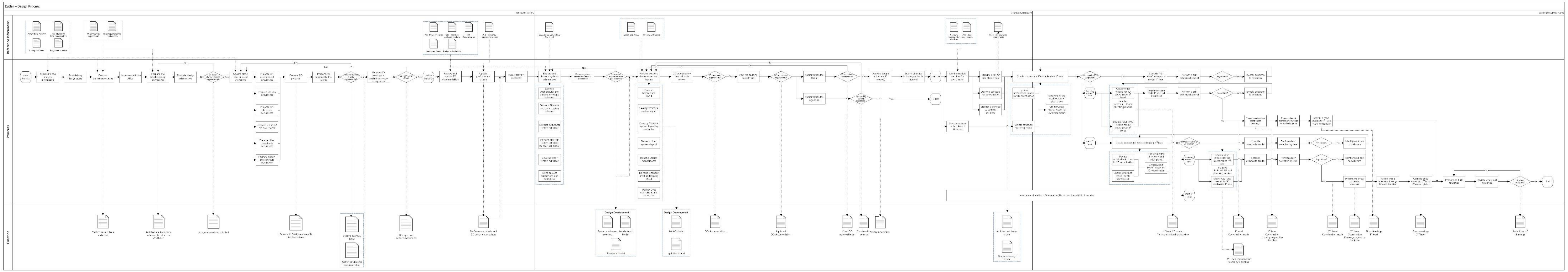
☐ Other (please specify)



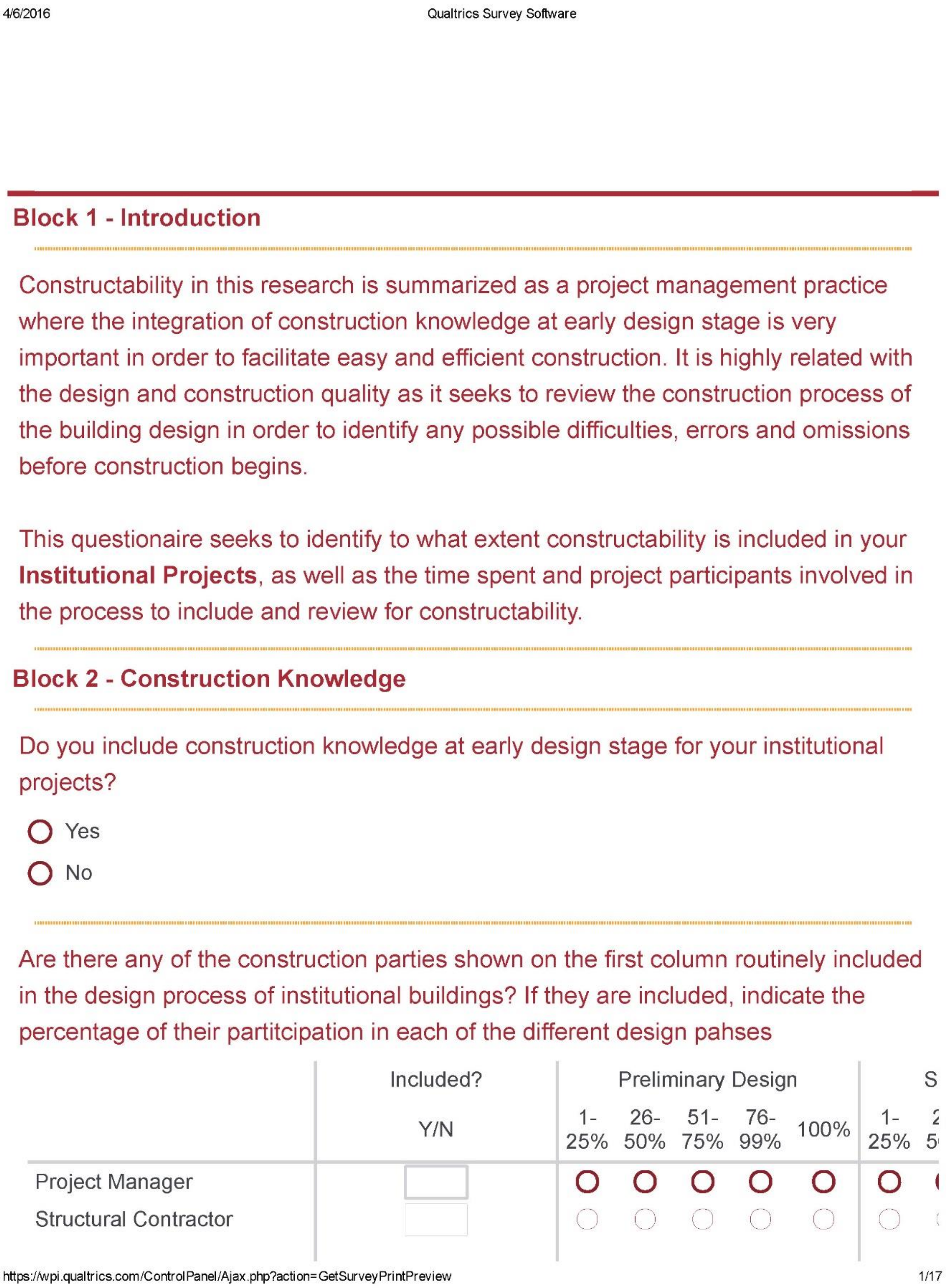
Three most common types of projects where you leverage BIM for design optimization (select top 3)

☐ Health care
☐ Higher Education
☐ Manudacturing
☐ Low-rise Office
☐ Public Buildings
☐ Commercial Warehouse
☐ K-12 school
☐ High-rise Office (+5 stories)
☐ Hospitality
☐ Retail
☐ Multifamily
☐ Infrastructure
☐ Other (please select)

Appendix D. Cutler Process Map



Appendix E. Cutler PVO Questionnaires



Block 1 - Introduction

Constructability in this research is summarized as a project management practice where the integration of construction knowledge at early design stage is very important in order to facilitate easy and efficient construction. It is highly related with the design and construction quality as it seeks to review the construction process of the building design in order to identify any possible difficulties, errors and omissions before construction begins.

This questionaire seeks to identify to what extent constructability is included in your **Institutional Projects**, as well as the time spent and project participants involved in the process to include and review for constructability.

Block 2 - Construction Knowledge

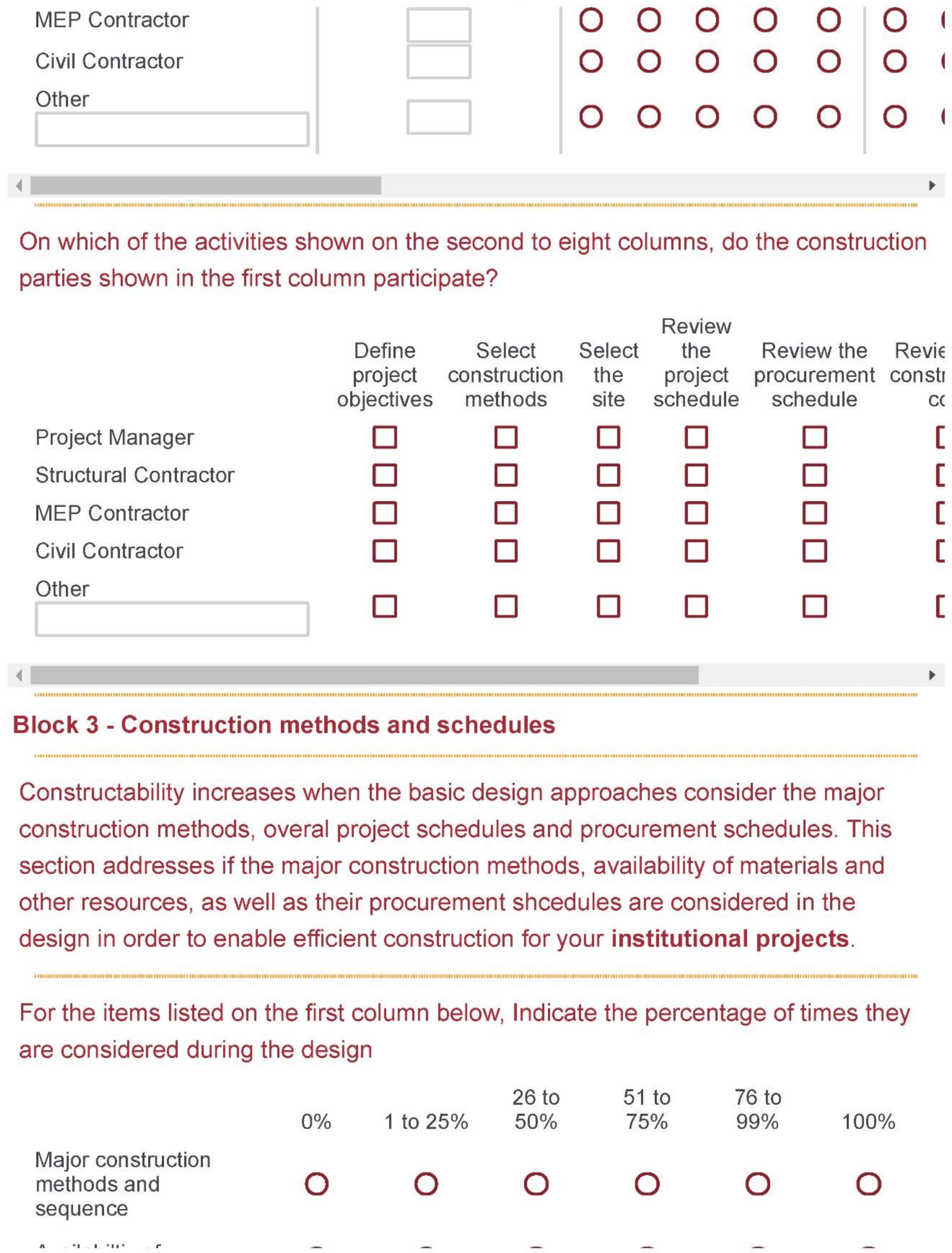
Do you include construction knowledge at early design stage for your institutional projects?

○ Yes

○ No

Are there any of the construction parties shown on the first column routinely included in the design process of institutional buildings? If they are included, indicate the percentage of their partitcipation in each of the different design pahses

	Included?	Preliminary Design					S	
	Y/N	1- 25%	26- 50%	51- 75%	76- 99%	100%	1- 25%	2 5
Project Manager		○	○	○	○	○	○	○
Structural Contractor		○	○	○	○	○	○	○



MEP Contractor		○	○	○	○	○	○
Civil Contractor		○	○	○	○	○	○
Other		○	○	○	○	○	○

On which of the activities shown on the second to eight columns, do the construction parties shown in the first column participate?

	Define project objectives	Select construction methods	Select the site	Review the project schedule	Review the procurement schedule	Revie constr c
Project Manager	☐	☐	☐	☐	☐	☐
Structural Contractor	☐	☐	☐	☐	☐	☐
MEP Contractor	☐	☐	☐	☐	☐	☐
Civil Contractor	☐	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐	☐

Block 3 - Construction methods and schedules

Constructability increases when the basic design approaches consider the major construction methods, overal project schedules and procurement schedules. This section addresses if the major construction methods, availability of materials and other resources, as well as their procurement shcedules are considered in the design in order to enable efficient construction for your **institutional projects**.

For the items listed on the first column below, Indicate the percentage of times they are considered during the design

	0%	1 to 25%	26 to 50%	51 to 75%	76 to 99%	100%
Major construction methods and sequence	○	○	○	○	○	○

Availability of Materials	○	○	○	○	○	○
Availability of tools and equipment	○	○	○	○	○	○
Availability of labor skills	○	○	○	○	○	○
Avoid the use of special labor skills and labor intesive methods	○	○	○	○	○	○
Use of methods and resources appropiate for location	○	○	○	○	○	○
Climate Conditions	○	○	○	○	○	○

Does the construction schedule considers possible timing to avoid carrying out structural and any other exterior work during rainy/snowing season?

○ Yes
○ No

How is the process of analyzing and improving the construction schedule conducted?

For each stage of the design shown on the first column below, indicate if the construction schedule analysis process is conducted,. If this happens, please enter the range of iterations (minimum and maximum), as well as the range of working hours (minimum and maximum) that this process usually takes

	Included? Y/N	Minimum # of iterations	Maximum # of iterations	Minimum working hours	Maximum working hours

Preliminary Design	☐	☐	☐	☐	☐
Schematic Design	☐	☐	☐	☐	☐
50% Design Development	☐	☐	☐	☐	☐
100% Design Development	☐	☐	☐	☐	☐
50% Construction Documents	☐	☐	☐	☐	☐
100% Construction Documents	☐	☐	☐	☐	☐
100% Construction Completion	☐	☐	☐	☐	☐
Other ________	☐	☐	☐	☐	☐

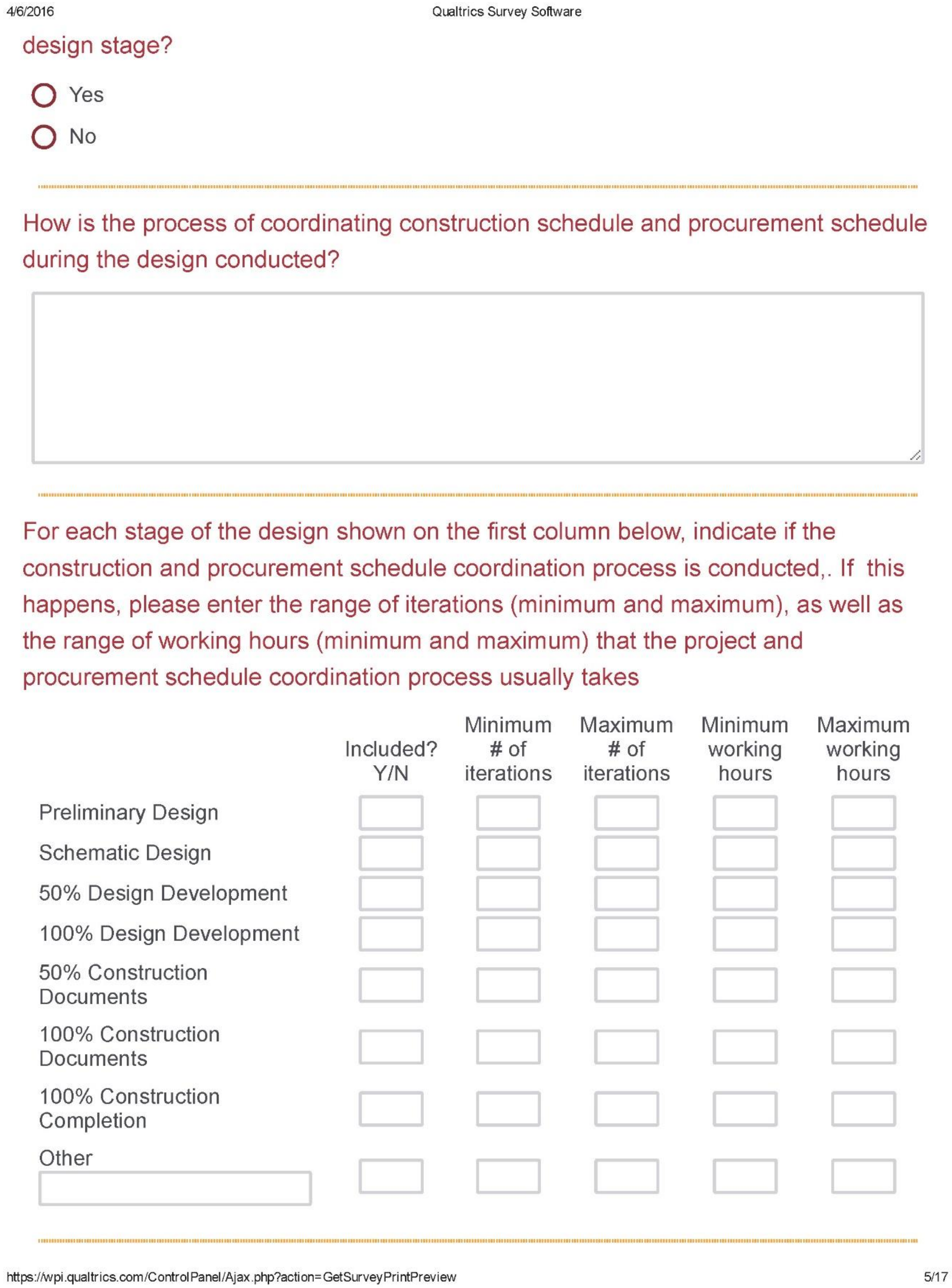
Who is usually involved in the project and procurement schedule coordination process? Select all that apply

☐ Architect
☐ Project Manager
☐ Structural Designer/Contractor
☐ MEP Designer/Contractor
☐ Civil Engineer Designer/Contractor
☐ Owner / Owner Representative
☐ Other ________

Do you use any special software or tool to assist in the coordination of the project and procurement schedules? If so, please specify it

○ No
○ Yes ________

Are the construction schedule and the procurement schedule coordinated at the



design stage?

○ Yes

○ No

How is the process of coordinating construction schedule and procurement schedule during the design conducted?

For each stage of the design shown on the first column below, indicate if the construction and procurement schedule coordination process is conducted,. If this happens, please enter the range of iterations (minimum and maximum), as well as the range of working hours (minimum and maximum) that the project and procurement schedule coordination process usually takes

	Included? Y/N	Minimum # of iterations	Maximum # of iterations	Minimum working hours	Maximum working hours
Preliminary Design					
Schematic Design					
50% Design Development					
100% Design Development					
50% Construction Documents					
100% Construction Documents					
100% Construction Completion					
Other					

Who is usually involved in the project and procurement schedule coordination process? Select all that apply

☐ Architect
☐ Project Manager
☐ Structural Designer/Contractor
☐ MEP Designer/Contractor
☐ Civil Engineer Designer/Contractor
☐ Owner / Owner Representative
☐ Other

Do you use any special software or tool to assist in the coordination of the project and procurement schedules? If so, please specify it

○ No
○ Yes

Block 4 - Site Layout

Site layout refers to the sufficient working space for labour and plant. This section includes questions related with access for material, equipment, tools and personnel to the site and from different site locations, as well as the adequate space for material storage, transportation on site, and minimizing wet areas on site for your **institutional projects**.

Does the site layout is analyzed during the design process to promote efficient construction?

○ Yes
○ No

For the items listed on the first column below, Indicate the percentage of times they are considered during the design

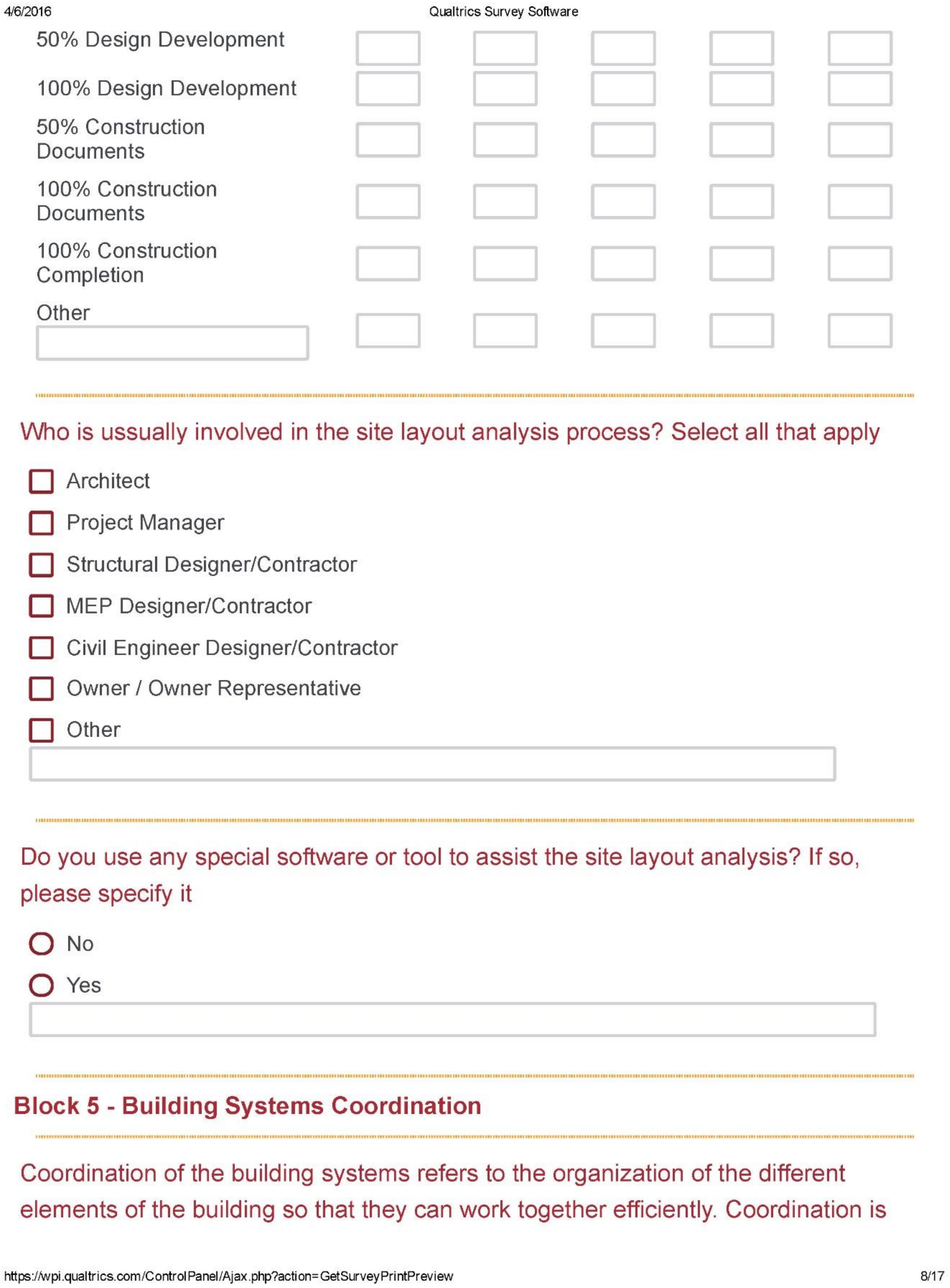
	0%	1 to 25%	26 to 50%	51 to 75%	76 to 99%	100%
Adequate space(s) and location(s) for storage, laydown and fabrication yards	○	○	○	○	○	○
Space(s) for temporary facilities	○	○	○	○	○	○
Use of existing facilities/areas as temporary construction	○	○	○	○	○	○
Access routes for equipment, material and personnel	○	○	○	○	○	○
Adecuate drainage system	○	○	○	○	○	○

How is the site layout analysis process conducted?

☐

For each percentage of design completion shown below, indicate if the site layout analysis is conducted,. If this happens, please enter the range of iterations (minimum and maximum), as well as the range of working hours (minimum and maximum) that this process usually takes

	Included? Y/N	Minimum # of iterations	Maximum # of iterations	Minimum working hours	Maximum working hours
Preliminary Design	☐	☐	☐	☐	☐
Schematic Design	☐	☐	☐	☐	☐



50% Design Development	☐	☐	☐	☐	☐
100% Design Development	☐	☐	☐	☐	☐
50% Construction Documents	☐	☐	☐	☐	☐
100% Construction Documents	☐	☐	☐	☐	☐
100% Construction Completion	☐	☐	☐	☐	☐
Other ☐	☐	☐	☐	☐	☐

Who is ussually involved in the site layout analysis process? Select all that apply

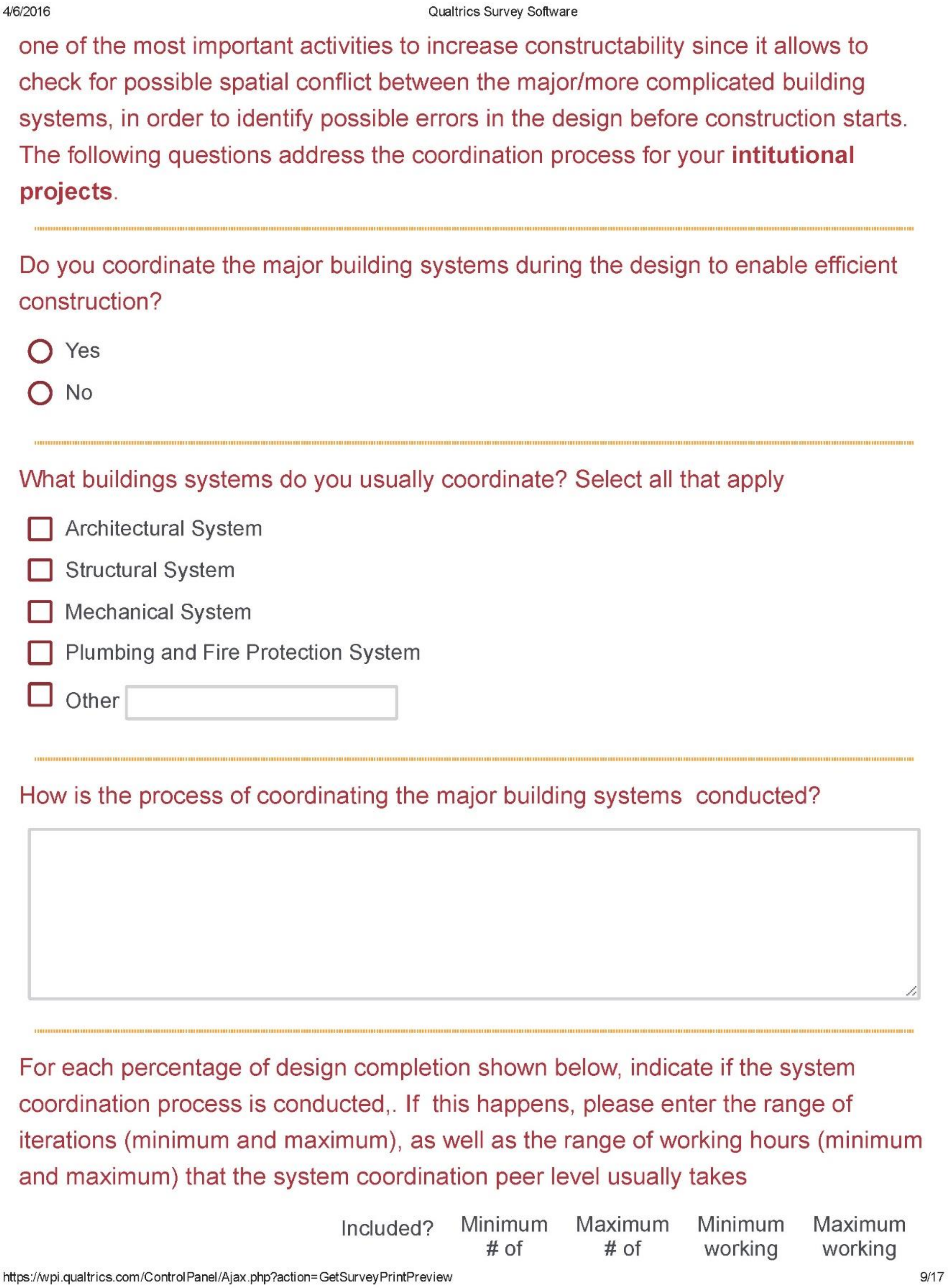
☐ Architect
☐ Project Manager
☐ Structural Designer/Contractor
☐ MEP Designer/Contractor
☐ Civil Engineer Designer/Contractor
☐ Owner / Owner Representative
☐ Other ☐

Do you use any special software or tool to assist the site layout analysis? If so, please specify it

○ No
○ Yes ☐

Block 5 - Building Systems Coordination

Coordination of the building systems refers to the organization of the different elements of the building so that they can work together efficiently. Coordination is



one of the most important activities to increase constructability since it allows to check for possible spatial conflict between the major/more complicated building systems, in order to identify possible errors in the design before construction starts. The following questions address the coordination process for your **intitutional projects**.

Do you coordinate the major building systems during the design to enable efficient construction?

○ Yes

○ No

What buildings systems do you usually coordinate? Select all that apply

☐ Architectural System

☐ Structural System

☐ Mechanical System

☐ Plumbing and Fire Protection System

☐ Other ______

How is the process of coordinating the major building systems conducted?

For each percentage of design completion shown below, indicate if the system coordination process is conducted,. If this happens, please enter the range of iterations (minimum and maximum), as well as the range of working hours (minimum and maximum) that the system coordination peer level usually takes

	Included?	Minimum # of	Maximum # of	Minimum working	Maximum working

	Y/N	iterations	iterations	hours	hours
Preliminary Design	☐	☐	☐	☐	☐
Schematic Design	☐	☐	☐	☐	☐
50% Design Development	☐	☐	☐	☐	☐
100% Design Development	☐	☐	☐	☐	☐
50% Construction Documents	☐	☐	☐	☐	☐
100% Construction Documents	☐	☐	☐	☐	☐
100% Construction Completion	☐	☐	☐	☐	☐
Other ☐	☐	☐	☐	☐	☐

Who is ussually involved in the system coordination process? Select all that apply

- ☐ Architect
- ☐ Project Manager
- ☐ Structural Designer/Contractor
- ☐ MEP Designer/Contractor
- ☐ Civil Engineer Designer/Contractor
- ☐ Owner / Owner Representative
- ☐ Other ☐

Do you use any special software or tool to assist in the system coordination process? If so, please specify it

- ○ No
- ○ Yes ☐

Block 6 - Standarization

Standardization in the context of this research, refers the use of preassembled, prefabricated or offsite fabricated products in the design, as well as the repetition of elements, dimensions and distances, and modularity of layouts, with the objective to simplify construction operations and maximizing safety and quality. The following questions address the standarization process during the design fot your **insititutional projects.**

Do you include standardrized and prefabricated elements in the design to enable efficient construction?

○ Yes

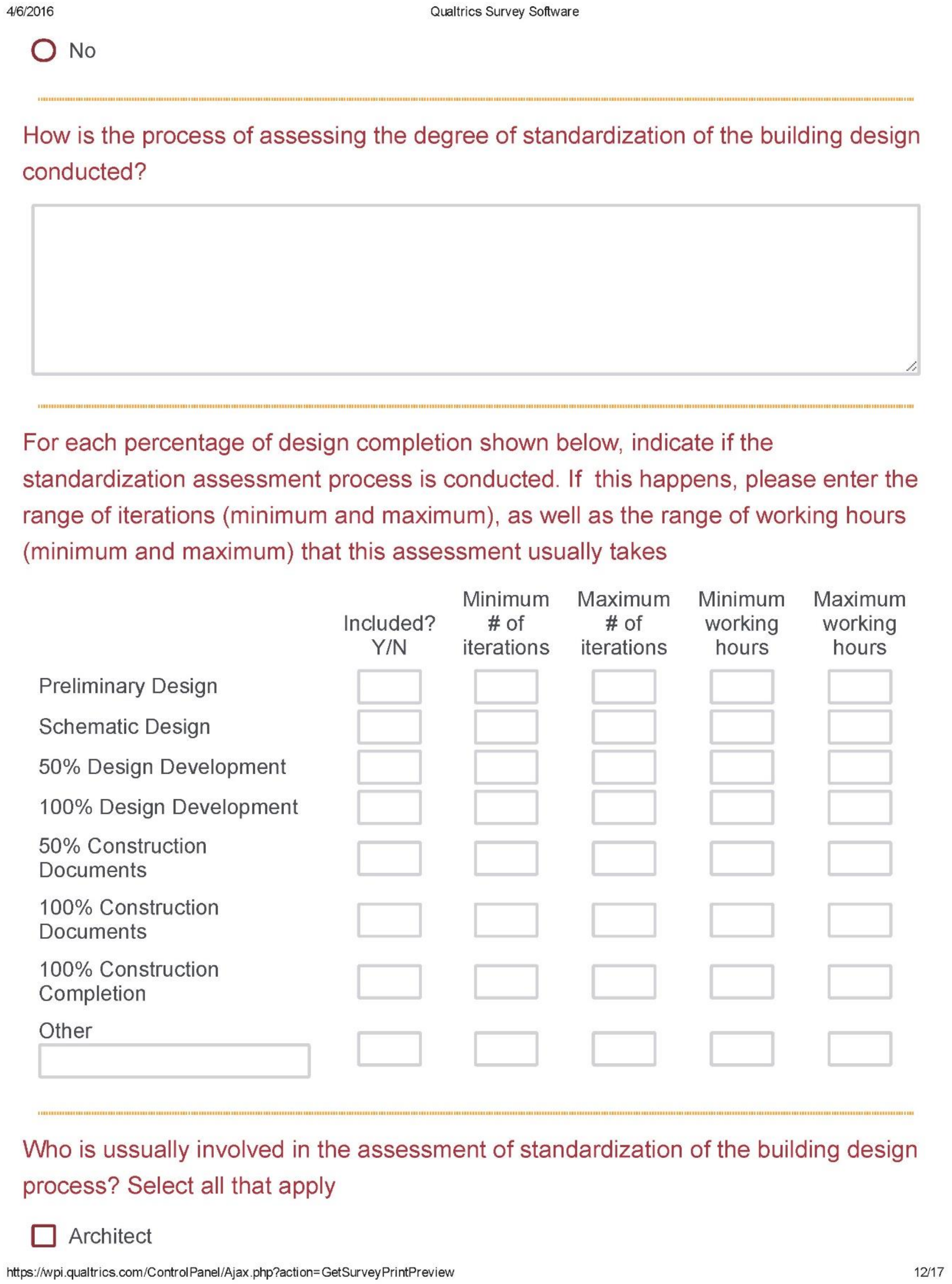
○ No

For the items listed on the first column below, Indicate the percentage of times they are considered during the design

	0%	1 to 25%	26 to 50%	51 to 75%	76 to 99%	100%
Standard High volume Materials	○	○	○	○	○	○
Standard Local Meterials	○	○	○	○	○	○
Standard /Repetitive Construction Methods	○	○	○	○	○	○
Standard Building Dimensions / Grid layout	○	○	○	○	○	○
Simplied Geometry, layout and shape for typical floor buildings	○	○	○	○	○	○
Prefabricated elements	○	○	○	○	○	○
Use of integrated system assemblies	○	○	○	○	○	○
Other ☐	○	○	○	○	○	○

Do you assess the level or degree of standarization of the buidlign design?

○ Yes



○ No

How is the process of assessing the degree of standardization of the building design conducted?

For each percentage of design completion shown below, indicate if the standardization assessment process is conducted. If this happens, please enter the range of iterations (minimum and maximum), as well as the range of working hours (minimum and maximum) that this assessment usually takes

	Included? Y/N	Minimum # of iterations	Maximum # of iterations	Minimum working hours	Maximum working hours
Preliminary Design					
Schematic Design					
50% Design Development					
100% Design Development					
50% Construction Documents					
100% Construction Documents					
100% Construction Completion					
Other					

Who is ussually involved in the assessment of standardization of the building design process? Select all that apply

☐ Architect

☐ Project Manager
☐ Structural Designer/Contractor
☐ MEP Designer/Contractor
☐ Civil Engineer Designer/Contractor
☐ Owner / Owner Representative
☐ Other

Do you use any special software or tool to assist in standardization assessment process? If so, please specify it

○ No
○ Yes

Block 7 - Design Documentation

Design documents communicate the design intent to the builder for the construction of the building project. Drawings and specifications depict the components of the intended building in such a way that construction personnel can clearly understand what results are desired, therefore, errors and omissions in the construction documentation will represent changes in the design, and more time and money spent to do those changes.

Who is ussually involved in the development of construction documents and specification process? Select all that apply

☐ Architect
☐ Project Manager
☐ Structural Designer/Contractor
☐ MEP Designer/Contractor
☐ Civil Engineer Designer/Contractor
☐ CAD Technicitian

☐ Other

Is the documentation used for construction reviewed to include the constructability aspects previouly identified?

○ Yes

○ No

How is the process of reviewing the documentation used for construction conducted?

For each percentage of design completion shown below, indicate if the process of reviewing constructabilituy in the documentation used for construction is conducted,. If this happens, please enter the range of iterations (minimum and maximum), as well as the range of working hours (minimum and maximum) that this process usually takes

	Included? Y/N	Minimum # of iterations	Maximum # of iterations	Minimum working hours	Maximum working hours
Preliminary Design					
Schematic Design					
50% Design Development					
100% Design Development					
50% Construction Documents					
100% Construction Documents					
100% Construction					

Completion

Other

Who is ussually involved in the assessment of standardization of the building design process? Select all that apply

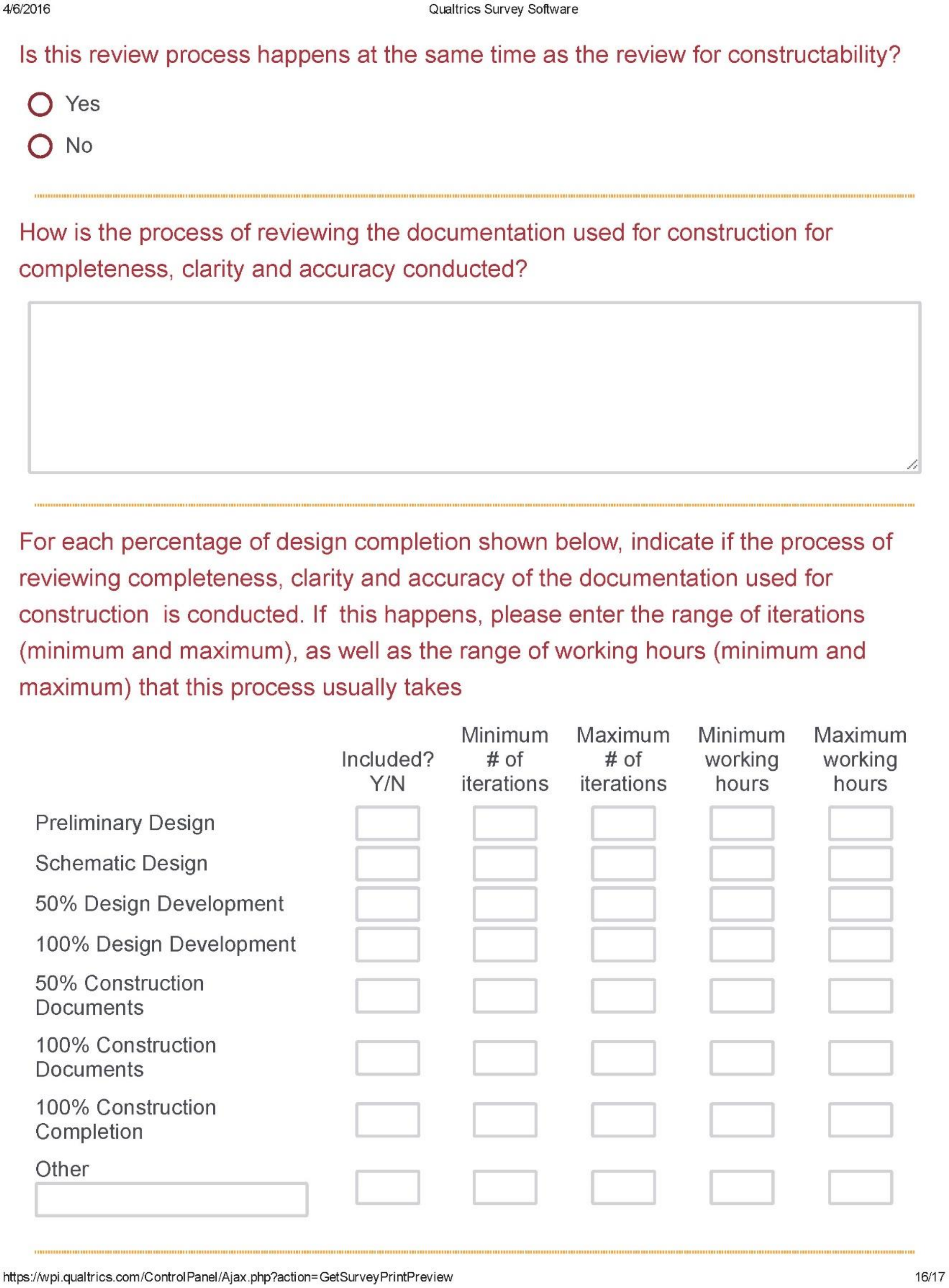
☐ Architect
☐ Project Manager
☐ Structural Designer/Contractor
☐ MEP Designer/Contractor
☐ Civil Engineer Designer/Contractor
☐ Owner / Owner Representative
☐ Other

Do you use any special software or tool to assist in the process of reviewing the documentation used for construction? If so, please specify it

○ No
○ Yes

Is the documentation used for construction reviewed for the following? (Select all that apply)

☐ Completness
☐ Clarity
☐ Accuracy
☐ Error free
☐ None



Is this review process happens at the same time as the review for constructability?

○ Yes

○ No

How is the process of reviewing the documentation used for construction for completeness, clarity and accuracy conducted?

For each percentage of design completion shown below, indicate if the process of reviewing completeness, clarity and accuracy of the documentation used for construction is conducted. If this happens, please enter the range of iterations (minimum and maximum), as well as the range of working hours (minimum and maximum) that this process usually takes

	Included? Y/N	Minimum # of iterations	Maximum # of iterations	Minimum working hours	Maximum working hours
Preliminary Design					
Schematic Design					
50% Design Development					
100% Design Development					
50% Construction Documents					
100% Construction Documents					
100% Construction Completion					
Other					

Who is ussually involved in reviewing completeness, clarity and accuracy of the documentation used for construction process? Select all that apply

- ☐ Architect
- ☐ Project Manager
- ☐ Structural Designer/Contractor
- ☐ MEP Designer/Contractor
- ☐ Civil Engineer Designer/Contractor
- ☐ Owner / Owner Representative
- ☐ Other

Do you use any special software or tool to assist in the review process of the design documentation? If so, please specify it

- ○ No
- ○ Yes

Powered by Qualtrics

Block 0 - Introduction

Facilities operation and maintenance are the decisions and actions regarding the control and upkeep of property and equipment in accordance with the documented design intent and the owner's operational needs. **Maintenance activities** encompass all actions and day to day activities required to maintain the building and its surrounding infrastructure in proper operating conditions. **Operation activities** are all actions focused on the scheduling of the equipment, procedures, optimization of energy efficiency, and control of user comfort.

In the context of this research, the objective of operation and maintenance efficiency includes all aspects and features that must be considered in the design in order to make the building easier and less expensive to operate and maintain, such as accessibility equipment and reliable information of building systems.

Block 1 - FM knowledge

Do you include the Facility Management (FM) staff early in the design?

○ Yes
○ No

What kind of information is usually provided by FM staff into the design? Select all that apply

☐ Space, accesibility and ergonomics requirements for the equipment
☐ Space/room information to be considered in the design and documentation
☐ Type and size of the space needed
☐ Requirements for energy consumption
☐ None

☐ Other (s)

At which stage of the design process is the FM staff typically involved? Select all that apply

☐ Preliminary Design
☐ Schematic Design
☐ Design Development 50%
☐ Design Development 100%
☐ Construction Documents 50%
☐ Construction Documents 100%

Block 2 - Space requirements

Accessibility and ergonomics requirements are important for the FM staff to perform operation and maintenance activities safely and efficiently. **Accessibility requirements** includes aspects in the design such as providing lifting devices, dedicated routes, walkways ad access platform to all areas and equipment. **Ergonomics requirements** include aspects such as providing enough space for a person(s) to easy clean and repair the equipment.

Do you incorporate information of accessibility and ergonomics requirements for the equipment into the design?

○ Yes
○ No

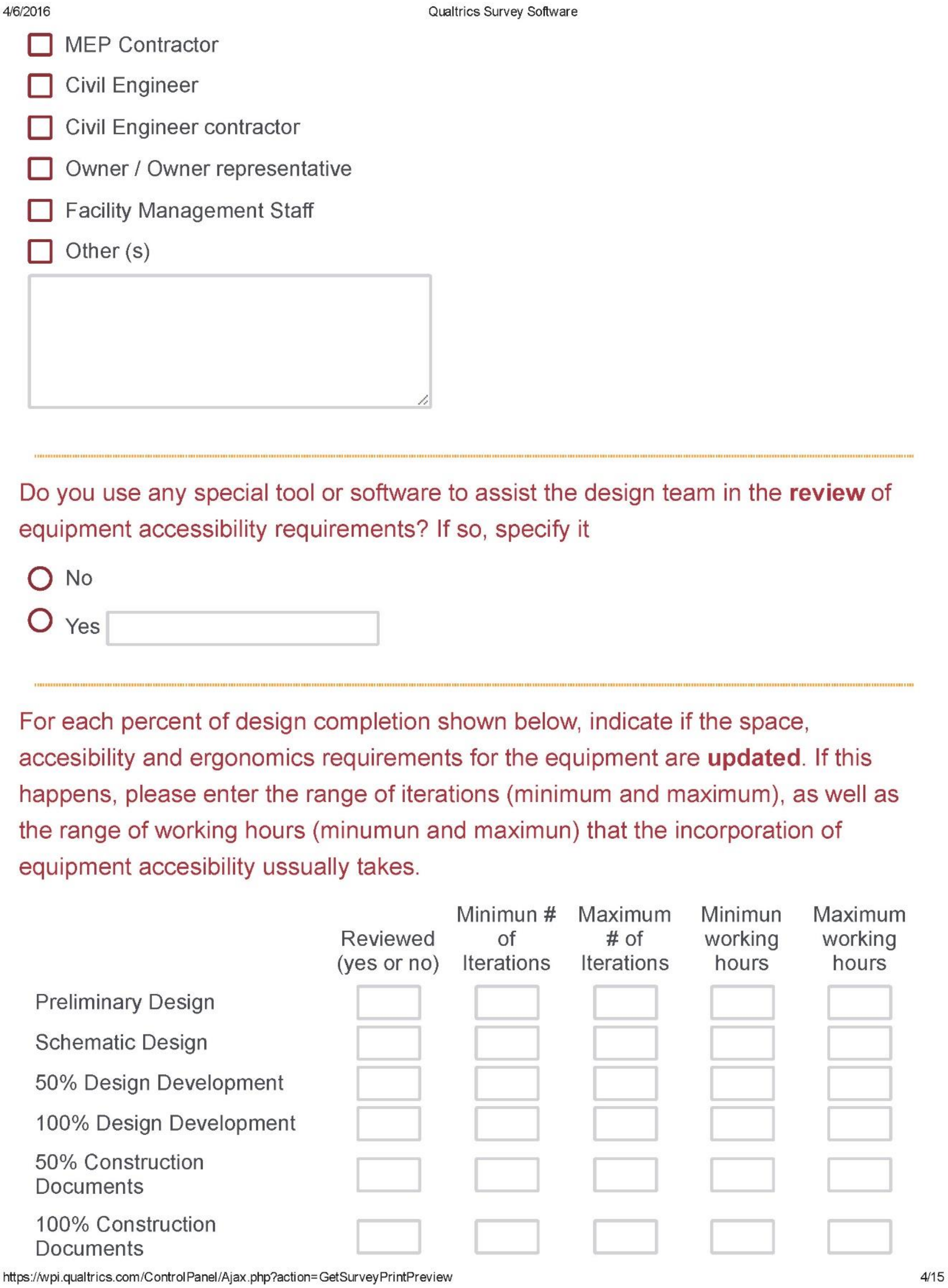
For each percent of design completion shown below, indicate if the space, accesibility and ergonomics requirements for the equipment are **reviewed**. If this happens, please enter the range of iterations (minimum and maximum), as well as the range of working hours (minumun and maximun) that the incorporation of equipment accesibility ussually takes.

	Included? (yes or no)	Minimun # of Iterations	Maximum # of Iterations	Minimun working hours	Maximum working hours
Preliminary Design					
Schematic Design					
50% Design Development					
100% Design Development					
50% Construction Documents					
100% Construction Documents					
100% construction completion					
Other					

How do you conduct the review process for checking space, accessibility and ergonomics requirements for the equipment?

Who is usually involved in the review of equipment accesibility requirements and ergonomics? Select all that apply

☐ Architect
☐ Structural Engineer Consultant
☐ Structural Contractor
☐ MEP Engineer Consultat



☐ MEP Contractor
☐ Civil Engineer
☐ Civil Engineer contractor
☐ Owner / Owner representative
☐ Facility Management Staff
☐ Other (s)

Do you use any special tool or software to assist the design team in the **review** of equipment accessibility requirements? If so, specify it

○ No
○ Yes

For each percent of design completion shown below, indicate if the space, accesibility and ergonomics requirements for the equipment are **updated**. If this happens, please enter the range of iterations (minimum and maximum), as well as the range of working hours (minumun and maximun) that the incorporation of equipment accesibility ussually takes.

	Reviewed (yes or no)	Minimun # of Iterations	Maximum # of Iterations	Minimun working hours	Maximum working hours
Preliminary Design					
Schematic Design					
50% Design Development					
100% Design Development					
50% Construction Documents					
100% Construction Documents					

100% construction completion	☐	☐	☐	☐	☐
Other ☐	☐	☐	☐	☐	☐

Do you use any special tool or software to assist the design team in **updating** of equipment accessibility requirements? If so, specify it

○ No

○ Yes ☐

Block 3 - Space management

To efficiently manage and perform the operation and maintenance of a building, the FM staff requires reliable and timely information to support decision making throughout the building life-cycle. Space management is one of the most important activities performed by the FM staff were information such as room number, capacity, finishes, gross, net usable and net assignable area, among others is required for maintenance operations.

Do you identify and incorporate into the design documentation the information of rooms/spaces required by FM?

○ Yes

○ No

For each percent of design completion shown below, indicate if the information of rooms required by FM is **reviewed**. If this happens, please enter the range of iterations (minimum and maximum), as well as the range of working hours (minumun and maximun) that the incorporation of equipment accesibility ussually takes.

	Reviewed (yes or no)	Minimun # of Iterations	Maximum # of Iterations	Minimun working hours	Maximum working hours
Prelimanry Design					

Schematic Design					
50% Design Development					
100% Design Development					
50% Construction Documents					
100% Construction Documents					
100% construction completion					
Other					

How do you conduct the review process for checking completeness and accuracy of rooms/spaces information required for FM staff conducted?

Who is usually involved in the review of the information of rooms required by FM? Select all that apply

☐ Architect
☐ Structural Engineer Consultant
☐ Structural Contractor
☐ MEP Engineer Consultat
☐ MEP Contractor
☐ Civil Engineer
☐ Civil Engineer contractor
☐ Owner / Owner representative
☐ Facility Management Staff

☐ Other (s)

Is any special tool or software used to assist the design team in **reviewing** the information of rooms required by FM? If so, specify it

○ No

○ Yes

For each percent of design completion shown below, indicate if the information of rooms required by FM is **updated**. If this happens, please enter the range of iterations (minimum and maximum), as well as the range of working hours (minumun and maximun) that the incorporation of equipment accesibility ussually takes.

	Updated (yes or no)	Minimun # of Iterations	Maximum # of Iterations	Minimun working hours	Maximum working hours
Preliminary Design					
Schematic Design					
50% Design Development					
100% Design Development					
50% Construction Documents					
100% Construction Documents					
100% construction completion					
Other					

Is any special tool or software used to assist the design team in **updating** the information of rooms required by FM? If so, specify it

○ No

○ Yes ☐

How is the rooms/space information delivered to FM staff? (select all that apply)

☐ Printed documents as part of the handover package

☐ Printed and digital (PDF and CAD) documents as part of the handover package

☐ Printed documents separate from the handover package with this specific information for FM staff

☐ Printed and digital (PDF and CAD) documents separate from the handover package with this specific information for FM staff

☐ 3D model specifically created for O&M activities

☐ Other ☐

Block 4 - Location of major systems

To efficiently manage and perform the operation and maintenance of a building, the FM staff requires reliable and timely information to support decision making throughout the building life-cycle. The accurate location and specifications of the major building systems and equipment will reduce disruptions and time to perform maintenance operations.

Do you identify and incorporate information into the design documentation of accurate location of the major building systems and equipment required by FM staff?

○ Yes

○ No

Is this process conducted at the same time as the information for room/space requirements?

○ Yes

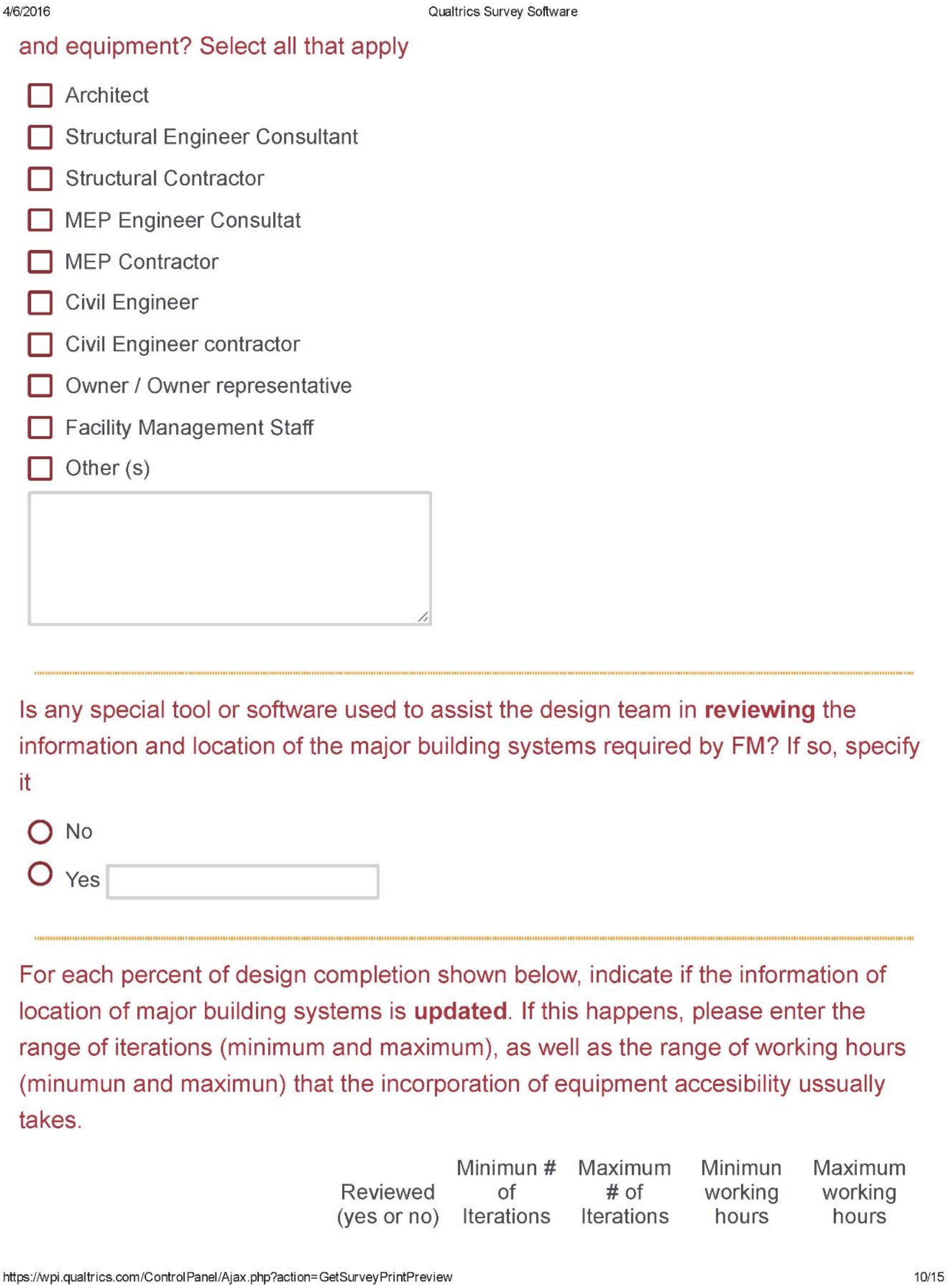
○ No

For each percent of design completion shown below, indicate if the information of location of major building systems is **reviewed**. If this happens, please enter the range of iterations (minimum and maximum), as well as the range of working hours (minumun and maximun) that the incorporation of equipment accesibility ussually takes.

	Reviewed (yes or no)	Minimun # of Iterations	Maximum # of Iterations	Minimun working hours	Maximum working hours
Preliminary Design					
Schematci Design					
50% Design Development					
100% Design Development					
50% Construction Documents					
100% Construction Documents					
100% construction completion					
Other					

How do you conduct the review process for checking completeness and accuracy of the information and location of major systems and equipment required for FM staff conducted?

Who is usually involved in the review of the location of the major building systems



and equipment? Select all that apply

☐ Architect
☐ Structural Engineer Consultant
☐ Structural Contractor
☐ MEP Engineer Consultat
☐ MEP Contractor
☐ Civil Engineer
☐ Civil Engineer contractor
☐ Owner / Owner representative
☐ Facility Management Staff
☐ Other (s)

Is any special tool or software used to assist the design team in **reviewing** the information and location of the major building systems required by FM? If so, specify it

○ No
○ Yes

For each percent of design completion shown below, indicate if the information of location of major building systems is **updated**. If this happens, please enter the range of iterations (minimum and maximum), as well as the range of working hours (minumun and maximun) that the incorporation of equipment accesibility ussually takes.

	Reviewed (yes or no)	Minimun # of Iterations	Maximum # of Iterations	Minimun working hours	Maximum working hours

Conceptual Design	☐	☐	☐	☐	☐
Schematic Design	☐	☐	☐	☐	☐
50% Design Development	☐	☐	☐	☐	☐
100% Design Development	☐	☐	☐	☐	☐
50% Construction Documents	☐	☐	☐	☐	☐
100% Construction Documents	☐	☐	☐	☐	☐
100% construction completion	☐	☐	☐	☐	☐
Other ☐	☐	☐	☐	☐	☐

Is any special tool or software used to assist the design team in **updating** the information and location of the major systems and equipment required by FM? If so, specify it

○ No

○ Yes ☐

How is the information and location of the major systems and equipment delivered to FM staff? (select all that apply)

☐ Printed documents as part of the handover package

☐ Printed and digital (PDF and CAD) documents as part of the handover package

☐ Printed documents separate from the handover package with this specific information for FM staff

☐ Printed and digital (PDF and CAD) documents separate from the handover package with this specific information for FM staff

☐ In a 3D model created specifically for O&M activities

☐ Other ☐

Block 5 - Mechanical and Electrical Equipment standarization

Standardization of equipment helps to the FM staff to reduce specialized maintenance skills, and therefore, minimize disruptive of operation.

To what extend do you standardize the mechanical and electrical equipment during the design?

○ None
○ Between 1% and 25%
○ Between 26% and 50%
○ Between 51% and 75%
○ Between 76% and 100%

Block 6 - Energy Efficiency

Operation Efficiency is directly associate with buidling energy consumption and control of user comfort. The following questions focus on how the buidlign design addresses energy and resource consumtption in order to reduce operation costs

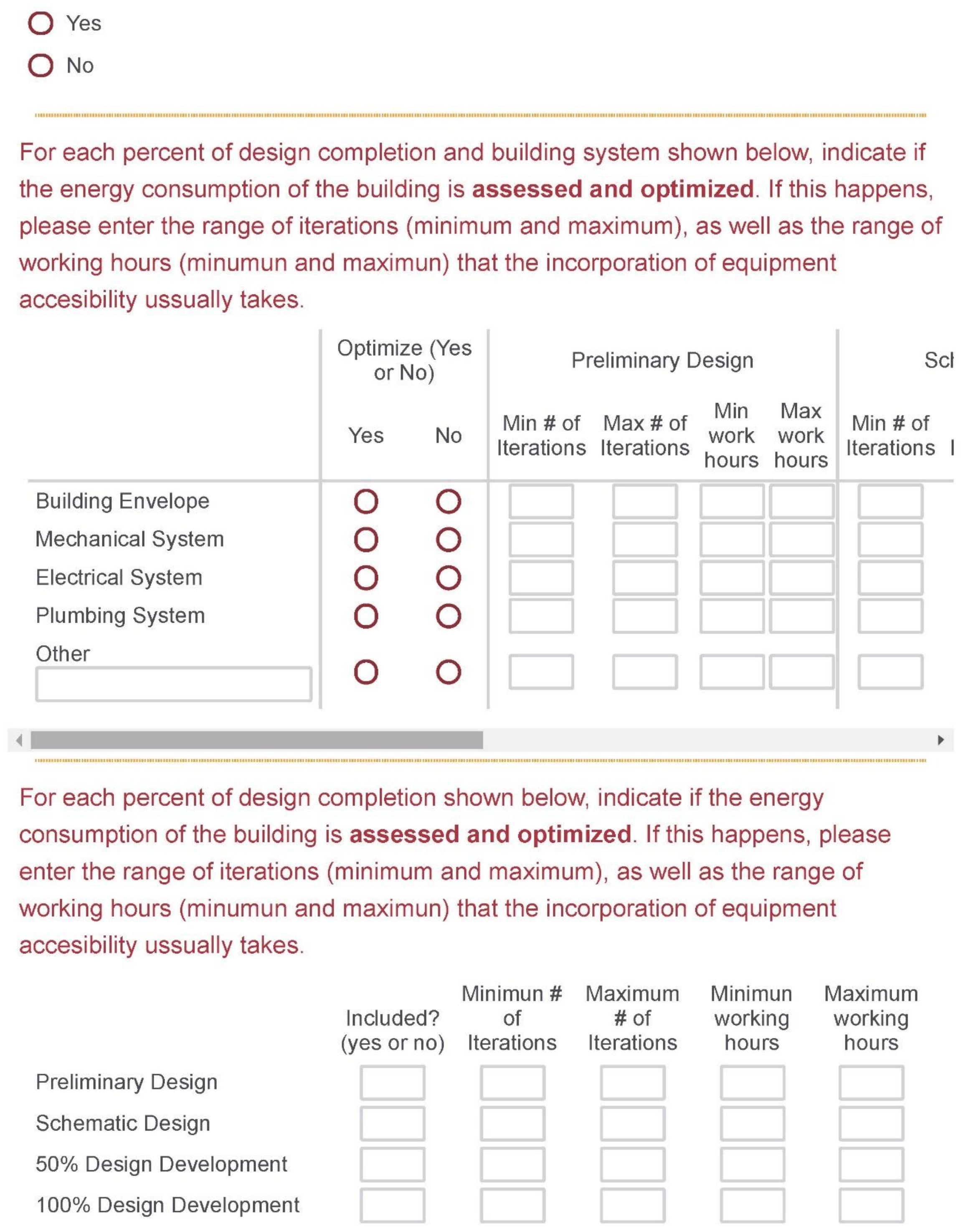
Do you assess and optimize building energy consumption to reduce operation costs?

○ Yes
○ No

What building systems do you assess and optimize in order to reduce the building energy consumption? (select all that apply)

☐ Building Envelope
☐ Mechanical System
☐ Electrical System
☐ Plumbing System
☐ Other ____

Are those systems assessed and optimized simultaneously as a unit?



○ Yes

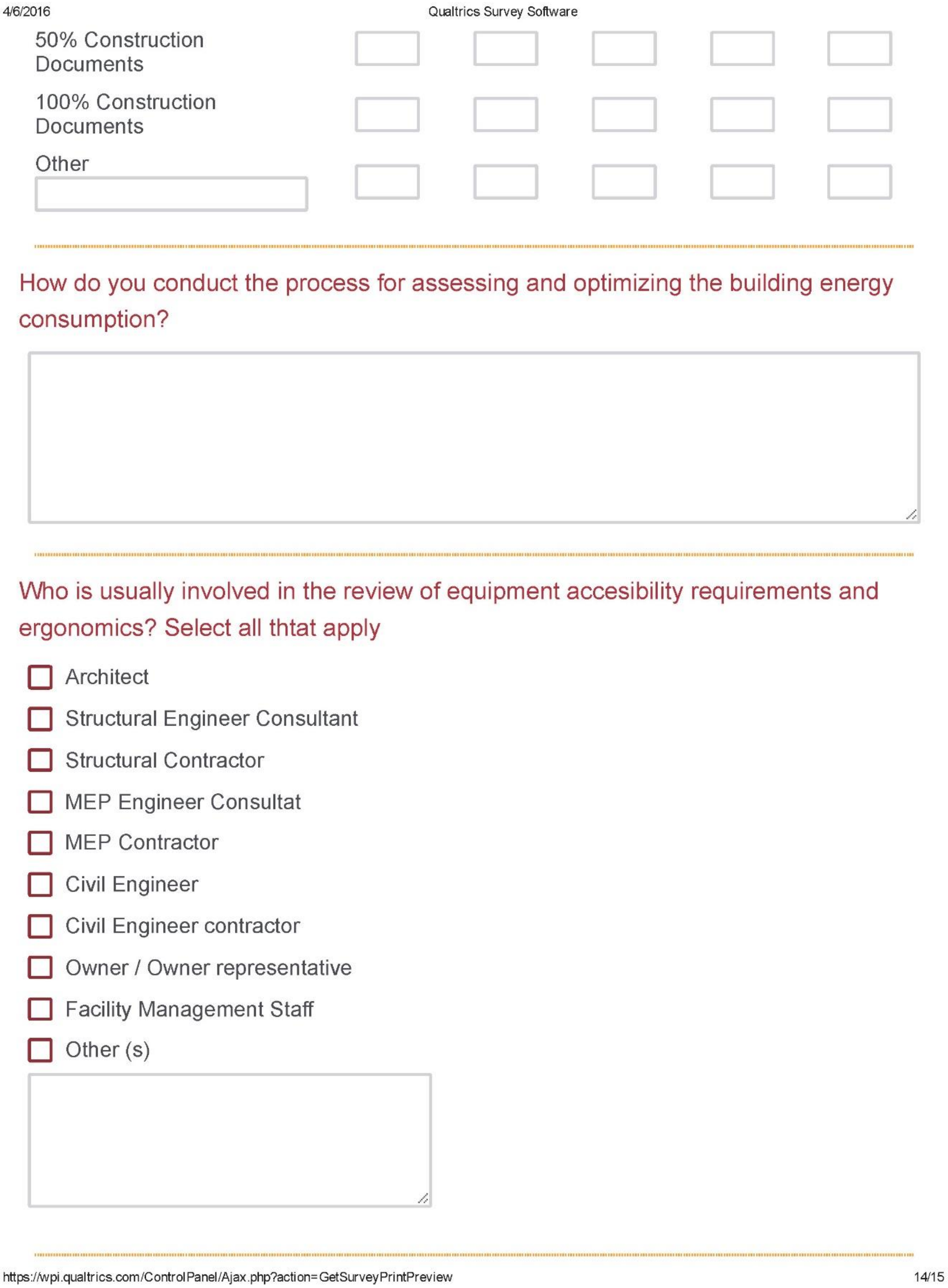
○ No

For each percent of design completion and building system shown below, indicate if the energy consumption of the building is **assessed and optimized**. If this happens, please enter the range of iterations (minimum and maximum), as well as the range of working hours (minumun and maximun) that the incorporation of equipment accesibility ussually takes.

	Optimize (Yes or No)		Preliminary Design				Scl	
	Yes	No	Min # of Iterations	Max # of Iterations	Min work hours	Max work hours	Min # of Iterations	I
Building Envelope	○	○	☐	☐	☐	☐	☐	
Mechanical System	○	○	☐	☐	☐	☐	☐	
Electrical System	○	○	☐	☐	☐	☐	☐	
Plumbing System	○	○	☐	☐	☐	☐	☐	
Other ☐	○	○	☐	☐	☐	☐	☐	

For each percent of design completion shown below, indicate if the energy consumption of the building is **assessed and optimized**. If this happens, please enter the range of iterations (minimum and maximum), as well as the range of working hours (minumun and maximun) that the incorporation of equipment accesibility ussually takes.

	Included? (yes or no)	Minimun # of Iterations	Maximum # of Iterations	Minimun working hours	Maximum working hours
Preliminary Design	☐	☐	☐	☐	☐
Schematic Design	☐	☐	☐	☐	☐
50% Design Development	☐	☐	☐	☐	☐
100% Design Development	☐	☐	☐	☐	☐



50% Construction Documents	☐	☐	☐	☐	☐
100% Construction Documents	☐	☐	☐	☐	☐
Other ☐	☐	☐	☐	☐	☐

How do you conduct the process for assessing and optimizing the building energy consumption?

☐

Who is usually involved in the review of equipment accesibility requirements and ergonomics? Select all thtat apply

- ☐ Architect
- ☐ Structural Engineer Consultant
- ☐ Structural Contractor
- ☐ MEP Engineer Consultat
- ☐ MEP Contractor
- ☐ Civil Engineer
- ☐ Civil Engineer contractor
- ☐ Owner / Owner representative
- ☐ Facility Management Staff
- ☐ Other (s)

☐

Do you use any special tool or software to assist the design team in the assessment and optimization of the building energy consumption? If so, specify it

○ No

○ Yes

Do you consider and include building automation systems into the design?

○ Yes

○ No

To what extend each of the building systems shown below is automated?

	None	1%-25%	26%-50%	51%-75%	76%-100%
HVAC System	○	○	○	○	○
Interior Lighting System	○	○	○	○	○
Natural lighting - curtains	○	○	○	○	○
Irrigation System	○	○	○	○	○
Security System	○	○	○	○	○
Other	○	○	○	○	○
Other	○	○	○	○	○

Do you use any special tool or software to assist the design team in the automation of the building systems? If so, specify it

○ No

○ Yes

Powered by Qualtrics

Default Question Block

Questions Regarding the objective: "Regulatory and Standard Compliance"

The research objective "Regulatory and Standard Compliance" implies that the design meets all applicable codes and regulations. It may also imply that the design is adaptable to emerging codes and regulations, that the documentation effectively communicate code compliance and facilitates timely acquisition of permits, and finally, meets requirements for optional design certifications such as LEED and ISO

Block Emerging Codes and Standards

Do you include or consider emerging standards, codes, and regulations in the building design?

○ Yes

○ No

Describe the steps followed to include emerging codes in the building design

Block Code review/validation process

The code validation is the process to confirm that the building design is compliant with required establised codes and standards, like the building codes, ADA standards, sustainability standards, among others. The following questions are focused on describing the process and the people involved in it.

In order to check the design against required established codes, how is the code review/validation process conducted?

According to your previous response, identify what action starts and ends the code review/validation process? (This action can be other process, activity, event, or document)

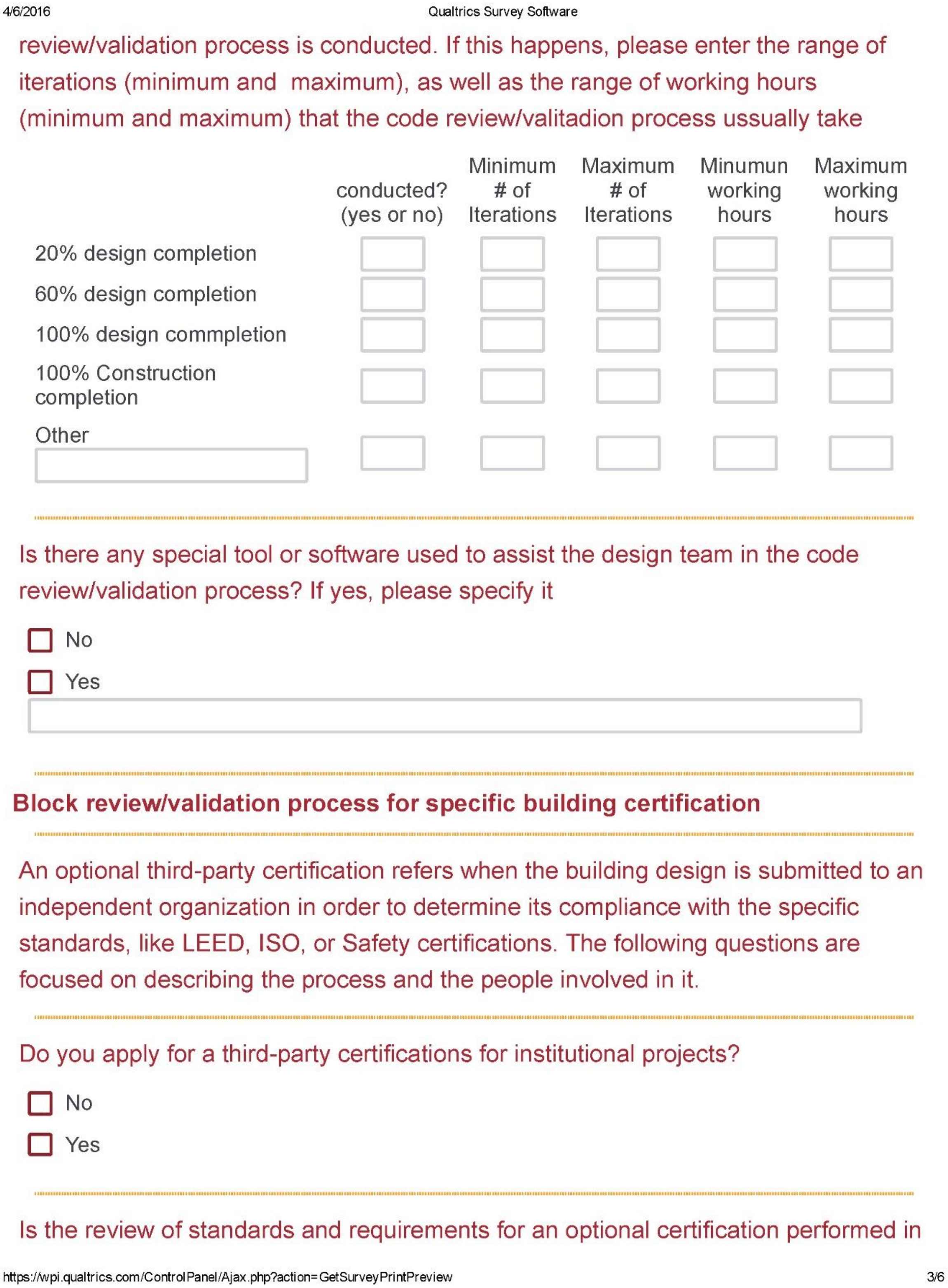
Start of the process

Finish of the process

Who is usually involved in the code review/validation process described above? (Select all that apply)

☐ Architect
☐ Structural Engineer Consultant
☐ Structural Contractor
☐ MEP Engineer Consultat
☐ MEP Contractor
☐ Civil Engineer
☐ Civil Engineer Contractor
☐ Other(s)

For each percent of design completion shown below, indicate if the code



review/validation process is conducted. If this happens, please enter the range of iterations (minimum and maximum), as well as the range of working hours (minimum and maximum) that the code review/valitadion process ussually take

	conducted? (yes or no)	Minimum # of Iterations	Maximum # of Iterations	Minumun working hours	Maximum working hours
20% design completion					
60% design completion					
100% design commpletion					
100% Construction completion					
Other					

Is there any special tool or software used to assist the design team in the code review/validation process? If yes, please specify it

☐ No

☐ Yes

Block review/validation process for specific building certification

An optional third-party certification refers when the building design is submitted to an independent organization in order to determine its compliance with the specific standards, like LEED, ISO, or Safety certifications. The following questions are focused on describing the process and the people involved in it.

Do you apply for a third-party certifications for institutional projects?

☐ No

☐ Yes

Is the review of standards and requirements for an optional certification performed in conjunction with the code validation process?

○ Yes

○ No

In order to check the design against standards and requirements for an optional certification, how is the review process conducted?

According to your previous response, identify what action starts and ends the process of reviewing the standards and requirements for an optional certification? (This action can be other process, activity, event, or document)

Start of the process

Finish of the process

Who is usually involved in the process of applying and reviewing the standards and requirements for that particular cetification? (Select all that apply)

☐ Architect

☐ Structural Engineer Consultant

☐ Structural Contractor

☐ MEP Engineer Consultat

☐ MEP Contractor

☐ Civil Engineer

☐ Civil Engineer Contractor

☐ Other(s)

For each percent of design completion shown below, indicate if the review process for an optional certification is conducted. If this happens, please enter the range of iterations (minimum and maximum), as well as the range of working hours (minimum and maximum) that the review/validation process usually take

	conducted? (yes or no)	Minimum # of Iterations	Maximum # of Iterations	Minumun working hours	Maximum working hours
20% design completion					
60% design completion					
100% design commpletion					
100% Construction completion					
Other					

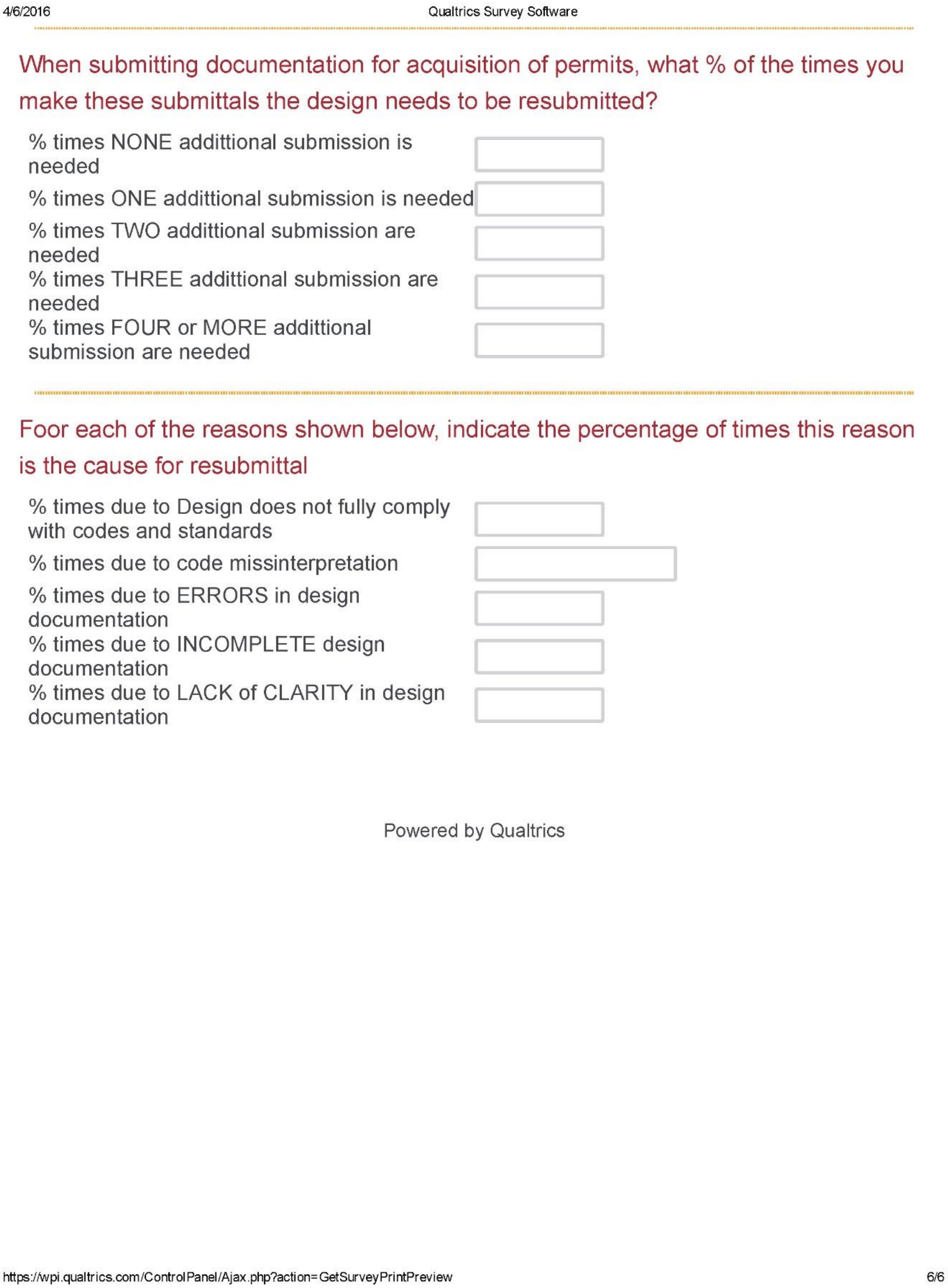
Is there any special tool or software used to assist the design team in the review/validation process for an optional certification? If yes, please specify it

☐ No

☐ Yes

Block Design documentation

Design documentation includes all plans and other documents required by the code official in order to issue the building permits. The following questions are concerned how well the documentation communicate code compliance and facilitates timely acquisition of permits.



When submitting documentation for acquisition of permits, what % of the times you make these submittals the design needs to be resubmitted?

% times NONE addittional submission is needed	
% times ONE addittional submission is needed	
% times TWO addittional submission are needed	
% times THREE addittional submission are needed	
% times FOUR or MORE addittional submission are needed	

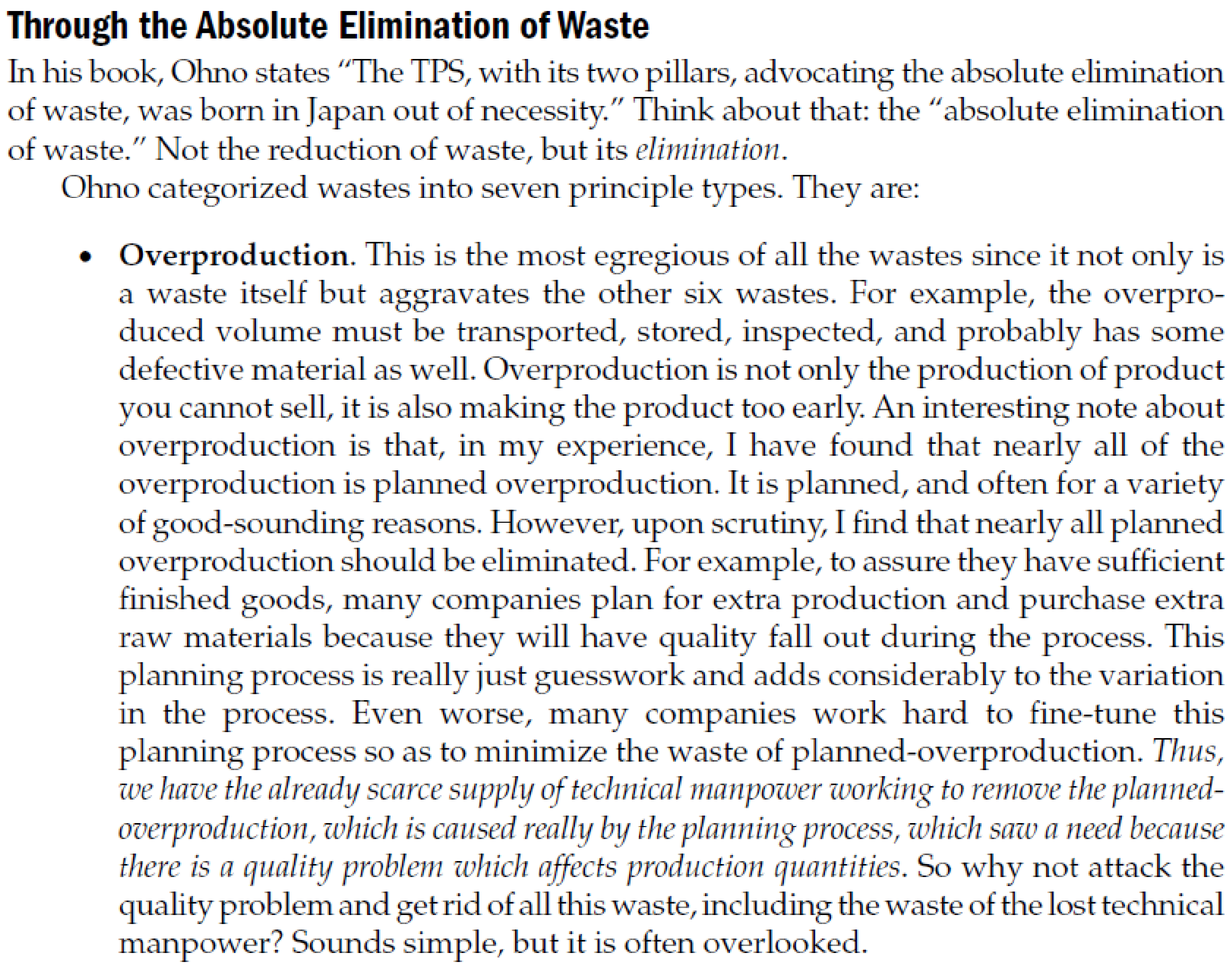
Foor each of the reasons shown below, indicate the percentage of times this reason is the cause for resubmittal

% times due to Design does not fully comply with codes and standards	
% times due to code missinterpretation	
% times due to ERRORS in design documentation	
% times due to INCOMPLETE design documentation	
% times due to LACK of CLARITY in design documentation	

Powered by Qualtrics

Appendix F. Seven Lean Wastes Definitions

This section presents a section of the book How to implement lean manufacturing (Wilson, 2010), where the seven lean wastes are defined.



Through the Absolute Elimination of Waste

In his book, Ohno states "The TPS, with its two pillars, advocating the absolute elimination of waste, was born in Japan out of necessity." Think about that: the "absolute elimination of waste." Not the reduction of waste, but its *elimination*.

Ohno categorized wastes into seven principle types. They are:

- **Overproduction**. This is the most egregious of all the wastes since it not only is a waste itself but aggravates the other six wastes. For example, the overproduced volume must be transported, stored, inspected, and probably has some defective material as well. Overproduction is not only the production of product you cannot sell, it is also making the product too early. An interesting note about overproduction is that, in my experience, I have found that nearly all of the overproduction is planned overproduction. It is planned, and often for a variety of good-sounding reasons. However, upon scrutiny, I find that nearly all planned overproduction should be eliminated. For example, to assure they have sufficient finished goods, many companies plan for extra production and purchase extra raw materials because they will have quality fall out during the process. This planning process is really just guesswork and adds considerably to the variation in the process. Even worse, many companies work hard to fine-tune this planning process so as to minimize the waste of planned-overproduction. *Thus, we have the already scarce supply of technical manpower working to remove the planned-overproduction, which is caused really by the planning process, which saw a need because there is a quality problem which affects production quantities*. So why not attack the quality problem and get rid of all this waste, including the waste of the lost technical manpower? Sounds simple, but it is often overlooked.

Point of Clarity Don't work at getting good at something which should not be done at all!

- **Waiting.** This is simply workers not working for whatever reason. It could be short-term waiting, such as what occurs in an unbalanced line (see the story of the Bravo Line in Chap. 15), or longer waits, such as for stock outs or machinery failure.
- **Transportation.** This is the waste of moving parts around. It occurs between processing steps, between processing lines, and happens when product is shipped to the customer.
- **Overprocessing.** This is the waste of processing a product beyond what the customer wants. Engineers who make specifications that are beyond the needs of the customer often create this waste in the design stage. Choosing poor processing equipment or inefficient processing equipment increase this waste also.
- **Movement.** This is the unnecessary movement of people—such as operators and mechanics walking around, looking for tools or materials. All too often, this is frequently overlooked as a waste. After all, the people are active; they are moving; they look busy. The criterion is not whether they are moving, it is: Are they adding value or not? I can't think of any example of people movement that is value added. Work design and workstation design is a key factor here.

Point of Clarity The TPS is a batch destruction technique.

- **Inventory.** This is the classic waste. All inventories are waste unless the inventory translates directly into sales. It makes no difference whether the inventory is raw materials, WIP, or finished goods. It is waste if it does not directly protect sales.
- **Making defective parts.** This waste is usually called scrap. But the phrase Ohno uses, "making defective parts" is classic Ohno. Most people use the term "scrap," so they view the defective part as waste. Ohno moves far beyond this. He not only categorizes the part as scrap, but the effort and materials to make it. Ohno was a natural process thinker. In this case, he not only lamented the loss of a production unit but the fact that people spent valuable time, effort, and energy to make the unit—all of which was lost, not just the production unit.

Appendix G. – Design Inefficiencies

Inefficiencies/Problems of the design process due to fragmentation - Literature review

Year	Author (s)	Citation	Design Inefficiency	Type of waste
1994	Mitropoulus		Scope uncertainty, scope ambiguity and unclear priorities	
			Unindentified needs and constraints	
			Sub-optimum alternatives	**Overproduction**
			Low constructability of selected alternatives	CONSTRUCTABILITY
			Lack of communication of design information to contractors or vendors - changes & rework	
			Unidentified vendor's constraints and requirements - rework and iterations	**Inventory**
			Design errors and ommisnions that are not discovered before construction	Defects/Rework
			Lack of adequate level of detail for construction operations	CONSTRUCTABILITY
			Lack of considerations of construction constraints	CONSTRUCTABILITY
1999	Tzortzopoulos		Poor comunication	Workflow
	Formoso		Lack of adequate documentation	**Inventory**
2002	Freire		Deficient ot missing input information	**Inventory**
	Alarcon		Unbalanced resource allocation	
			Lack of coordination between disciplines	Workflow
			Erratic decision making	Workflow
			The Information available to complete design tasks is not sufficient	**Inventory**
			Inconsistencies within construction documents	Defects/rework
			Not all requirements are identified at the beginning of the project	**Inventory**
			Design errors are detected in later phases, leading to costly rework	Defects/Rework
			Time consuming or insufficient interactions for improving the design	**Over-Procesing**
			Large incidence of non value adding actiivities in the design process	
			Waiting, moving and inspection of information	**Waiting**
2002	Freire		The time used to design (VA) is a small fraction of the total cycle time to produce the products (draw	**Over-Procesing**
	Alarcon		Clarification of needs	**Inventory**
			Rework	
			Control of internal activities	**Over-Procesing**
			Interdisciplinary revision	**Over-Procesing**
			Interruptions	**Waiting**
			Waiting times (information problems and changes)	**Waiting**
			Irrelevant detailing in drawings	**Overproduction**
			Excessive checking	**Over-Procesing**
			Incomplete work	Defects/Rework
			Delays in accessing to work	**Waiting**
			Delays	**Waiting**
			Defects	Defects/Rework
			Additional processing	**Over-Procesing**
			Ineffective supervision	**Over-Procesing**
			Material loss	
			Unnecessary workforce movement	**Motion**

Inefficiencies/Problems of the design process due to fragmentation - Literature review

2012	Marzouk	Coles	Poor briefing	**Inventory**
			Poor communication	
			Inadequancies in technical knowledge of designers	CONSTRUCTABILITY
			Lack of confidence in preplanning for deign work	
		Pekka	Uncertainity waste	
			Waiting time waste	**Waiting**
			Lot of effort needed for information transfer	**Waiting**
			Unclear description of the client's needs and requests	**Inventory**
			Lack of coordination due to discrepancies between diff departments' design	**Motion**
2014	Chien-Ho		Imporoper Design, Design errors	Defects/Rework
	Neng-Fu		Lack of coordinating design with construction	CONSTRUCTABILITY
			Lack of design input from structural and mechanical designers during the architectural	CONSTRUCTABILITY
			Each design is perfomed independently, so any change requires the plans to be retu	CONSTRUCTABILITY
			Lack of construction expertise during design	CONSTRUCTABILITY
			Poor understandign of the owner's requirements	**Inventory**
2011	Forbes		Poor coordination	CONSTRUCTABILITY
			Poor anticipation of design impacts	CONSTRUCTABILITY

Appendix H. – Cutler Associates Execution Times

Schematic Design Phase Activities Durations

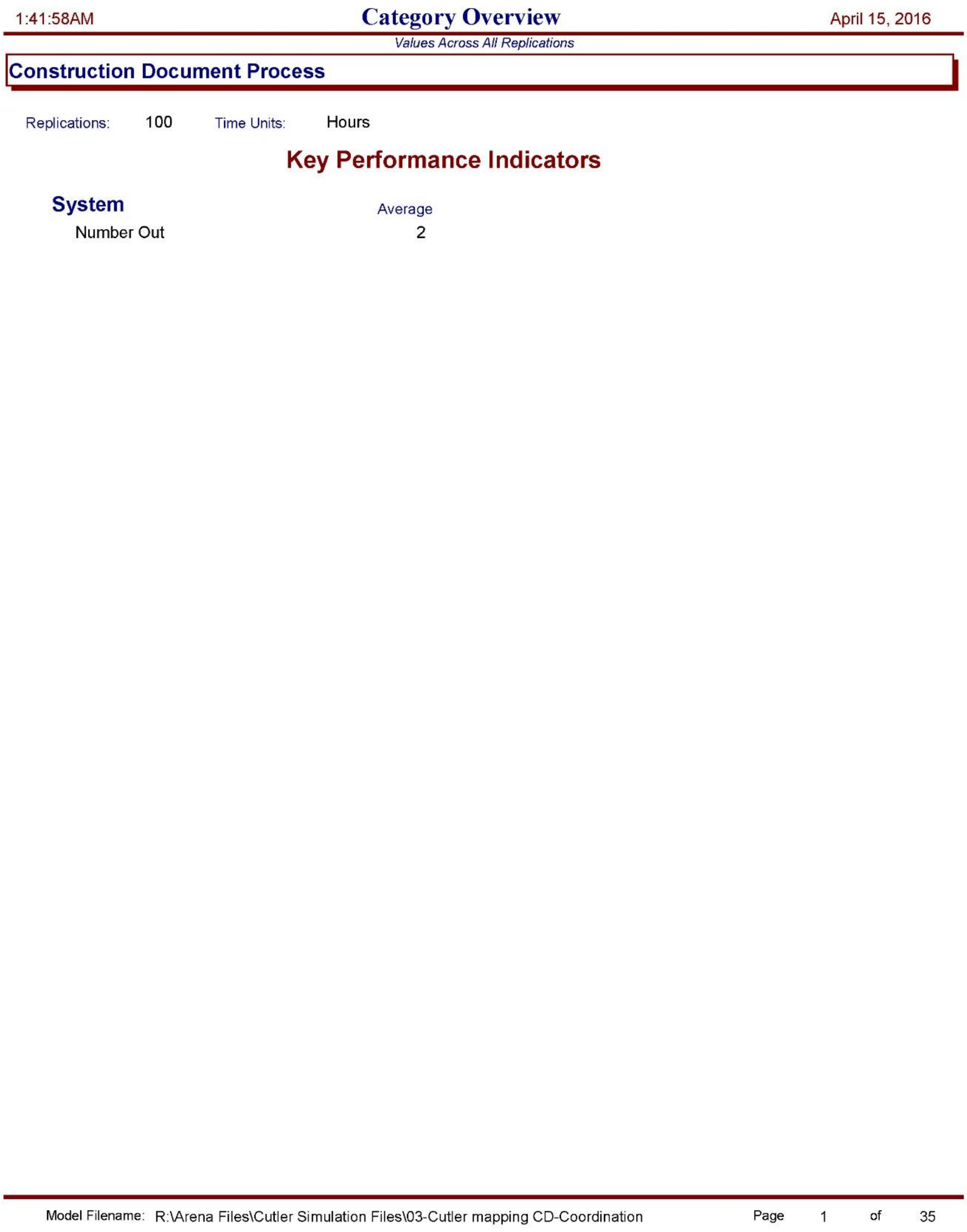
Activity	Duration								
	weeks			days			Hours		
	Min	Max	Most L	Min	Max	Most L	Min	Max	Most L
Asimilate and Analize info	0.25	0.5		1.5	3		12	24	18
Establishing design goals	0.25	0.5		1.5	3		12	24	18
Perform prelimary studies	1	2		6	12		48	96	72
1st review with the AHJs	0.05	0.1		0.3	0.6		2.4	4.8	3.6
Prepare and develop design alternatives	1	2		6	12		48	96	72
Evaluating design alternatives	0.05	0.1		0.3	0.6		2.4	4.8	3.6
Update selected design alternative	0.13	0.3		0.75	1.5		6	12	9
Develop architectural design system	1	2		6	12		48	96	72
Prepare schematic design proposal	0.13	0.3		0.75	1.5		6	12	9
Present SD proposal to the client	0.05	0.1		0.3	0.6		2.4	4.8	3.6
Preliminary Code Compliance all systems				0.625	2.5		5	20	12.5
Submit SD to the Agencies	0.5	1		3	6		24	48	36
Activities at 20% of oridinal duration									
Perform prelimary studies I2	0.2	0.4		1.2	2.4		9.6	19.2	14.4
Prepare and develop design alternatives I2	0.2	0.4		1.2	2.4		9.6	19.2	14.4
Evaluating design alternatives I2	0.05	0.1		0.3	0.6		2.4	4.8	3.6
Update selected design alternative I2	0.13	0.3		0.75	1.5		6	12	9
Develop architectural design system I2	0.2	0.4		1.2	2.4		9.6	19.2	14.4
Prepare schematic design proposal I2	0.13	0.3		0.75	1.5		6	12	9
	5.3	11	0	32.43	66	0	259	529	394
Total time estimated	**9**	**11**		**54**	**66**		**432**	**528**	**480**

1	week	6	days
1	day	8	hours

Design Development Phase Activities Durations

Activity	Duration								
	weeks			days			Hours		
	Min	Max	Most L	Min	Max	Most L	Min	Max	Most L
Update SD Performance Criteria - Select MEP	0.5	1.2		3	7		24	56.2	40.1
DD System Schemes	2	3		12	18		96	144	120
Evaluating SA and Code Review	0.42	0.9		2.52	5.1		20.2	40.8	30.5
DD System Schemes2	0.25	0.5		1.5	3		12	24	18
Evaluating SA and Code Review	0.03	0.1		0.15	0.3		1.2	2.4	1.8
DD Systems Layout	2	3		12	18		96	144	120
2D Coordination and Code Review	0.42	0.9		2.52	5.1		20.2	40.8	30.5
Meet the Buildign Department	0.2	0.3		1.2	1.8		9.6	14.4	12
Submit DD to the Client	0.1	0.1		0.6	0.8		4.8	6.24	5.52
Submit DD to the Agencies	1	1.5		6	9		48	72	60
Create Addenda	0.5	1		3	6		24	48	36
Submit addenda to the Agencies	1	1.5		6	9		48	72	60
DD Systems Layout2	0.5	0.8		3	4.5		24	36	30
2D Coordination and Code Review2	0.42	0.9		2.52	5.1		20.2	40.8	30.5
Meet the Buildign Department2	0.2	0.3		1.2	1.8		9.6	14.4	12
	9.54	16	0	57.21	95	0	458	756	607
Total time estimated	**12**	**16**		**72**	**96**		**576**	**768**	**672**

Appendix I. – Cutler Associates Simulation Results



1:41:58AM **Category Overview** April 15, 2016

Values Across All Replications

Construction Document Process

Replications: 100 Time Units: Hours

Key Performance Indicators

System	Average
Number Out	2

Model Filename: R:\Arena Files\Cutler Simulation Files\03-Cutler mapping CD-Coordination Page 1 of 35

Construction Document Process

Replications: 100 Time Units: Hours

Entity

Time

VA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	63.6223	3.20	37.3792	117.88	26.8696	175.89

NVA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	0.00	0.00	0.00	0.00	0.00	0.00

Wait Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	67.2097	4.84	35.7361	144.69	24.3321	160.51

Transfer Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	0.00	0.00	0.00	0.00	0.00	0.00

Other Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	0.00	0.00	0.00	0.00	0.00	0.00

Total Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	95.4486	5.82	52.7606	196.61	44.5453	223.92

Other

Number In	Average	Half Width	Minimum Average	Maximum Average
SD	16.6100	0.92	11.0000	34.0000

Number Out	Average	Half Width	Minimum Average	Maximum Average
SD	16.6100	0.92	11.0000	34.0000

WIP	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	8.4663	0.49	4.9695	16.7054	0.00	27.0000

Values Across All Replications

Construction Document Process

Replications: 100 Time Units: Hours

Process

Time per Entity

Construction Document Process

Replications: 100 Time Units: Hours

Process

Time per Entity

VA Time Per Entity	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Compile all disciplines model 1L	2.7170	0.09	2.0213	3.8973	2.0213	3.9494
Compile all disciplines model 2L	2.6921	0.08	2.0142	3.9490	2.0040	3.9490
Complile ASH models 1L	2.7080	0.10	2.0070	3.8241	2.0070	3.8241
Complile ASH models 2 level	2.6851	0.09	2.0250	3.9122	2.0130	3.9122
Create arch model for coordination 1L	2.6971	0.10	2.0171	3.8848	2.0171	3.8848
Create architectural model for coordination 2L	2.7422	0.09	2.0141	3.9182	2.0036	3.9182
Create HVAC model for coordination 1L	2.7341	0.10	2.0009	3.7344	2.0009	3.7344
Create HVAC model for coordination 2L	2.5503	0.08	2.0029	3.7105	2.0029	3.7105
Create remaining models 1L	2.6435	0.08	2.0077	3.7961	2.0003	3.9112
Create remaining models 2L	2.6574	0.08	2.0019	3.8688	2.0019	3.8688
Create stuctural model for coordination 1L	2.6521	0.09	2.0236	3.7943	2.0236	3.7943
Create stuctural model for coordination 2L	2.7097	0.10	2.0032	3.7238	2.0032	3.7583
Establish LOD and coordination schedule	2.6632	0.10	2.0041	3.8536	2.0041	3.8536
Identify models required for coordination	15.3586	0.61	8.3640	23.4652	8.3640	23.4652
Identify solutions 1 level	1.5116	0.28	0.00	3.7310	0.00	3.7310
Identify solutions all disciplines 1L	1.2795	0.27	0.00	3.2766	0.00	3.9691
Identify solutions all disciplines 2L	1.3110	0.28	0.00	3.9488	0.00	3.9488
Identify solutions ASH 2L	1.4849	0.28	0.00	3.8471	0.00	3.8471
Perform clash detection all disciplines 1L	2.7106	0.08	2.0087	3.7993	2.0087	3.8339
Perform clash detection all disciplines 2L	2.6987	0.08	2.0033	3.7250	2.0033	3.8934
Perform clash detection ASH 1L	2.6854	0.09	2.0030	3.7981	2.0030	3.7981
Perform clash detection ASH 2L	2.6342	0.09	2.0253	3.7215	2.0173	3.7674
Prepare coordination drawings 1L	2.6889	0.08	2.0133	3.6814	2.0099	3.8619
Prepare coordination drawings 2L	2.6854	0.08	2.0052	3.7325	2.0031	3.8972
Review coordination drawings 1L	2.6492	0.08	2.0005	3.6829	2.0005	3.9217
Review coordination drawings 2L	2.6111	0.07	2.0112	3.7328	2.0015	3.7793

Values Across All Replications

Construction Document Process

Replications: 100 Time Units: Hours

Process

Time per Entity

VA Time Per Entity	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Update arch model for coordination 1L	0.5069	0.21	0.00	3.7087	0.00	3.7087
Update coordinated ASH models 1L	2.6931	0.08	2.0198	3.7286	2.0043	3.7286
Update coordinated ASH models 2L	2.6142	0.08	2.0003	3.8390	2.0003	3.8658
Update HVAC model for coordination 1L	0.4912	0.21	0.00	3.7487	0.00	3.7487
Update stuctural model for coordination 1L	0.5094	0.22	0.00	3.5161	0.00	3.5161

Construction Document Process

Replications: 100 Time Units: Hours

Process

Time per Entity

Wait Time Per Entity	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Compile all disciplines model 1L	6.6547	0.36	1.9736	10.2950	0.00	10.2950
Compile all disciplines model 2L	2.2901	0.37	0.00	6.5538	0.00	6.8110
Complile ASH models 1L	0.00	0.00	0.00	0.00	0.00	0.00
Complile ASH models 2 level	2.6624	0.13	0.9163	4.0639	0.00	5.7996
Create arch model for coordination 1L	0.00	0.00	0.00	0.00	0.00	0.00
Create architectural model for coordination 2L	5.0865	0.18	2.3707	7.1954	0.00	7.1954
Create HVAC model for coordination 1L	0.00	0.00	0.00	0.00	0.00	0.00
Create HVAC model for coordination 2L	10.5384	0.22	7.3393	13.1537	5.1962	13.1537
Create remaining models 1L	1.0643	0.26	0.00	5.2471	0.00	8.8582
Create remaining models 2L	2.5119	0.34	0.00	6.2817	0.00	7.0512
Create stuctural model for coordination 1L	2.6971	0.10	2.0171	3.8848	2.0171	3.8848
Create stuctural model for coordination 2L	7.8287	0.20	4.8428	10.3987	2.1704	10.3987
Establish LOD and coordination schedule	0.00	0.00	0.00	0.00	0.00	0.00
Identify models required for coordination	0.00	0.00	0.00	0.00	0.00	0.00
Identify solutions 1 level	0.00	0.00	0.00	0.00	0.00	0.00
Identify solutions all disciplines 1L	1.2371	0.27	0.00	3.7317	0.00	3.8397
Identify solutions all disciplines 2L	0.5775	0.22	0.00	3.7285	0.00	3.7285
Identify solutions ASH 2L	1.3502	0.27	0.00	3.8106	0.00	3.8106
Perform clash detection all disciplines 1L	2.5357	0.11	0.8342	3.8682	0.00	3.9122
Perform clash detection all disciplines 2L	1.5519	0.25	0.00	3.5950	0.00	3.8339
Perform clash detection ASH 1L	0.00	0.00	0.00	0.00	0.00	0.00
Perform clash detection ASH 2L	2.5885	0.13	0.8067	3.7993	0.00	3.7993
Prepare coordination drawings 1L	2.4549	0.23	0.00	4.6566	0.00	7.4324
Prepare coordination drawings 2L	1.1885	0.29	0.00	4.5976	0.00	6.4237
Review coordination drawings 1L	2.9656	0.37	0.00	8.0643	0.00	9.0185
Review coordination drawings 2L	1.1618	0.33	0.00	6.8752	0.00	6.8752

Construction Document Process

Replications: 100 Time Units: Hours

Process

Time per Entity

Wait Time Per Entity	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Update arch model for coordination 1L	0.00	0.00	0.00	0.00	0.00	0.00
Update coordinated ASH models 1L	3.7078	0.26	2.0077	7.8089	2.0042	11.1992
Update coordinated ASH models 2L	5.1693	0.35	2.0272	9.4117	2.0216	9.4855
Update HVAC model for coordination 1L	1.0162	0.43	0.00	6.1884	0.00	6.1884
Update stuctural model for coordination 1L	0.5069	0.21	0.00	3.7087	0.00	3.7087

Construction Document Process

Replications: 100 Time Units: Hours

Process

Time per Entity

Total Time Per Entity	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Compile all disciplines model 1L	9.3717	0.37	4.5756	14.1923	2.3450	14.1923
Compile all disciplines model 2L	4.9822	0.39	2.0414	9.0598	2.0069	10.3701
Complile ASH models 1L	2.7080	0.10	2.0070	3.8241	2.0070	3.8241
Complile ASH models 2 level	5.3476	0.15	3.4398	7.4613	2.3294	8.7007
Create arch model for coordination 1L	2.6971	0.10	2.0171	3.8848	2.0171	3.8848
Create architectural model for coordination 2L	7.8287	0.20	4.8428	10.3987	2.1704	10.3987
Create HVAC model for coordination 1L	2.7341	0.10	2.0009	3.7344	2.0009	3.7344
Create HVAC model for coordination 2L	13.0888	0.23	9.9084	15.4409	7.3806	16.2408
Create remaining models 1L	3.7078	0.26	2.0077	7.8089	2.0042	11.1992
Create remaining models 2L	5.1693	0.35	2.0272	9.4117	2.0216	9.4855
Create stuctural model for coordination 1L	5.3492	0.14	4.1955	7.5965	4.1955	7.5965
Create stuctural model for coordination 2L	10.5384	0.22	7.3393	13.1537	5.1962	13.1537
Establish LOD and coordination schedule	2.6632	0.10	2.0041	3.8536	2.0041	3.8536
Identify models required for coordination	15.3586	0.61	8.3640	23.4652	8.3640	23.4652
Identify solutions 1 level	1.5116	0.28	0.00	3.7310	0.00	3.7310
Identify solutions all disciplines 1L	2.5166	0.53	0.00	6.3807	0.00	7.1894
Identify solutions all disciplines 2L	1.8885	0.43	0.00	6.4087	0.00	6.8196
Identify solutions ASH 2L	2.8351	0.53	0.00	7.4770	0.00	7.4770
Perform clash detection all disciplines 1L	5.2463	0.13	3.5670	6.9843	2.0504	7.4946
Perform clash detection all disciplines 2L	4.2506	0.25	2.0805	6.6451	2.0198	7.2611
Perform clash detection ASH 1L	2.6854	0.09	2.0030	3.7981	2.0030	3.7981
Perform clash detection ASH 2L	5.2227	0.15	3.4194	6.8770	2.0350	7.3957
Prepare coordination drawings 1L	5.1438	0.25	2.0706	7.5924	2.0706	10.1211
Prepare coordination drawings 2L	3.8739	0.30	2.0052	7.4308	2.0031	9.1218
Review coordination drawings 1L	5.6148	0.37	2.1427	10.0841	2.0588	12.8730
Review coordination drawings 2L	3.7729	0.33	2.0673	9.6369	2.0015	9.6369

Construction Document Process

Replications: 100 Time Units: Hours

Process

Time per Entity

Total Time Per Entity	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Update arch model for coordination 1L	0.5069	0.21	0.00	3.7087	0.00	3.7087
Update coordinated ASH models 1L	6.4009	0.28	4.1124	10.5136	4.1124	13.8841
Update coordinated ASH models 2L	7.7835	0.34	5.1176	12.6860	4.2306	12.6860
Update HVAC model for coordination 1L	1.5074	0.63	0.00	9.7318	0.00	9.7318
Update stuctural model for coordination 1L	1.0162	0.43	0.00	6.1884	0.00	6.1884

Accumulated Time

Construction Document Process

Replications: 100 Time Units: Hours

Process

Accumulated Time

Accum VA Time	Average	Half Width	Minimum Average	Maximum Average
Compile all disciplines model 1L	5.4670	0.76	2.0213	16.9777
Compile all disciplines model 2L	5.4212	0.80	2.0142	25.5430
Complile ASH models 1L	3.3155	0.29	2.0070	8.7301
Complile ASH models 2 level	3.4227	0.32	2.0250	10.8216
Create arch model for coordination 1L	2.6971	0.10	2.0171	3.8848
Create architectural model for coordination 2L	3.4749	0.31	2.0141	9.8903
Create HVAC model for coordination 1L	2.7341	0.10	2.0009	3.7344
Create HVAC model for coordination 2L	3.2676	0.32	2.0029	9.9142
Create remaining models 1L	5.3322	0.74	2.0077	18.1640
Create remaining models 2L	5.4062	0.83	2.0019	27.8792
Create stuctural model for coordination 1L	2.6521	0.09	2.0236	3.7943
Create stuctural model for coordination 2L	3.4983	0.37	2.0032	13.0429
Establish LOD and coordination schedule	2.6632	0.10	2.0041	3.8536
Identify models required for coordination	15.3586	0.61	8.3640	23.4652
Identify solutions 1 level	1.6206	0.32	0.00	5.8337
Identify solutions all disciplines 1L	2.7179	0.75	0.00	14.4176
Identify solutions all disciplines 2L	2.7249	0.79	0.00	22.6127
Identify solutions ASH 2L	1.8455	0.41	0.00	11.3312
Perform clash detection all disciplines 1L	5.4780	0.75	2.0087	16.5091
Perform clash detection all disciplines 2L	5.4464	0.80	2.0033	28.0284
Perform clash detection ASH 1L	3.3059	0.30	2.0030	8.4957
Perform clash detection ASH 2L	3.3912	0.35	2.0253	12.3343
Prepare coordination drawings 1L	5.3245	0.83	2.0133	28.5761
Prepare coordination drawings 2L	6.5305	1.01	2.0052	25.1305
Review coordination drawings 1L	5.2572	0.84	2.0005	29.3822
Review coordination drawings 2L	6.3409	0.99	2.0112	25.0470

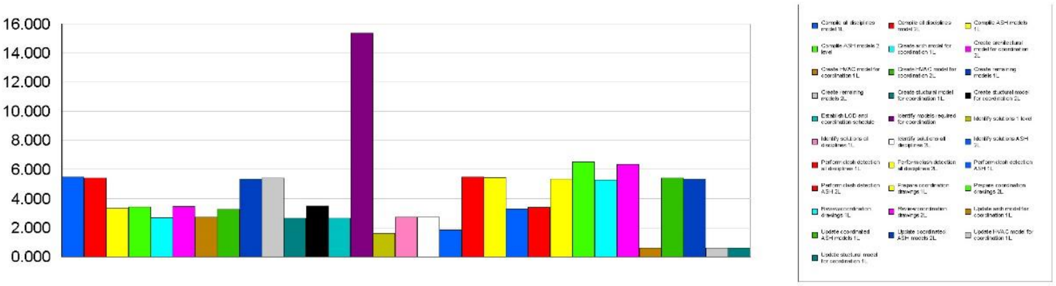
Construction Document Process

Replications: 100 Time Units: Hours

Process

Accumulated Time

Accum VA Time	Average	Half Width	Minimum Average	Maximum Average
Update arch model for coordination 1L	0.6078	0.27	0.00	5.4059
Update coordinated ASH models 1L	5.4021	0.74	2.0225	16.7399
Update coordinated ASH models 2L	5.3298	0.81	2.0003	26.2987
Update HVAC model for coordination 1L	0.5948	0.27	0.00	6.0979
Update stuctural model for coordination 1L	0.6158	0.28	0.00	6.4160



Construction Document Process

Replications: 100 Time Units: Hours

Process

Accumulated Time

Accum Wait Time	Average	Half Width	Minimum Average	Maximum Average
Compile all disciplines model 1L	11.4283	1.00	6.4042	31.2234
Compile all disciplines model 2L	3.7365	0.77	0.00	20.8484
Complile ASH models 1L	0.00	0.00	0.00	0.00
Complile ASH models 2 level	3.2865	0.30	2.0213	12.1918
Create arch model for coordination 1L	0.00	0.00	0.00	0.00
Create architectural model for coordination 2L	6.1779	0.37	4.3313	13.0897
Create HVAC model for coordination 1L	0.00	0.00	0.00	0.00
Create HVAC model for coordination 2L	13.1511	0.99	9.1779	36.0229
Create remaining models 1L	3.3715	0.93	0.00	20.9886
Create remaining models 2L	4.1015	0.71	0.00	18.2317
Create stuctural model for coordination 1L	2.6971	0.10	2.0171	3.8848
Create stuctural model for coordination 2L	9.6528	0.64	6.5518	22.9800
Establish LOD and coordination schedule	0.00	0.00	0.00	0.00
Identify models required for coordination	0.00	0.00	0.00	0.00
Identify solutions 1 level	0.00	0.00	0.00	0.00
Identify solutions all disciplines 1L	2.4474	0.65	0.00	14.4826
Identify solutions all disciplines 2L	1.0272	0.45	0.00	12.3726
Identify solutions ASH 2L	1.6005	0.34	0.00	6.1149
Perform clash detection all disciplines 1L	4.8097	0.58	2.0250	14.3106
Perform clash detection all disciplines 2L	2.4824	0.50	0.00	13.3927
Perform clash detection ASH 1L	0.00	0.00	0.00	0.00
Perform clash detection ASH 2L	3.1617	0.26	2.0087	8.2193
Prepare coordination drawings 1L	5.1103	0.99	0.00	31.5577
Prepare coordination drawings 2L	2.7688	0.87	0.00	20.7469
Review coordination drawings 1L	5.6227	0.99	0.00	25.1029
Review coordination drawings 2L	2.5200	0.83	0.00	21.8019

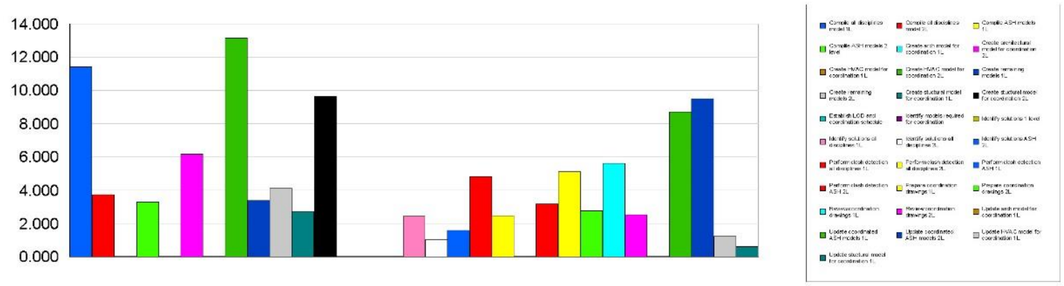
Construction Document Process

Replications: 100 Time Units: Hours

Process

Accumulated Time

Accum Wait Time	Average	Half Width	Minimum Average	Maximum Average
Update arch model for coordination 1L	0.00	0.00	0.00	0.00
Update coordinated ASH models 1L	8.7037	1.60	2.0077	31.2357
Update coordinated ASH models 2L	9.5077	1.22	2.1855	33.6821
Update HVAC model for coordination 1L	1.2236	0.54	0.00	11.8219
Update stuctural model for coordination 1L	0.6078	0.27	0.00	5.4059



Other

Construction Document Process

Replications: 100 Time Units: Hours

Process

Other

Number In	Average	Half Width	Minimum Average	Maximum Average
Compile all disciplines model 1L	2.0200	0.28	1.0000	6.0000
Compile all disciplines model 2L	2.0200	0.30	1.0000	10.0000
Complile ASH models 1L	1.2300	0.10	1.0000	3.0000
Complile ASH models 2 level	1.2800	0.12	1.0000	4.0000
Create arch model for coordination 1L	1.0000	0.00	1.0000	1.0000
Create architectural model for coordination 2L	1.2800	0.12	1.0000	4.0000
Create HVAC model for coordination 1L	1.0000	0.00	1.0000	1.0000
Create HVAC model for coordination 2L	1.2800	0.12	1.0000	4.0000
Create remaining models 1L	2.0200	0.28	1.0000	6.0000
Create remaining models 2L	2.0200	0.30	1.0000	10.0000
Create stuctural model for coordination 1L	1.0000	0.00	1.0000	1.0000
Create stuctural model for coordination 2L	1.2800	0.12	1.0000	4.0000
Establish LOD and coordination schedule	1.0000	0.00	1.0000	1.0000
Identify models required for coordination	1.0000	0.00	1.0000	1.0000
Identify solutions 1 level	0.6000	0.11	0.00	2.0000
Identify solutions all disciplines 1L	1.0200	0.28	0.00	5.0000
Identify solutions all disciplines 2L	1.0200	0.30	0.00	9.0000
Identify solutions ASH 2L	0.6900	0.15	0.00	4.0000
Perform clash detection all disciplines 1L	2.0200	0.28	1.0000	6.0000
Perform clash detection all disciplines 2L	2.0200	0.30	1.0000	10.0000
Perform clash detection ASH 1L	1.2300	0.10	1.0000	3.0000
Perform clash detection ASH 2L	1.2800	0.12	1.0000	4.0000
Prepare coordination drawings 1L	1.9800	0.31	1.0000	11.0000
Prepare coordination drawings 2L	2.4300	0.37	1.0000	9.0000
Review coordination drawings 1L	1.9800	0.31	1.0000	11.0000
Review coordination drawings 2L	2.4300	0.37	1.0000	9.0000

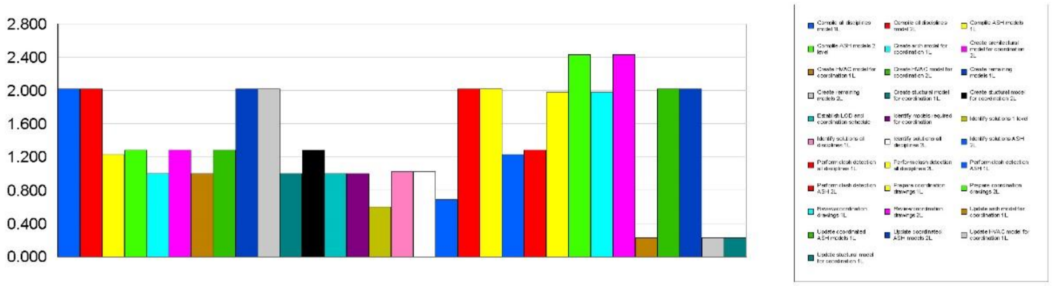
Construction Document Process

Replications: 100 Time Units: Hours

Process

Other

Number In	Average	Half Width	Minimum Average	Maximum Average
Update arch model for coordination 1L	0.2300	0.10	0.00	2.0000
Update coordinated ASH models 1L	2.0200	0.28	1.0000	6.0000
Update coordinated ASH models 2L	2.0200	0.30	1.0000	10.0000
Update HVAC model for coordination 1L	0.2300	0.10	0.00	2.0000
Update stuctural model for coordination 1L	0.2300	0.10	0.00	2.0000



Construction Document Process

Replications: 100 Time Units: Hours

Process

Other

Number Out	Average	Half Width	Minimum Average	Maximum Average
Compile all disciplines model 1L	2.0200	0.28	1.0000	6.0000
Compile all disciplines model 2L	2.0200	0.30	1.0000	10.0000
Complile ASH models 1L	1.2300	0.10	1.0000	3.0000
Complile ASH models 2 level	1.2800	0.12	1.0000	4.0000
Create arch model for coordination 1L	1.0000	0.00	1.0000	1.0000
Create architectural model for coordination 2L	1.2800	0.12	1.0000	4.0000
Create HVAC model for coordination 1L	1.0000	0.00	1.0000	1.0000
Create HVAC model for coordination 2L	1.2800	0.12	1.0000	4.0000
Create remaining models 1L	2.0200	0.28	1.0000	6.0000
Create remaining models 2L	2.0200	0.30	1.0000	10.0000
Create stuctural model for coordination 1L	1.0000	0.00	1.0000	1.0000
Create stuctural model for coordination 2L	1.2800	0.12	1.0000	4.0000
Establish LOD and coordination schedule	1.0000	0.00	1.0000	1.0000
Identify models required for coordination	1.0000	0.00	1.0000	1.0000
Identify solutions 1 level	0.6000	0.11	0.00	2.0000
Identify solutions all disciplines 1L	1.0200	0.28	0.00	5.0000
Identify solutions all disciplines 2L	1.0200	0.30	0.00	9.0000
Identify solutions ASH 2L	0.6900	0.15	0.00	4.0000
Perform clash detection all disciplines 1L	2.0200	0.28	1.0000	6.0000
Perform clash detection all disciplines 2L	2.0200	0.30	1.0000	10.0000
Perform clash detection ASH 1L	1.2300	0.10	1.0000	3.0000
Perform clash detection ASH 2L	1.2800	0.12	1.0000	4.0000
Prepare coordination drawings 1L	1.9800	0.31	1.0000	11.0000
Prepare coordination drawings 2L	2.4300	0.37	1.0000	9.0000
Review coordination drawings 1L	1.9800	0.31	1.0000	11.0000
Review coordination drawings 2L	2.4300	0.37	1.0000	9.0000

Construction Document Process

Replications: 100 Time Units: Hours

Process

Other

Number Out	Average	Half Width	Minimum Average	Maximum Average
Update arch model for coordination 1L	0.2300	0.10	0.00	2.0000
Update coordinated ASH models 1L	2.0200	0.28	1.0000	6.0000
Update coordinated ASH models 2L	2.0200	0.30	1.0000	10.0000
Update HVAC model for coordination 1L	0.2300	0.10	0.00	2.0000
Update stuctural model for coordination 1L	0.2300	0.10	0.00	2.0000

Construction Document Process

Replications: 100 Time Units: Hours

Queue

Time

Construction Document Process

Replications: 100 Time Units: Hours

Queue

Time

Waiting Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
All disciplines Batch 1L.Queue	1.3465	0.04	1.0099	1.8643	0.00	3.7286
All disciplines Batch 2L.Queue	1.3071	0.04	1.0002	1.9195	0.00	3.8658
Arch and Struct Batch 1L.Queue	1.3261	0.04	1.0118	1.8971	0.00	3.7943
Compile all disciplines model 1L.Queue	6.6547	0.36	1.9736	10.2950	0.00	10.2950
Compile all disciplines model 2L.Queue	2.2901	0.37	0.00	6.5538	0.00	6.8110
Complile ASH models 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Complile ASH models 2 level.Queue	2.6624	0.13	0.9163	4.0639	0.00	5.7996
Coordination model 2L batch.Queue	2.6035	0.06	2.0068	3.3990	0.00	6.9471
Create arch model for coordination 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Create architectural model for coordination 2L.Queue	5.0865	0.18	2.3707	7.1954	0.00	7.1954
Create HVAC model for coordination 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Create HVAC model for coordination 2L.Queue	10.5384	0.22	7.3393	13.1537	5.1962	13.1537
Create remaining models 1L.Queue	1.0643	0.26	0.00	5.2471	0.00	8.8582
Create remaining models 2L.Queue	2.5119	0.34	0.00	6.2817	0.00	7.0512
Create stuctural model for coordination 1L.Queue	2.6971	0.10	2.0171	3.8848	2.0171	3.8848
Create stuctural model for coordination 2L.Queue	7.8287	0.20	4.8428	10.3987	2.1704	10.3987
Establish LOD and coordination schedule.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Identify models required for coordination.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Identify solutions 1 level.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Identify solutions all disciplines 1L.Queue	1.2371	0.27	0.00	3.7317	0.00	3.8397
Identify solutions all disciplines 2L.Queue	0.5775	0.22	0.00	3.7285	0.00	3.7285
Identify solutions ASH 2L.Queue	1.3502	0.27	0.00	3.8106	0.00	3.8106
Perform clash detection all disciplines 1L.Queue	2.5357	0.11	0.8342	3.8682	0.00	3.9122
Perform clash detection all disciplines 2L.Queue	1.5519	0.25	0.00	3.5950	0.00	3.8339
Perform clash detection ASH 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00

Construction Document Process

Replications: 100 Time Units: Hours

Queue

Time

Waiting Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Perform clash detection ASH 2L.Queue	2.5885	0.13	0.8067	3.7993	0.00	3.7993
Prepare coordination drawings 1L.Queue	2.4549	0.23	0.00	4.6566	0.00	7.4324
Prepare coordination drawings 2L.Queue	1.1885	0.29	0.00	4.5976	0.00	6.4237
Review coordination drawings 1L.Queue	2.9656	0.37	0.00	8.0643	0.00	9.0185
Review coordination drawings 2L.Queue	1.1618	0.33	0.00	6.8752	0.00	6.8752
Update arch model for coordination 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Update coordinated ASH models 1L.Queue	3.7078	0.26	2.0077	7.8089	2.0042	11.1992
Update coordinated ASH models 2L.Queue	5.1693	0.35	2.0272	9.4117	2.0216	9.4855
Update HVAC model for coordination 1L.Queue	1.0162	0.43	0.00	6.1884	0.00	6.1884
Update stuctural model for coordination 1L.Queue	0.5069	0.21	0.00	3.7087	0.00	3.7087
Updated ASH model batch.Queue	0.4972	0.21	0.00	3.4381	0.00	6.6551

Other

Construction Document Process

Replications: 100 Time Units: Hours

Queue

Other

Number Waiting	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
All disciplines Batch 1L.Queue	0.04137120	0.00	0.01401593	0.1059	0.00	2.0000
All disciplines Batch 2L.Queue	0.04024168	0.00	0.01249580	0.1115	0.00	2.0000
Arch and Struct Batch 1L.Queue	0.02217840	0.00	0.01039118	0.04184375	0.00	2.0000
Compile all disciplines model 1L.Queue	0.0902	0.01	0.04411805	0.1603	0.00	1.0000
Compile all disciplines model 2L.Queue	0.02811621	0.00	0.00	0.1161	0.00	1.0000
Complile ASH models 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Complile ASH models 2 level.Queue	0.02657024	0.00	0.01013413	0.06451760	0.00	1.0000
Coordination model 2L batch.Queue	0.08075640	0.01	0.03594268	0.1986	0.00	3.0000
Create arch model for coordination 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Create architectural model for coordination 2L.Queue	0.05032028	0.00	0.01991120	0.1018	0.00	1.0000
Create HVAC model for coordination 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Create HVAC model for coordination 2L.Queue	0.1064	0.01	0.04924416	0.2229	0.00	1.0000
Create remaining models 1L.Queue	0.02350976	0.01	0.00	0.1111	0.00	1.0000
Create remaining models 2L.Queue	0.03136865	0.00	0.00	0.08729013	0.00	1.0000
Create stuctural model for coordination 1L.Queue	0.02237288	0.00	0.01153336	0.04241204	0.00	1.0000
Create stuctural model for coordination 2L.Queue	0.07821257	0.00	0.03359182	0.1541	0.00	1.0000
Establish LOD and coordination schedule.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Identify models required for coordination.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Identify solutions 1 level.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Identify solutions all disciplines 1L.Queue	0.01695340	0.00	0.00	0.08095555	0.00	1.0000
Identify solutions all disciplines 2L.Queue	0.00656852	0.00	0.00	0.06053578	0.00	1.0000
Identify solutions ASH 2L.Queue	0.01294487	0.00	0.00	0.04615848	0.00	1.0000
Perform clash detection all disciplines 1L.Queue	0.03693432	0.00	0.01533256	0.07618131	0.00	1.0000
Perform clash detection all disciplines 2L.Queue	0.01836643	0.00	0.00	0.06552714	0.00	1.0000
Perform clash detection ASH 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00

Construction Document Process

Replications: 100 Time Units: Hours

Queue

Other

Number Waiting	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Perform clash detection ASH 2L.Queue	0.02560384	0.00	0.00972937	0.06293017	0.00	1.0000
Prepare coordination drawings 1L.Queue	0.04083402	0.01	0.00	0.1887	0.00	1.0000
Prepare coordination drawings 2L.Queue	0.02050774	0.01	0.00	0.1240	0.00	1.0000
Review coordination drawings 1L.Queue	0.04493105	0.01	0.00	0.1501	0.00	1.0000
Review coordination drawings 2L.Queue	0.01824566	0.01	0.00	0.1303	0.00	1.0000
Update arch model for coordination 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Update coordinated ASH models 1L.Queue	0.06431606	0.01	0.01365786	0.1764	0.00	1.0000
Update coordinated ASH models 2L.Queue	0.07225998	0.01	0.02278489	0.1648	0.00	1.0000
Update HVAC model for coordination 1L.Queue	0.00916865	0.00	0.00	0.0991	0.00	1.0000
Update stuctural model for coordination 1L.Queue	0.00454339	0.00	0.00	0.05157596	0.00	1.0000
Updated ASH model batch.Queue	0.01334480	0.01	0.00	0.1382	0.00	3.0000

Construction Document Process

Replications: 100 Time Units: Hours

Resource

Usage

Instantaneous Utilization	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Architect	1.0000	0.00	1.0000	1.0000	0.00	1.0000
Civil Consultant	0.00	0.00	0.00	0.00	0.00	0.00
MEP Consultant	0.00	0.00	0.00	0.00	0.00	0.00
Other Consultant	0.00	0.00	0.00	0.00	0.00	0.00
Owner	0.8727	0.01	0.7708	0.9525	0.00	1.0000
Str Consultant	0.00	0.00	0.00	0.00	0.00	0.00

Number Busy	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Architect	1.0000	0.00	1.0000	1.0000	0.00	1.0000
Civil Consultant	0.00	0.00	0.00	0.00	0.00	0.00
MEP Consultant	0.00	0.00	0.00	0.00	0.00	0.00
Other Consultant	0.00	0.00	0.00	0.00	0.00	0.00
Owner	0.8727	0.01	0.7708	0.9525	0.00	1.0000
Str Consultant	0.00	0.00	0.00	0.00	0.00	0.00

Number Scheduled	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Architect	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Civil Consultant	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
MEP Consultant	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Other Consultant	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Owner	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Str Consultant	1.0000	0.00	1.0000	1.0000	1.0000	1.0000

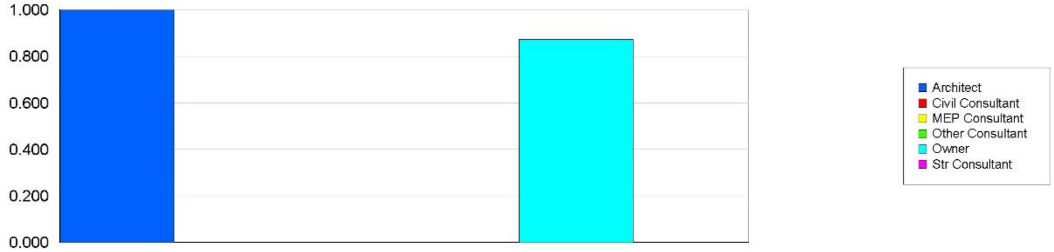
Construction Document Process

Replications: 100 Time Units: Hours

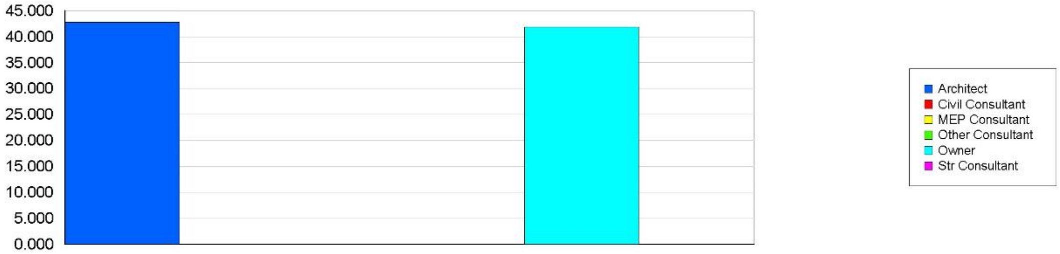
Resource

Usage

Scheduled Utilization	Average	Half Width	Minimum Average	Maximum Average
Architect	1.0000	0.00	1.0000	1.0000
Civil Consultant	0.00	0.00	0.00	0.00
MEP Consultant	0.00	0.00	0.00	0.00
Other Consultant	0.00	0.00	0.00	0.00
Owner	0.8727	0.01	0.7708	0.9525
Str Consultant	0.00	0.00	0.00	0.00



Total Number Seized	Average	Half Width	Minimum Average	Maximum Average
Architect	42.8600	2.42	24.0000	85.0000
Civil Consultant	0.00	0.00	0.00	0.00
MEP Consultant	0.00	0.00	0.00	0.00
Other Consultant	0.00	0.00	0.00	0.00
Owner	41.8600	2.42	23.0000	84.0000
Str Consultant	0.00	0.00	0.00	0.00



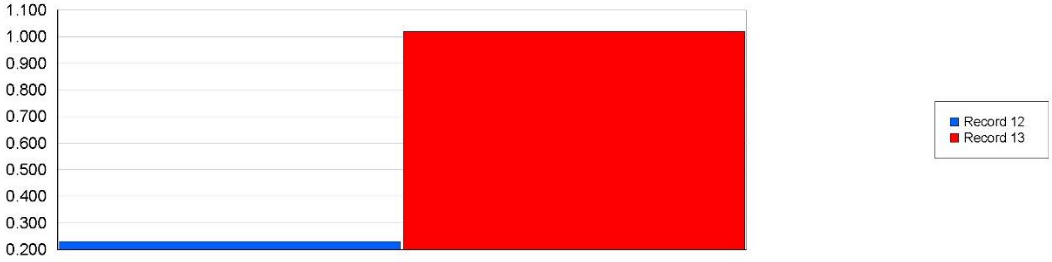
Construction Document Process

Replications: 100 Time Units: Hours

User Specified

Counter

Count	Average	Half Width	Minimum Average	Maximum Average
Record 12	0.2300	0.10	0.00	2.0000
Record 13	1.0200	0.30	0.00	9.0000



Values Across All Replications

Schematic Design Process

Replications: 3 Time Units: Hours

Schematic Design Process

Replications: 3 Time Units: Hours

Key Performance Indicators

System	Average
Number Out	1

Schematic Design Process

Replications: 3 Time Units: Hours

Entity

Time

VA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	38.5194	88.11	0.00	69.8189	0.00	71.1660

NVA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	0.00	0.00	0.00	0.00	0.00	0.00

Wait Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	34.9936	77.49	0.00	59.8761	0.00	62.5671

Transfer Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	0.00	0.00	0.00	0.00	0.00	0.00

Other Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	0.00	0.00	0.00	0.00	0.00	0.00

Total Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	53.3147	123.54	0.00	98.4352	0.00	102.67

Other

Number In	Average	Half Width	Minimum Average	Maximum Average
SD	11.6667	10.04	7.0000	14.0000

Number Out	Average	Half Width	Minimum Average	Maximum Average
SD	9.3333	20.08	0.00	14.0000

WIP	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	5.2884	7.78	1.7491	7.6977	0.00	14.0000

Schematic Design Process

Replications: 3 Time Units: Hours

Queue

Time

Schematic Design Process

Replications: 3 Time Units: Hours

Queue

Time

Waiting Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
All disciplines Batch 1L.Queue	0.7813	1.69	0.00	1.2490	0.00	2.4980
All disciplines Batch 2L.Queue	0.8434	1.87	0.00	1.4453	0.00	2.8906
Arch and Struct Batch 1L.Queue	1.1909	0.35	1.0296	1.2998	0.00	2.5996
Compile all disciplines model 1L.Queue	5.6718	12.99	0.00	10.2950	0.00	10.2950
Compile all disciplines model 2L.Queue	1.0785	4.64	0.00	3.2354	0.00	3.2354
Complile ASH models 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Complile ASH models 2 level.Queue	2.1720	4.94	0.00	3.8973	0.00	3.8973
Coordination model 2L batch.Queue	1.8025	4.17	0.00	3.3161	0.00	6.6170
Create arch model for coordination 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Create architectural model for coordination 2L.Queue	3.2801	7.18	0.00	5.4522	0.00	5.4522
Create HVAC model for coordination 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Create HVAC model for coordination 2L.Queue	7.1641	15.49	0.00	11.3520	0.00	11.3520
Create remaining models 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Create remaining models 2L.Queue	1.6858	3.63	0.00	2.5904	0.00	2.5904
Create stuctural model for coordination 1L.Queue	2.6945	1.36	2.2528	3.3084	2.2528	3.3084
Create stuctural model for coordination 2L.Queue	5.3322	11.47	0.00	8.0662	0.00	8.0662
Establish LOD and coordination schedule.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Identify models required for coordination.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Identify solutions 1 level.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Identify solutions ASH 2L.Queue	1.6261	3.65	0.00	2.8604	0.00	2.8604
Perform clash detection all disciplines 1L.Queue	2.3571	5.14	0.00	3.8682	0.00	3.8682
Perform clash detection all disciplines 2L.Queue	0.7122	3.06	0.00	2.1365	0.00	2.1365
Perform clash detection ASH 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Perform clash detection ASH 2L.Queue	1.8461	4.01	0.00	2.9884	0.00	2.9884
Prepare coordination drawings 1L.Queue	1.8444	4.32	0.00	3.4535	0.00	5.0006

Schematic Design Process

Replications: 3 Time Units: Hours

Queue

Time

Waiting Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Prepare coordination drawings 2L.Queue	0.1198	0.52	0.00	0.3594	0.00	2.5159
Review coordination drawings 1L.Queue	1.7820	3.85	0.00	2.7989	0.00	3.0215
Review coordination drawings 2L.Queue	0.0994	0.43	0.00	0.2981	0.00	2.0864
Update arch model for coordination 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Update coordinated ASH models 1L.Queue	1.7175	3.81	0.00	2.9541	0.00	2.9541
Update coordinated ASH models 2L.Queue	3.3982	7.33	0.00	5.2977	0.00	5.2977
Update HVAC model for coordination 1L.Queue	3.6302	7.81	0.00	5.5504	0.00	5.5504
Update stuctural model for coordination 1L.Queue	1.9732	4.29	0.00	3.2040	0.00	3.2040
Updated ASH model batch.Queue	1.7184	3.74	0.00	2.8136	0.00	5.2885

Other

Schematic Design Process

Replications: 3 Time Units: Hours

Queue

Other

Number Waiting	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
All disciplines Batch 1L.Queue	0.01433023	0.03	0.00	0.02730733	0.00	2.0000
All disciplines Batch 2L.Queue	0.01571230	0.04	0.00	0.03159801	0.00	2.0000
Arch and Struct Batch 1L.Queue	0.04659039	0.11	0.01474727	0.0978	0.00	2.0000
Compile all disciplines model 1L.Queue	0.04906352	0.11	0.00	0.07372666	0.00	1.0000
Compile all disciplines model 2L.Queue	0.00772343	0.03	0.00	0.02317028	0.00	1.0000
Complile ASH models 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Complile ASH models 2 level.Queue	0.01884565	0.04	0.00	0.02862719	0.00	1.0000
Coordination model 2L batch.Queue	0.04661112	0.10	0.00	0.07124324	0.00	3.0000
Create arch model for coordination 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Create architectural model for coordination 2L.Queue	0.03034202	0.07	0.00	0.05960038	0.00	1.0000
Create HVAC model for coordination 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Create HVAC model for coordination 2L.Queue	0.06404770	0.14	0.00	0.1108	0.00	1.0000
Create remaining models 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Create remaining models 2L.Queue	0.01532776	0.04	0.00	0.02831651	0.00	1.0000
Create stuctural model for coordination 1L.Queue	0.04907539	0.10	0.01613299	0.0949	0.00	1.0000
Create stuctural model for coordination 2L.Queue	0.04815228	0.11	0.00	0.08669134	0.00	1.0000
Establish LOD and coordination schedule.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Identify models required for coordination.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Identify solutions 1 level.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Identify solutions all disciplines 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Identify solutions all disciplines 2L.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Identify solutions ASH 2L.Queue	0.01524011	0.04	0.00	0.03126859	0.00	1.0000
Perform clash detection all disciplines 1L.Queue	0.02174117	0.05	0.00	0.04228498	0.00	1.0000
Perform clash detection all disciplines 2L.Queue	0.00510000	0.02	0.00	0.01529999	0.00	1.0000
Perform clash detection ASH 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00

Schematic Design Process

Replications: 3 Time Units: Hours

Queue

Other

Number Waiting	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Perform clash detection ASH 2L.Queue	0.01642503	0.04	0.00	0.02787377	0.00	1.0000
Prepare coordination drawings 1L.Queue	0.03231003	0.09	0.00	0.07419553	0.00	1.0000
Prepare coordination drawings 2L.Queue	0.00600581	0.03	0.00	0.01801744	0.00	1.0000
Review coordination drawings 1L.Queue	0.02843907	0.07	0.00	0.05472070	0.00	1.0000
Review coordination drawings 2L.Queue	0.00498051	0.02	0.00	0.01494154	0.00	1.0000
Update arch model for coordination 1L.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Update coordinated ASH models 1L.Queue	0.01601179	0.04	0.00	0.03229305	0.00	1.0000
Update coordinated ASH models 2L.Queue	0.03048966	0.07	0.00	0.05352981	0.00	1.0000
Update HVAC model for coordination 1L.Queue	0.03297272	0.08	0.00	0.06067439	0.00	1.0000
Update stuctural model for coordination 1L.Queue	0.01754309	0.04	0.00	0.02968391	0.00	1.0000
Updated ASH model batch.Queue	0.04574682	0.10	0.00	0.07679244	0.00	3.0000

Schematic Design Process

Replications: 3 Time Units: Hours

Resource

Usage

Instantaneous Utilization	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Architect	1.0000	0.00	1.0000	1.0000	0.00	1.0000
Civil Consultant	0.00	0.00	0.00	0.00	0.00	0.00
MEP Consultant	0.00	0.00	0.00	0.00	0.00	0.00
Other Consultant	0.00	0.00	0.00	0.00	0.00	0.00
Owner	0.7728	0.49	0.5464	0.8989	0.00	1.0000
Str Consultant	0.00	0.00	0.00	0.00	0.00	0.00

Number Busy	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Architect	1.0000	0.00	1.0000	1.0000	0.00	1.0000
Civil Consultant	0.00	0.00	0.00	0.00	0.00	0.00
MEP Consultant	0.00	0.00	0.00	0.00	0.00	0.00
Other Consultant	0.00	0.00	0.00	0.00	0.00	0.00
Owner	0.7728	0.49	0.5464	0.8989	0.00	1.0000
Str Consultant	0.00	0.00	0.00	0.00	0.00	0.00

Number Scheduled	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Architect	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Civil Consultant	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
MEP Consultant	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Other Consultant	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Owner	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Str Consultant	1.0000	0.00	1.0000	1.0000	1.0000	1.0000

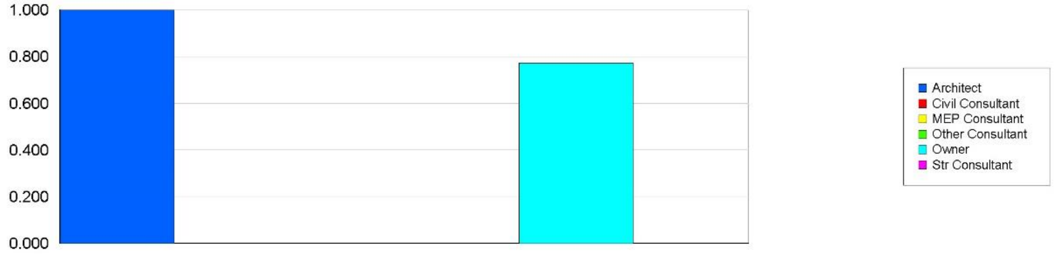
Schematic Design Process

Replications: 3 Time Units: Hours

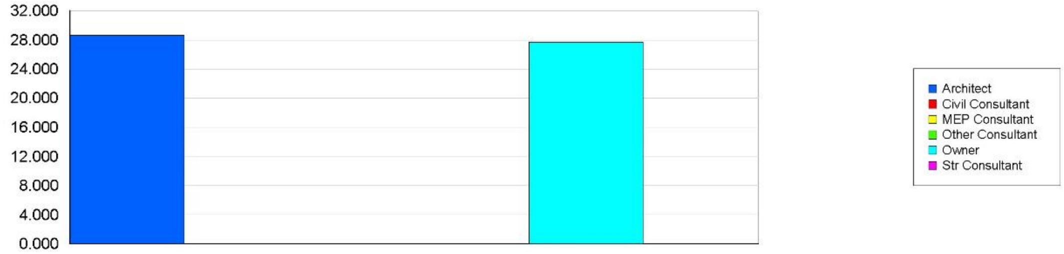
Resource

Usage

Scheduled Utilization	Average	Half Width	Minimum Average	Maximum Average
Architect	1.0000	0.00	1.0000	1.0000
Civil Consultant	0.00	0.00	0.00	0.00
MEP Consultant	0.00	0.00	0.00	0.00
Other Consultant	0.00	0.00	0.00	0.00
Owner	0.7728	0.49	0.5464	0.8989
Str Consultant	0.00	0.00	0.00	0.00



Total Number Seized	Average	Half Width	Minimum Average	Maximum Average
Architect	28.6667	48.70	8.0000	47.0000
Civil Consultant	0.00	0.00	0.00	0.00
MEP Consultant	0.00	0.00	0.00	0.00
Other Consultant	0.00	0.00	0.00	0.00
Owner	27.6667	48.70	7.0000	46.0000
Str Consultant	0.00	0.00	0.00	0.00



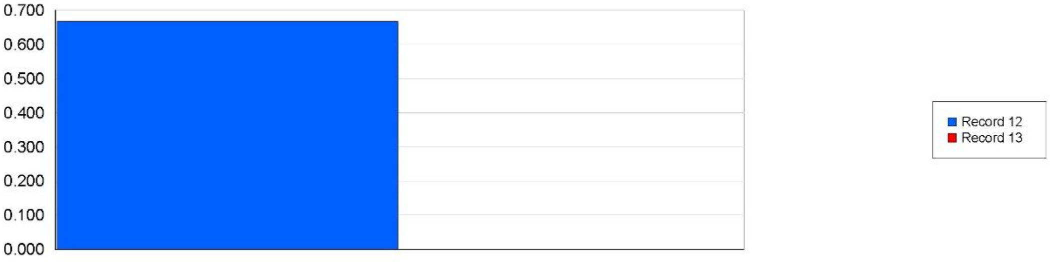
Schematic Design Process

Replications: 3 Time Units: Hours

User Specified

Counter

Count	Average	Half Width	Minimum Average	Maximum Average
Record 12	0.6667	1.43	0.00	1.0000
Record 13	0.00	0.00	0.00	0.00



Schematic Design Process

Replications: 100 Time Units: Hours

Key Performance Indicators

System

	Average
Number Out	1

Category Overview

Values Across All Replications

Schematic Design Process

Replications: 100 Time Units: Hours

Entity

Time

VA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	1194.61	73.55	844.27	3634.00	844.27	3634.00

NVA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	0.00	0.00	0.00	0.00	0.00	0.00

Wait Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	1728.58	301.35	447.36	4927.80	447.36	4927.80

Transfer Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	0.00	0.00	0.00	0.00	0.00	0.00

Other Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	0.00	0.00	0.00	0.00	0.00	0.00

Total Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	769.62	77.28	383.20	2120.65	383.20	2120.65

Other

Number In	Average	Half Width	Minimum Average	Maximum Average
SD	19.9500	2.23	11.0000	91.0000

Number Out	Average	Half Width	Minimum Average	Maximum Average
SD	19.9500	2.23	11.0000	91.0000

WIP	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	12.2404	1.04	7.3609	39.7653	0.00	91.0000

Values Across All Replications

Schematic Design Process

Replications: 100 Time Units: Hours

Process

Time per Entity

VA Time Per Entity	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
2D Coordination and Code Review	30.0787	0.70	22.1014	38.4681	20.2715	39.2729
2D Coordination and Code Review3	1.5483	1.37	0.00	34.0514	0.00	34.0514
Architectural and Envelop System Schemes	119.86	2.09	98.1708	141.52	98.1708	141.52
Architectural and Envelop System Schemes2	7.0431	1.77	0.00	21.9870	0.00	21.9870
Architectural Layout	72.2563	12.02	0.00	139.43	0.00	139.43
Architectural Layout2	14.5198	3.06	0.00	34.5937	0.00	35.2428
Architectural Layout3	1.5363	1.36	0.00	33.8728	0.00	33.8728
Create Addenda	0.9023	0.20	0.00	2.6340	0.00	2.6340
Evaluating SA and Code Review	29.9511	0.75	20.7786	38.0409	20.7786	38.5725
Meet the Buildign Department	11.7048	0.19	9.7060	13.9191	9.3360	13.9191
MEPFP System Layout	70.7927	11.76	0.00	140.54	0.00	140.54
MEPFP System Layout2	14.5289	3.07	0.00	33.5847	0.00	35.6584
MEPFP System Layout3	1.4118	1.25	0.00	35.1965	0.00	35.1965
MEPFP System Schemes	4.0986	0.17	2.0835	5.6244	2.0835	5.6244
MEPFP System Schemes2	7.1318	1.80	0.00	23.2697	0.00	23.2697
Other System Schemes	4.0512	0.18	2.2357	5.7512	2.2357	5.7512
Other System Schemes2	7.1188	1.78	0.00	22.8282	0.00	23.2688
Other Systems Layout	120.25	1.85	98.0377	142.61	98.0377	143.13
Other Systems Layout2	14.2823	3.02	0.00	33.8948	0.00	35.0973
Other Systems Layout3	1.4597	1.29	0.00	31.0809	0.00	31.0809
Site and Utilities Requirements	72.5926	12.09	0.00	139.20	0.00	139.20
Site and Utilities Requirements2	14.4827	3.06	0.00	33.9476	0.00	35.3897
Site and Utilities Requirements3	1.5146	1.34	0.00	34.1086	0.00	34.1086
Sitework and Landscaping System Schemes	4.0600	0.16	2.3690	5.8370	2.3690	5.8370
Sitework and Landscaping System Schemes2	7.1341	1.79	0.00	22.7642	0.00	22.7642
Structural System Layout	71.6987	11.92	0.00	139.41	0.00	139.41
Structural System Layout2	14.5850	3.08	0.00	35.3126	0.00	35.3169
Structural System Layout3	1.4069	1.24	0.00	30.7948	0.00	30.7948
Structural System Schemes	3.9956	0.15	2.4336	5.7090	2.4336	5.7090
Structural System Schemes2	7.3414	1.84	0.00	22.8486	0.00	22.8486
Submit DD to the Agencies	60.1165	1.06	48.5699	70.9859	48.5699	70.9859
Update SD Performance Criteria	38.7173	1.22	24.7280	54.9303	24.7280	54.9303

Schematic Design Process

Replications: 100 Time Units: Hours

Process

Time per Entity

Wait Time Per Entity	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
2D Coordination and Code Review	0.00	0.00	0.00	0.00	0.00	0.00
2D Coordination and Code Review3	0.00	0.00	0.00	0.00	0.00	0.00
Architectural and Envelop System Schemes	0.00	0.00	0.00	0.00	0.00	0.00
Architectural and Envelop System Schemes2	0.00	0.00	0.00	0.00	0.00	0.00
Architectural Layout	0.00	0.00	0.00	0.00	0.00	0.00
Architectural Layout2	0.00	0.00	0.00	0.00	0.00	0.00
Architectural Layout3	0.00	0.00	0.00	0.00	0.00	0.00
Create Addenda	0.00	0.00	0.00	0.00	0.00	0.00
Evaluating SA and Code Review	0.00	0.00	0.00	0.00	0.00	0.00
Meet the Buildign Department	0.00	0.00	0.00	0.00	0.00	0.00
MEPFP System Layout	0.00	0.00	0.00	0.00	0.00	0.00
MEPFP System Layout2	0.00	0.00	0.00	0.00	0.00	0.00
MEPFP System Layout3	0.00	0.00	0.00	0.00	0.00	0.00
MEPFP System Schemes	0.00	0.00	0.00	0.00	0.00	0.00
MEPFP System Schemes2	21.5186	5.35	0.00	62.8023	0.00	62.8023
Other System Schemes	0.00	0.00	0.00	0.00	0.00	0.00
Other System Schemes2	23.3351	6.10	0.00	78.9535	0.00	80.7986
Other Systems Layout	96.3133	23.86	0.00	258.95	0.00	515.21
Other Systems Layout2	0.00	0.00	0.00	0.00	0.00	0.00
Other Systems Layout3	0.00	0.00	0.00	0.00	0.00	0.00
Site and Utilities Requirements	0.00	0.00	0.00	0.00	0.00	0.00
Site and Utilities Requirements2	0.00	0.00	0.00	0.00	0.00	0.00
Site and Utilities Requirements3	0.00	0.00	0.00	0.00	0.00	0.00
Sitework and Landscaping System Schemes	0.00	0.00	0.00	0.00	0.00	0.00
Sitework and Landscaping System Schemes2	7.0431	1.77	0.00	21.9870	0.00	21.9870
Structural System Layout	0.00	0.00	0.00	0.00	0.00	0.00
Structural System Layout2	0.00	0.00	0.00	0.00	0.00	0.00
Structural System Layout3	0.00	0.00	0.00	0.00	0.00	0.00
Structural System Schemes	0.00	0.00	0.00	0.00	0.00	0.00
Structural System Schemes2	14.1772	3.53	0.00	44.3733	0.00	44.3733
Submit DD to the Agencies	0.00	0.00	0.00	0.00	0.00	0.00
Update SD Performance Criteria	0.00	0.00	0.00	0.00	0.00	0.00

Values Across All Replications

Schematic Design Process

Replications: 100 Time Units: Hours

Process

Time per Entity

Total Time Per Entity	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
2D Coordination and Code Review	30.0787	0.70	22.1014	38.4681	20.2715	39.2729
2D Coordination and Code Review3	1.5483	1.37	0.00	34.0514	0.00	34.0514
Architectural and Envelop System Schemes	119.86	2.09	98.1708	141.52	98.1708	141.52
Architectural and Envelop System Schemes2	7.0431	1.77	0.00	21.9870	0.00	21.9870
Architectural Layout	72.2563	12.02	0.00	139.43	0.00	139.43
Architectural Layout2	14.5198	3.06	0.00	34.5937	0.00	35.2428
Architectural Layout3	1.5363	1.36	0.00	33.8728	0.00	33.8728
Create Addenda	0.9023	0.20	0.00	2.6340	0.00	2.6340
Evaluating SA and Code Review	29.9511	0.75	20.7786	38.0409	20.7786	38.5725
Meet the Buildign Department	11.7048	0.19	9.7060	13.9191	9.3360	13.9191
MEPFP System Layout	70.7927	11.76	0.00	140.54	0.00	140.54
MEPFP System Layout2	14.5289	3.07	0.00	33.5847	0.00	35.6584
MEPFP System Layout3	1.4118	1.25	0.00	35.1965	0.00	35.1965
MEPFP System Schemes	4.0986	0.17	2.0835	5.6244	2.0835	5.6244
MEPFP System Schemes2	28.6504	7.11	0.00	80.0615	0.00	80.0615
Other System Schemes	4.0512	0.18	2.2357	5.7512	2.2357	5.7512
Other System Schemes2	30.4539	7.79	0.00	101.24	0.00	101.24
Other Systems Layout	216.56	23.97	98.0377	382.29	98.0377	638.59
Other Systems Layout2	14.2823	3.02	0.00	33.8948	0.00	35.0973
Other Systems Layout3	1.4597	1.29	0.00	31.0809	0.00	31.0809
Site and Utilities Requirements	72.5926	12.09	0.00	139.20	0.00	139.20
Site and Utilities Requirements2	14.4827	3.06	0.00	33.9476	0.00	35.3897
Site and Utilities Requirements3	1.5146	1.34	0.00	34.1086	0.00	34.1086
Sitework and Landscaping System Schemes	4.0600	0.16	2.3690	5.8370	2.3690	5.8370
Sitework and Landscaping System Schemes2	14.1772	3.53	0.00	44.3733	0.00	44.3733
Structural System Layout	71.6987	11.92	0.00	139.41	0.00	139.41
Structural System Layout2	14.5850	3.08	0.00	35.3126	0.00	35.3169
Structural System Layout3	1.4069	1.24	0.00	30.7948	0.00	30.7948
Structural System Schemes	3.9956	0.15	2.4336	5.7090	2.4336	5.7090
Structural System Schemes2	21.5186	5.35	0.00	62.8023	0.00	62.8023
Submit DD to the Agencies	60.1165	1.06	48.5699	70.9859	48.5699	70.9859
Update SD Performance Criteria	38.7173	1.22	24.7280	54.9303	24.7280	54.9303

Schematic Design Process

Replications: 100 Time Units: Hours

Process

Accumulated Time

Schematic Design Process

Replications: 100 Time Units: Hours

Process

Accumulated Time

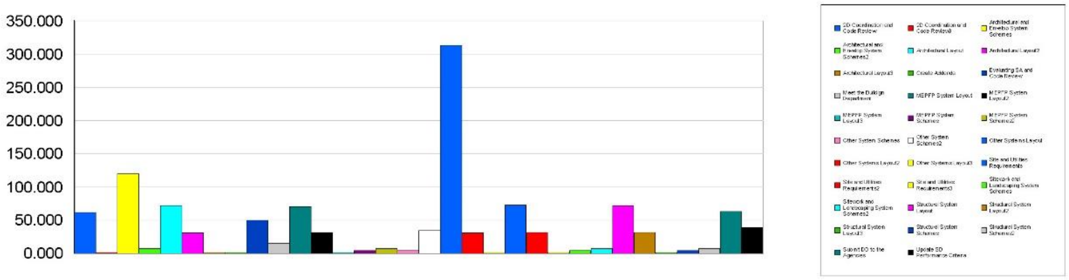
Accum VA Time	Average	Half Width	Minimum Average	Maximum Average
2D Coordination and Code Review	61.4121	10.18	22.1014	396.68
2D Coordination and Code Review3	1.5483	1.37	0.00	34.0514
Architectural and Envelop System Schemes	119.86	2.09	98.1708	141.52
Architectural and Envelop System Schemes2	7.0431	1.77	0.00	21.9870
Architectural Layout	72.2563	12.02	0.00	139.43
Architectural Layout2	31.1785	9.82	0.00	345.01
Architectural Layout3	1.5363	1.36	0.00	33.8728
Create Addenda	0.9023	0.20	0.00	2.6340
Evaluating SA and Code Review	50.2872	6.47	20.7786	201.24
Meet the Buildign Department	15.1894	1.40	9.7060	47.3950
MEPFP System Layout	70.7927	11.76	0.00	140.54
MEPFP System Layout2	31.5479	10.01	0.00	353.37
MEPFP System Layout3	1.4118	1.25	0.00	35.1965
MEPFP System Schemes	4.0986	0.17	2.0835	5.6244
MEPFP System Schemes2	7.1318	1.80	0.00	23.2697
Other System Schemes	4.0512	0.18	2.2357	5.7512
Other System Schemes2	34.2354	15.49	0.00	456.17
Other Systems Layout	312.93	47.80	98.0377	638.59
Other Systems Layout2	31.1773	10.00	0.00	356.85
Other Systems Layout3	1.4597	1.29	0.00	31.0809
Site and Utilities Requirements	72.5926	12.09	0.00	139.20
Site and Utilities Requirements2	31.4683	10.04	0.00	358.32
Site and Utilities Requirements3	1.5146	1.34	0.00	34.1086
Sitework and Landscaping System Schemes	4.0600	0.16	2.3690	5.8370
Sitework and Landscaping System Schemes2	7.1341	1.79	0.00	22.7642
Structural System Layout	71.6987	11.92	0.00	139.41
Structural System Layout2	31.4619	10.07	0.00	364.25
Structural System Layout3	1.4069	1.24	0.00	30.7948
Structural System Schemes	3.9956	0.15	2.4336	5.7090
Structural System Schemes2	7.3414	1.84	0.00	22.8486
Submit DD to the Agencies	63.1698	2.95	48.5699	135.00
Update SD Performance Criteria	38.7173	1.22	24.7280	54.9303

Schematic Design Process

Replications: 100 Time Units: Hours

Process

Accumulated Time



Schematic Design Process

Replications: 100 Time Units: Hours

Process

Accumulated Time

Accum Wait Time	Average	Half Width	Minimum Average	Maximum Average
2D Coordination and Code Review	0.00	0.00	0.00	0.00
2D Coordination and Code Review3	0.00	0.00	0.00	0.00
Architectural and Envelop System Schemes	0.00	0.00	0.00	0.00
Architectural and Envelop System Schemes2	0.00	0.00	0.00	0.00
Architectural Layout	0.00	0.00	0.00	0.00
Architectural Layout2	0.00	0.00	0.00	0.00
Architectural Layout3	0.00	0.00	0.00	0.00
Create Addenda	0.00	0.00	0.00	0.00
Evaluating SA and Code Review	0.00	0.00	0.00	0.00
Meet the Buildign Department	0.00	0.00	0.00	0.00
MEPFP System Layout	0.00	0.00	0.00	0.00
MEPFP System Layout2	0.00	0.00	0.00	0.00
MEPFP System Layout3	0.00	0.00	0.00	0.00
MEPFP System Schemes	0.00	0.00	0.00	0.00
MEPFP System Schemes2	21.5186	5.35	0.00	62.8023
Other System Schemes	0.00	0.00	0.00	0.00
Other System Schemes2	82.8029	33.00	0.00	936.94
Other Systems Layout	481.57	119.29	0.00	1294.73
Other Systems Layout2	0.00	0.00	0.00	0.00
Other Systems Layout3	0.00	0.00	0.00	0.00
Site and Utilities Requirements	0.00	0.00	0.00	0.00
Site and Utilities Requirements2	0.00	0.00	0.00	0.00
Site and Utilities Requirements3	0.00	0.00	0.00	0.00
Sitework and Landscaping System Schemes	0.00	0.00	0.00	0.00
Sitework and Landscaping System Schemes2	7.0431	1.77	0.00	21.9870
Structural System Layout	0.00	0.00	0.00	0.00
Structural System Layout2	0.00	0.00	0.00	0.00
Structural System Layout3	0.00	0.00	0.00	0.00
Structural System Schemes	0.00	0.00	0.00	0.00
Structural System Schemes2	14.1772	3.53	0.00	44.3733
Submit DD to the Agencies	0.00	0.00	0.00	0.00
Update SD Performance Criteria	0.00	0.00	0.00	0.00

Category Overview

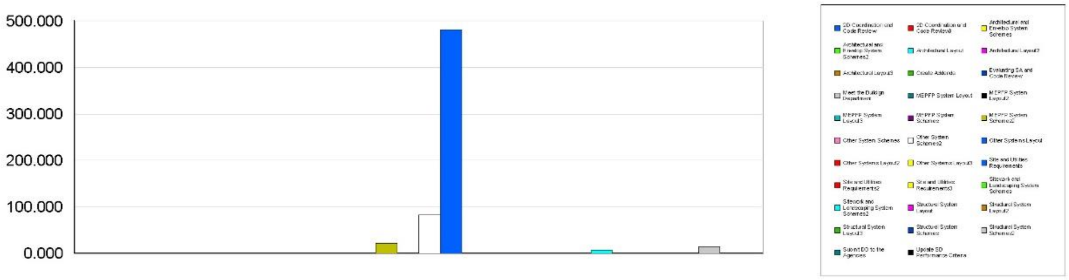
Values Across All Replications

Schematic Design Process

Replications: 100 Time Units: Hours

Process

Accumulated Time



Other

Schematic Design Process

Replications: 100 Time Units: Hours

Process

Other

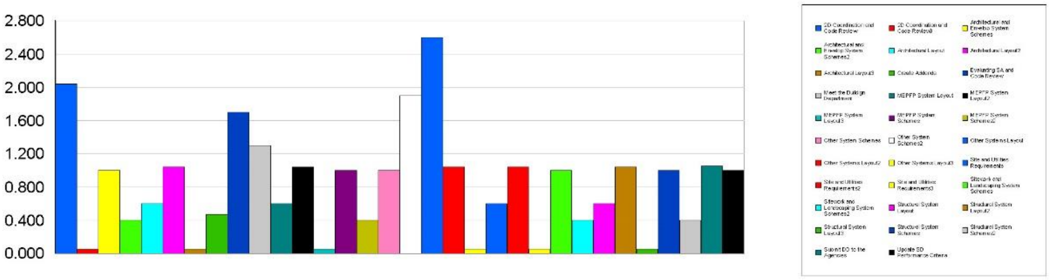
Number In	Average	Half Width	Minimum Average	Maximum Average
2D Coordination and Code Review	2.0400	0.33	1.0000	13.0000
2D Coordination and Code Review3	0.05000000	0.04	0.00	1.0000
Architectural and Envelop System Schemes	1.0000	0.00	1.0000	1.0000
Architectural and Envelop System Schemes2	0.4000	0.10	0.00	1.0000
Architectural Layout	0.6000	0.10	0.00	1.0000
Architectural Layout2	1.0400	0.33	0.00	12.0000
Architectural Layout3	0.05000000	0.04	0.00	1.0000
Create Addenda	0.4700	0.10	0.00	1.0000
Evaluating SA and Code Review	1.7000	0.23	1.0000	7.0000
Meet the Buildign Department	1.3000	0.12	1.0000	4.0000
MEPFP System Layout	0.6000	0.10	0.00	1.0000
MEPFP System Layout2	1.0400	0.33	0.00	12.0000
MEPFP System Layout3	0.05000000	0.04	0.00	1.0000
MEPFP System Schemes	1.0000	0.00	1.0000	1.0000
MEPFP System Schemes2	0.4000	0.10	0.00	1.0000
Other System Schemes	1.0000	0.00	1.0000	1.0000
Other System Schemes2	1.9000	0.86	0.00	26.0000
Other Systems Layout	2.6000	0.40	1.0000	5.0000
Other Systems Layout2	1.0400	0.33	0.00	12.0000
Other Systems Layout3	0.05000000	0.04	0.00	1.0000
Site and Utilities Requirements	0.6000	0.10	0.00	1.0000
Site and Utilities Requirements2	1.0400	0.33	0.00	12.0000
Site and Utilities Requirements3	0.05000000	0.04	0.00	1.0000
Sitework and Landscaping System Schemes	1.0000	0.00	1.0000	1.0000
Sitework and Landscaping System Schemes2	0.4000	0.10	0.00	1.0000
Structural System Layout	0.6000	0.10	0.00	1.0000
Structural System Layout2	1.0400	0.33	0.00	12.0000
Structural System Layout3	0.05000000	0.04	0.00	1.0000
Structural System Schemes	1.0000	0.00	1.0000	1.0000
Structural System Schemes2	0.4000	0.10	0.00	1.0000
Submit DD to the Agencies	1.0500	0.04	1.0000	2.0000
Update SD Performance Criteria	1.0000	0.00	1.0000	1.0000

Schematic Design Process

Replications: 100 Time Units: Hours

Process

Other



Schematic Design Process

Replications: 100 Time Units: Hours

Process

Other

Number Out	Average	Half Width	Minimum Average	Maximum Average
2D Coordination and Code Review	2.0400	0.33	1.0000	13.0000
2D Coordination and Code Review3	0.05000000	0.04	0.00	1.0000
Architectural and Envelop System Schemes	1.0000	0.00	1.0000	1.0000
Architectural and Envelop System Schemes2	0.4000	0.10	0.00	1.0000
Architectural Layout	0.6000	0.10	0.00	1.0000
Architectural Layout2	1.0400	0.33	0.00	12.0000
Architectural Layout3	0.05000000	0.04	0.00	1.0000
Create Addenda	0.4700	0.10	0.00	1.0000
Evaluating SA and Code Review	1.7000	0.23	1.0000	7.0000
Meet the Buildign Department	1.3000	0.12	1.0000	4.0000
MEPFP System Layout	0.6000	0.10	0.00	1.0000
MEPFP System Layout2	1.0400	0.33	0.00	12.0000
MEPFP System Layout3	0.05000000	0.04	0.00	1.0000
MEPFP System Schemes	1.0000	0.00	1.0000	1.0000
MEPFP System Schemes2	0.4000	0.10	0.00	1.0000
Other System Schemes	1.0000	0.00	1.0000	1.0000
Other System Schemes2	1.9000	0.86	0.00	26.0000
Other Systems Layout	2.6000	0.40	1.0000	5.0000
Other Systems Layout2	1.0400	0.33	0.00	12.0000
Other Systems Layout3	0.05000000	0.04	0.00	1.0000
Site and Utilities Requirements	0.6000	0.10	0.00	1.0000
Site and Utilities Requirements2	1.0400	0.33	0.00	12.0000
Site and Utilities Requirements3	0.05000000	0.04	0.00	1.0000
Sitework and Landscaping System Schemes	1.0000	0.00	1.0000	1.0000
Sitework and Landscaping System Schemes2	0.4000	0.10	0.00	1.0000
Structural System Layout	0.6000	0.10	0.00	1.0000
Structural System Layout2	1.0400	0.33	0.00	12.0000
Structural System Layout3	0.05000000	0.04	0.00	1.0000
Structural System Schemes	1.0000	0.00	1.0000	1.0000
Structural System Schemes2	0.4000	0.10	0.00	1.0000
Submit DD to the Agencies	1.0500	0.04	1.0000	2.0000
Update SD Performance Criteria	1.0000	0.00	1.0000	1.0000

Schematic Design Process

Replications: 100 Time Units: Hours

Queue

Time

Schematic Design Process

Replications: 100 Time Units: Hours

Queue

Time

Waiting Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
2D Coordination and Code Review.Queue	0.00	0.00	0.00	0.00	0.00	0.00
2D Coordination and Code Review3.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Architectural and Envelop System Schemes.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Architectural and Envelop System Schemes2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Architectural Layout.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Architectural Layout2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Architectural Layout3.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Create Addenda.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Evaluating SA and Code Review.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Meet the Buildign Department.Queue	0.00	0.00	0.00	0.00	0.00	0.00
MEPFP System Layout.Queue	0.00	0.00	0.00	0.00	0.00	0.00
MEPFP System Layout2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
MEPFP System Layout3.Queue	0.00	0.00	0.00	0.00	0.00	0.00
MEPFP System Schemes.Queue	0.00	0.00	0.00	0.00	0.00	0.00
MEPFP System Schemes2.Queue	21.5186	5.35	0.00	62.8023	0.00	62.8023
Other System Schemes.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Other System Schemes2.Queue	23.3351	6.10	0.00	78.9535	0.00	80.7986
Other Systems Layout.Queue	96.3133	23.86	0.00	258.95	0.00	515.21
Other Systems Layout2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Other Systems Layout3.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Site and Utilities Requirements.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Site and Utilities Requirements2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Site and Utilities Requirements3.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Sitework and Landscaping System Schemes.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Sitework and Landscaping System Schemes2.Queue	7.0431	1.77	0.00	21.9870	0.00	21.9870
Structural System Layout.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Structural System Layout2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Structural System Layout3.Queue	0.00	0.00	0.00	0.00	0.00	0.00

Schematic Design Process

Replications: 100 Time Units: Hours

Queue

Time

Waiting Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Structural System Schemes.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Structural System Schemes2.Queue	14.1772	3.53	0.00	44.3733	0.00	44.3733
Submit DD to the Agencies.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Systems Schemes Batch.Queue	92.6464	1.67	75.4285	109.48	0.00	138.70
Systems Schemes Batch2.Queue	14.3498	3.56	0.00	42.2869	0.00	83.4530
Systmes Layout Batch.Queue	103.23	22.77	2.4956	264.29	0.00	517.25
Systmes Layout Batch2.Queue	1.4207	0.32	0.00	5.1559	0.00	10.4865
Systmes Layout Batch3.Queue	0.1212	0.11	0.00	3.9378	0.00	8.7449
Update SD Performance Criteria.Queue	0.00	0.00	0.00	0.00	0.00	0.00

Other

Schematic Design Process

Replications: 100 Time Units: Hours

Queue

Other

Number Waiting	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
2D Coordination and Code Review.Queue	0.00	0.00	0.00	0.00	0.00	0.00
2D Coordination and Code Review3.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Architectural and Envelop System Schemes.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Architectural and Envelop System Schemes2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Architectural Layout.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Architectural Layout2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Architectural Layout3.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Create Addenda.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Evaluating SA and Code Review.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Meet the Buildign Department.Queue	0.00	0.00	0.00	0.00	0.00	0.00
MEPFP System Layout.Queue	0.00	0.00	0.00	0.00	0.00	0.00
MEPFP System Layout2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
MEPFP System Layout3.Queue	0.00	0.00	0.00	0.00	0.00	0.00
MEPFP System Schemes.Queue	0.00	0.00	0.00	0.00	0.00	0.00
MEPFP System Schemes2.Queue	0.01833651	0.00	0.00	0.05571147	0.00	1.0000
Other System Schemes.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Other System Schemes2.Queue	0.06371937	0.02	0.00	0.5713	0.00	4.0000
Other Systems Layout.Queue	0.4107	0.10	0.00	1.2446	0.00	4.0000
Other Systems Layout2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Other Systems Layout3.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Site and Utilities Requirements.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Site and Utilities Requirements2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Site and Utilities Requirements3.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Sitework and Landscaping System Schemes.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Sitework and Landscaping System Schemes2.Queue	0.00600359	0.00	0.00	0.02023999	0.00	1.0000
Structural System Layout.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Structural System Layout2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Structural System Layout3.Queue	0.00	0.00	0.00	0.00	0.00	0.00

Schematic Design Process

Replications: 100 Time Units: Hours

Queue

Other

Number Waiting	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Structural System Schemes.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Structural System Schemes2.Queue	0.01208758	0.00	0.00	0.03762126	0.00	1.0000
Submit DD to the Agencies.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Systems Schemes Batch.Queue	0.7458	0.06	0.1841	1.2259	0.00	5.0000
Systems Schemes Batch2.Queue	0.1005	0.03	0.00	0.6538	0.00	5.0000
Systmes Layout Batch.Queue	0.4839	0.09	0.02493971	1.2406	0.00	5.0000
Systmes Layout Batch2.Queue	0.01826995	0.01	0.00	0.0959	0.00	5.0000
Systmes Layout Batch3.Queue	0.00078413	0.00	0.00	0.03664332	0.00	5.0000
Update SD Performance Criteria.Queue	0.00	0.00	0.00	0.00	0.00	0.00

Schematic Design Process

Replications: 100 Time Units: Hours

Resource

Usage

Instantaneous Utilization	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
AHJs	0.2431	0.01	0.1501	0.3958	0.00	1.0000
Architect	0.7769	0.05	0.3976	1.0000	0.00	1.0000
Civil Consultant	0.1981	0.03	0.00188806	0.3775	0.00	1.0000
MEP Consultant	0.2003	0.03	0.00219459	0.3638	0.00	1.0000
Other Consultant	0.4045	0.03	0.2410	0.6071	0.00	1.0000
Owner	0.3409	0.02	0.1892	0.5108	0.00	1.0000
Str Consultant	0.1963	0.03	0.00267174	0.3831	0.00	1.0000

Number Busy	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
AHJs	0.2431	0.01	0.1501	0.3958	0.00	1.0000
Architect	0.7769	0.05	0.3976	1.0000	0.00	1.0000
Civil Consultant	0.1981	0.03	0.00188806	0.3775	0.00	1.0000
MEP Consultant	0.2003	0.03	0.00219459	0.3638	0.00	1.0000
Other Consultant	0.4045	0.03	0.2410	0.6071	0.00	1.0000
Owner	0.3409	0.02	0.1892	0.5108	0.00	1.0000
Str Consultant	0.1963	0.03	0.00267174	0.3831	0.00	1.0000

Number Scheduled	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
AHJs	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Architect	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Civil Consultant	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
MEP Consultant	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Other Consultant	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Owner	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Str Consultant	1.0000	0.00	1.0000	1.0000	1.0000	1.0000

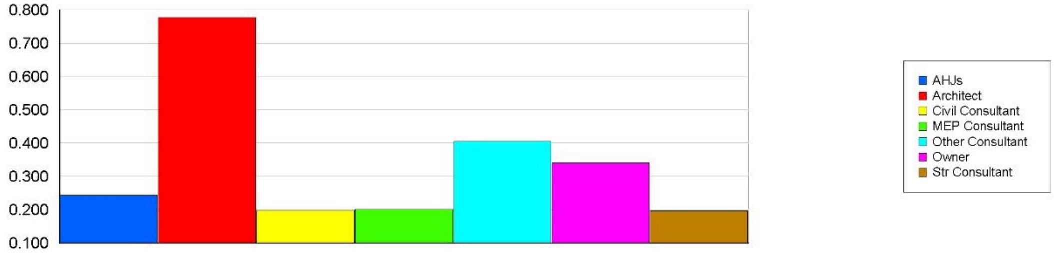
Schematic Design Process

Replications: 100 Time Units: Hours

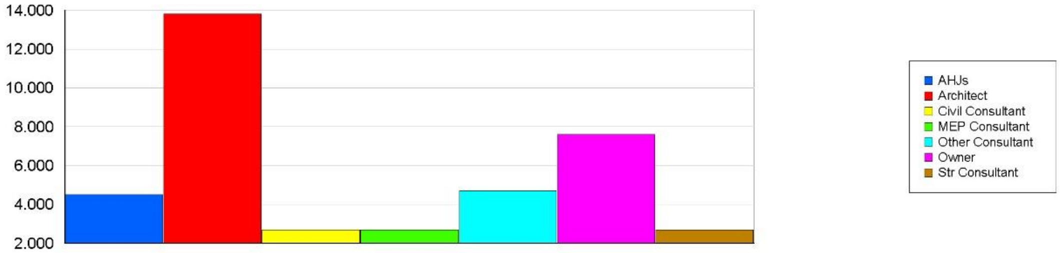
Resource

Usage

Scheduled Utilization	Average	Half Width	Minimum Average	Maximum Average
AHJs	0.2431	0.01	0.1501	0.3958
Architect	0.7769	0.05	0.3976	1.0000
Civil Consultant	0.1981	0.03	0.00188806	0.3775
MEP Consultant	0.2003	0.03	0.00219459	0.3638
Other Consultant	0.4045	0.03	0.2410	0.6071
Owner	0.3409	0.02	0.1892	0.5108
Str Consultant	0.1963	0.03	0.00267174	0.3831



Total Number Seized	Average	Half Width	Minimum Average	Maximum Average
AHJs	4.5000	1.13	1.0000	31.0000
Architect	13.8000	1.62	7.0000	54.0000
Civil Consultant	2.6900	0.34	1.0000	14.0000
MEP Consultant	2.6900	0.34	1.0000	14.0000
Other Consultant	4.6900	0.57	2.0000	19.0000
Owner	7.6100	0.54	5.0000	25.0000
Str Consultant	2.6900	0.34	1.0000	14.0000



Category Overview

Values Across All Replications

Schematic Design Process

Replications: 100 Time Units: Hours

User Specified

Counter

Count	Average	Half Width	Minimum Average	Maximum Average
Rework iterations	1.7400	0.43	0.00	15.0000

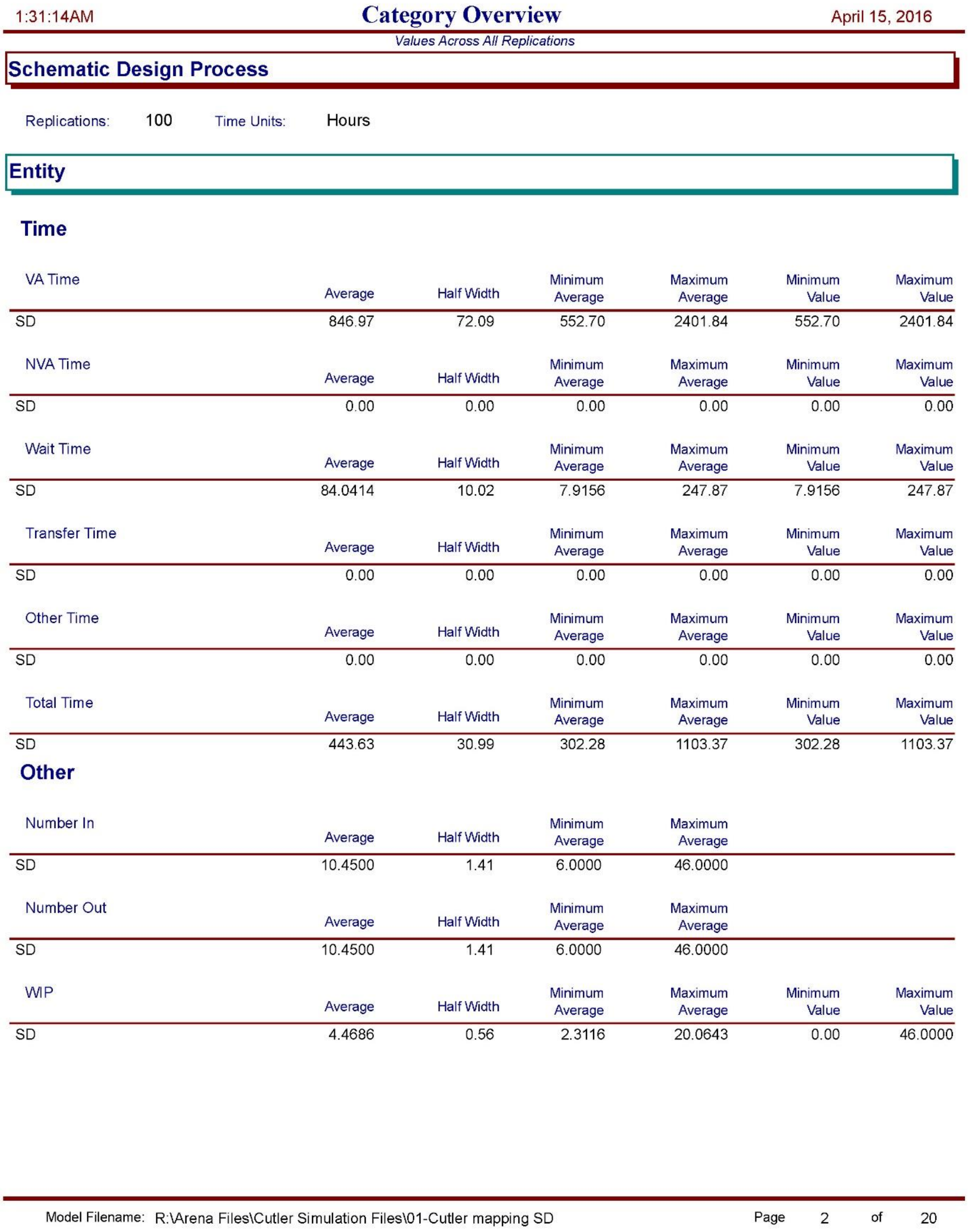
Values Across All Replications

Schematic Design Process

Replications: 100 Time Units: Hours

Key Performance Indicators

System	Average
Number Out	1



1:31:14AM **Category Overview** April 15, 2016

Values Across All Replications

Schematic Design Process

Replications: 100 Time Units: Hours

Entity

Time

VA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	846.97	72.09	552.70	2401.84	552.70	2401.84

NVA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	0.00	0.00	0.00	0.00	0.00	0.00

Wait Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	84.0414	10.02	7.9156	247.87	7.9156	247.87

Transfer Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	0.00	0.00	0.00	0.00	0.00	0.00

Other Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	0.00	0.00	0.00	0.00	0.00	0.00

Total Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	443.63	30.99	302.28	1103.37	302.28	1103.37

Other

Number In	Average	Half Width	Minimum Average	Maximum Average
SD	10.4500	1.41	6.0000	46.0000

Number Out	Average	Half Width	Minimum Average	Maximum Average
SD	10.4500	1.41	6.0000	46.0000

WIP	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
SD	4.4686	0.56	2.3116	20.0643	0.00	46.0000

Model Filename: R:\Arena Files\Cutler Simulation Files\01-Cutler mapping SD Page 2 of 20

Schematic Design Process

Replications: 100 Time Units: Hours

Process

Time per Entity

VA Time Per Entity	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
1st review with the AHJs	3.6025	0.09	2.6602	4.6254	2.6602	4.7128
Asimilate and Analize info	17.5190	0.46	12.2730	23.5989	12.2730	23.5989
Develop architectural design system	70.6086	1.82	54.8863	92.7480	49.4597	94.6126
Develop architectural design system I2	4.6302	1.38	0.00	17.5423	0.00	17.8143
Develop MEP design system	72.0034	1.91	48.9795	93.0788	48.9795	93.0788
Develop MEP design system I2	4.5562	1.36	0.00	17.5321	0.00	17.9257
Develop other design system	71.2035	1.91	50.0377	91.3128	50.0377	93.2505
Develop other design system I2	4.6944	1.40	0.00	18.5572	0.00	18.5572
Develop site design system	72.3757	1.73	50.9718	91.4060	50.9718	91.5567
Develop site design system I2	4.5734	1.36	0.00	17.9312	0.00	18.7546
Develop structural design system	71.7406	1.70	53.9281	92.5400	51.5033	93.7343
Develop structural design system I2	4.5548	1.35	0.00	17.4982	0.00	17.4982
Establishing design goals	18.0535	0.51	12.5427	23.3790	12.5427	23.3790
Evaluating design alternatives	3.6330	0.10	2.5414	4.6507	2.5414	4.6507
Evaluating design alternatives I2	1.1722	0.34	0.00	4.5528	0.00	4.5528
Perform prelimary studies	71.1741	1.72	53.8389	90.2907	51.2800	90.2907
Perform prelimary studies I2	4.7634	1.36	0.00	17.6348	0.00	18.3806
Preliminary Code Compliance all systems	12.7817	0.61	5.2036	18.2731	5.2036	18.4551
Prepare and develop design alternatives	73.0743	2.02	49.0023	91.4933	49.0023	91.4933
Prepare and develop design alternatives I2	4.9686	1.41	0.00	17.2873	0.00	17.6334
Prepare schematic design proposal	8.9291	0.23	6.2288	11.5743	6.2288	11.5743
Prepare schematic design proposal I2	2.9178	0.87	0.00	11.0543	0.00	11.3651
Present SD proposal to the client	3.5805	0.08	2.5889	4.5139	2.5889	4.6794
Submit SD to the Agencies	36.4070	0.91	26.0287	46.5376	26.0287	46.8609
Update selected design alternative	9.1000	0.25	6.3712	11.3996	6.3280	11.8903
Update selected design alternative I2	2.8866	0.86	0.00	10.8815	0.00	11.4196

Schematic Design Process

Replications: 100 Time Units: Hours

Process

Time per Entity

Wait Time Per Entity	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
1st review with the AHJs	0.00	0.00	0.00	0.00	0.00	0.00
Asimilate and Analize info	0.00	0.00	0.00	0.00	0.00	0.00
Develop architectural design system	0.00	0.00	0.00	0.00	0.00	0.00
Develop architectural design system I2	0.00	0.00	0.00	0.00	0.00	0.00
Develop MEP design system	0.00	0.00	0.00	0.00	0.00	0.00
Develop MEP design system I2	0.00	0.00	0.00	0.00	0.00	0.00
Develop other design system	0.00	0.00	0.00	0.00	0.00	0.00
Develop other design system I2	0.00	0.00	0.00	0.00	0.00	0.00
Develop site design system	0.00	0.00	0.00	0.00	0.00	0.00
Develop site design system I2	0.00	0.00	0.00	0.00	0.00	0.00
Develop structural design system	0.00	0.00	0.00	0.00	0.00	0.00
Develop structural design system I2	0.00	0.00	0.00	0.00	0.00	0.00
Establishing design goals	0.00	0.00	0.00	0.00	0.00	0.00
Evaluating design alternatives	0.00	0.00	0.00	0.00	0.00	0.00
Evaluating design alternatives I2	0.00	0.00	0.00	0.00	0.00	0.00
Perform prelimary studies	0.00	0.00	0.00	0.00	0.00	0.00
Perform prelimary studies I2	0.00	0.00	0.00	0.00	0.00	0.00
Preliminary Code Compliance all systems	0.00	0.00	0.00	0.00	0.00	0.00
Prepare and develop design alternatives	0.00	0.00	0.00	0.00	0.00	0.00
Prepare and develop design alternatives I2	0.00	0.00	0.00	0.00	0.00	0.00
Prepare schematic design proposal	0.00	0.00	0.00	0.00	0.00	0.00
Prepare schematic design proposal I2	0.00	0.00	0.00	0.00	0.00	0.00
Present SD proposal to the client	0.00	0.00	0.00	0.00	0.00	0.00
Submit SD to the Agencies	0.00	0.00	0.00	0.00	0.00	0.00
Update selected design alternative	0.00	0.00	0.00	0.00	0.00	0.00
Update selected design alternative I2	0.00	0.00	0.00	0.00	0.00	0.00

Schematic Design Process

Replications: 100 Time Units: Hours

Process

Time per Entity

Total Time Per Entity	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
1st review with the AHJs	3.6025	0.09	2.6602	4.6254	2.6602	4.7128
Asimilate and Analize info	17.5190	0.46	12.2730	23.5989	12.2730	23.5989
Develop architectural design system	70.6086	1.82	54.8863	92.7480	49.4597	94.6126
Develop architectural design system I2	4.6302	1.38	0.00	17.5423	0.00	17.8143
Develop MEP design system	72.0034	1.91	48.9795	93.0788	48.9795	93.0788
Develop MEP design system I2	4.5562	1.36	0.00	17.5321	0.00	17.9257
Develop other design system	71.2035	1.91	50.0377	91.3128	50.0377	93.2505
Develop other design system I2	4.6944	1.40	0.00	18.5572	0.00	18.5572
Develop site design system	72.3757	1.73	50.9718	91.4060	50.9718	91.5567
Develop site design system I2	4.5734	1.36	0.00	17.9312	0.00	18.7546
Develop structural design system	71.7406	1.70	53.9281	92.5400	51.5033	93.7343
Develop structural design system I2	4.5548	1.35	0.00	17.4982	0.00	17.4982
Establishing design goals	18.0535	0.51	12.5427	23.3790	12.5427	23.3790
Evaluating design alternatives	3.6330	0.10	2.5414	4.6507	2.5414	4.6507
Evaluating design alternatives I2	1.1722	0.34	0.00	4.5528	0.00	4.5528
Perform prelimary studies	71.1741	1.72	53.8389	90.2907	51.2800	90.2907
Perform prelimary studies I2	4.7634	1.36	0.00	17.6348	0.00	18.3806
Preliminary Code Compliance all systems	12.7817	0.61	5.2036	18.2731	5.2036	18.4551
Prepare and develop design alternatives	73.0743	2.02	49.0023	91.4933	49.0023	91.4933
Prepare and develop design alternatives I2	4.9686	1.41	0.00	17.2873	0.00	17.6334
Prepare schematic design proposal	8.9291	0.23	6.2288	11.5743	6.2288	11.5743
Prepare schematic design proposal I2	2.9178	0.87	0.00	11.0543	0.00	11.3651
Present SD proposal to the client	3.5805	0.08	2.5889	4.5139	2.5889	4.6794
Submit SD to the Agencies	36.4070	0.91	26.0287	46.5376	26.0287	46.8609
Update selected design alternative	9.1000	0.25	6.3712	11.3996	6.3280	11.8903
Update selected design alternative I2	2.8866	0.86	0.00	10.8815	0.00	11.4196

Accumulated Time

Schematic Design Process

Replications: 100 Time Units: Hours

Process

Accumulated Time

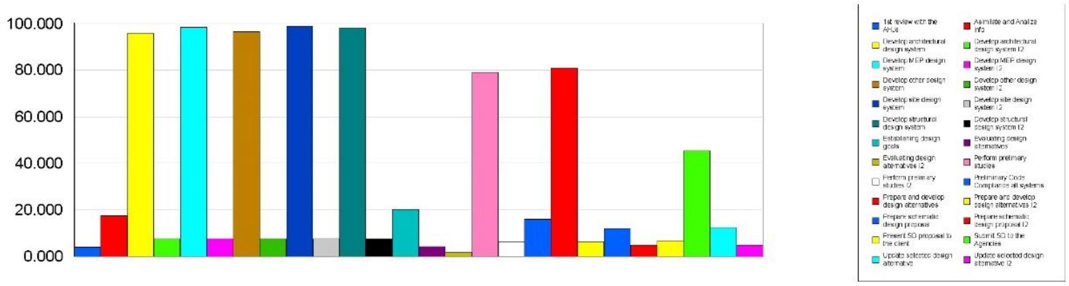
Accum VA Time	Average	Half Width	Minimum Average	Maximum Average
1st review with the AHJs	3.9813	0.25	2.6602	11.0605
Asimilate and Analize info	17.5190	0.46	12.2730	23.5989
Develop architectural design system	95.8115	9.47	54.8863	272.21
Develop architectural design system I2	7.5860	2.90	0.00	91.4354
Develop MEP design system	98.3831	10.19	48.9795	310.76
Develop MEP design system I2	7.5513	2.94	0.00	94.5591
Develop other design system	96.3312	9.26	50.0377	275.40
Develop other design system I2	7.6692	2.92	0.00	91.6843
Develop site design system	98.7972	9.99	50.9718	306.71
Develop site design system I2	7.5523	2.94	0.00	99.30
Develop structural design system	98.0204	10.18	53.9281	312.86
Develop structural design system I2	7.4813	2.92	0.00	99.18
Establishing design goals	20.0726	1.41	12.5427	58.2237
Evaluating design alternatives	4.0322	0.27	2.5414	9.8166
Evaluating design alternatives I2	1.5515	0.50	0.00	8.4329
Perform prelimary studies	78.9454	5.22	53.8389	220.82
Perform prelimary studies I2	6.2147	1.95	0.00	35.2696
Preliminary Code Compliance all systems	16.0253	1.53	5.2036	44.8629
Prepare and develop design alternatives	80.9298	5.29	49.0023	210.59
Prepare and develop design alternatives I2	6.4220	1.98	0.00	32.9454
Prepare schematic design proposal	12.0801	1.17	6.2288	37.5498
Prepare schematic design proposal I2	4.7218	1.75	0.00	53.4739
Present SD proposal to the client	6.8123	1.05	2.5889	33.9902
Submit SD to the Agencies	45.3385	3.61	26.0287	107.00
Update selected design alternative	12.4163	1.27	6.3712	35.5115
Update selected design alternative I2	4.7242	1.84	0.00	63.5491

Schematic Design Process

Replications: 100 Time Units: Hours

Process

Accumulated Time



Schematic Design Process

Replications: 100 Time Units: Hours

Process

Accumulated Time

Accum Wait Time	Average	Half Width	Minimum Average	Maximum Average
1st review with the AHJs	0.00	0.00	0.00	0.00
Asimilate and Analize info	0.00	0.00	0.00	0.00
Develop architectural design system	0.00	0.00	0.00	0.00
Develop architectural design system I2	0.00	0.00	0.00	0.00
Develop MEP design system	0.00	0.00	0.00	0.00
Develop MEP design system I2	0.00	0.00	0.00	0.00
Develop other design system	0.00	0.00	0.00	0.00
Develop other design system I2	0.00	0.00	0.00	0.00
Develop site design system	0.00	0.00	0.00	0.00
Develop site design system I2	0.00	0.00	0.00	0.00
Develop structural design system	0.00	0.00	0.00	0.00
Develop structural design system I2	0.00	0.00	0.00	0.00
Establishing design goals	0.00	0.00	0.00	0.00
Evaluating design alternatives	0.00	0.00	0.00	0.00
Evaluating design alternatives I2	0.00	0.00	0.00	0.00
Perform prelimary studies	0.00	0.00	0.00	0.00
Perform prelimary studies I2	0.00	0.00	0.00	0.00
Preliminary Code Compliance all systems	0.00	0.00	0.00	0.00
Prepare and develop design alternatives	0.00	0.00	0.00	0.00
Prepare and develop design alternatives I2	0.00	0.00	0.00	0.00
Prepare schematic design proposal	0.00	0.00	0.00	0.00
Prepare schematic design proposal I2	0.00	0.00	0.00	0.00
Present SD proposal to the client	0.00	0.00	0.00	0.00
Submit SD to the Agencies	0.00	0.00	0.00	0.00
Update selected design alternative	0.00	0.00	0.00	0.00
Update selected design alternative I2	0.00	0.00	0.00	0.00

Other

Schematic Design Process

Replications: 100 Time Units: Hours

Process

Other

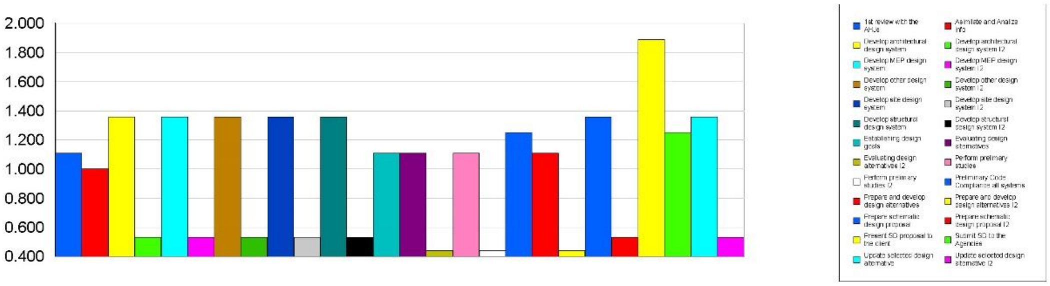
Number In	Average	Half Width	Minimum Average	Maximum Average
1st review with the AHJs	1.1100	0.07	1.0000	3.0000
Asimilate and Analize info	1.0000	0.00	1.0000	1.0000
Develop architectural design system	1.3600	0.13	1.0000	4.0000
Develop architectural design system I2	0.5300	0.21	0.00	7.0000
Develop MEP design system	1.3600	0.13	1.0000	4.0000
Develop MEP design system I2	0.5300	0.21	0.00	7.0000
Develop other design system	1.3600	0.13	1.0000	4.0000
Develop other design system I2	0.5300	0.21	0.00	7.0000
Develop site design system	1.3600	0.13	1.0000	4.0000
Develop site design system I2	0.5300	0.21	0.00	7.0000
Develop structural design system	1.3600	0.13	1.0000	4.0000
Develop structural design system I2	0.5300	0.21	0.00	7.0000
Establishing design goals	1.1100	0.07	1.0000	3.0000
Evaluating design alternatives	1.1100	0.07	1.0000	3.0000
Evaluating design alternatives I2	0.4400	0.13	0.00	2.0000
Perform prelimary studies	1.1100	0.07	1.0000	3.0000
Perform prelimary studies I2	0.4400	0.13	0.00	2.0000
Preliminary Code Compliance all systems	1.2500	0.10	1.0000	3.0000
Prepare and develop design alternatives	1.1100	0.07	1.0000	3.0000
Prepare and develop design alternatives I2	0.4400	0.13	0.00	2.0000
Prepare schematic design proposal	1.3600	0.13	1.0000	4.0000
Prepare schematic design proposal I2	0.5300	0.21	0.00	7.0000
Present SD proposal to the client	1.8900	0.28	1.0000	9.0000
Submit SD to the Agencies	1.2500	0.10	1.0000	3.0000
Update selected design alternative	1.3600	0.13	1.0000	4.0000
Update selected design alternative I2	0.5300	0.21	0.00	7.0000

Schematic Design Process

Replications: 100 Time Units: Hours

Process

Other



Schematic Design Process

Replications: 100 Time Units: Hours

Process

Other

Number Out	Average	Half Width	Minimum Average	Maximum Average
1st review with the AHJs	1.1100	0.07	1.0000	3.0000
Asimilate and Analize info	1.0000	0.00	1.0000	1.0000
Develop architectural design system	1.3600	0.13	1.0000	4.0000
Develop architectural design system I2	0.5300	0.21	0.00	7.0000
Develop MEP design system	1.3600	0.13	1.0000	4.0000
Develop MEP design system I2	0.5300	0.21	0.00	7.0000
Develop other design system	1.3600	0.13	1.0000	4.0000
Develop other design system I2	0.5300	0.21	0.00	7.0000
Develop site design system	1.3600	0.13	1.0000	4.0000
Develop site design system I2	0.5300	0.21	0.00	7.0000
Develop structural design system	1.3600	0.13	1.0000	4.0000
Develop structural design system I2	0.5300	0.21	0.00	7.0000
Establishing design goals	1.1100	0.07	1.0000	3.0000
Evaluating design alternatives	1.1100	0.07	1.0000	3.0000
Evaluating design alternatives I2	0.4400	0.13	0.00	2.0000
Perform prelimary studies	1.1100	0.07	1.0000	3.0000
Perform prelimary studies I2	0.4400	0.13	0.00	2.0000
Preliminary Code Compliance all systems	1.2500	0.10	1.0000	3.0000
Prepare and develop design alternatives	1.1100	0.07	1.0000	3.0000
Prepare and develop design alternatives I2	0.4400	0.13	0.00	2.0000
Prepare schematic design proposal	1.3600	0.13	1.0000	4.0000
Prepare schematic design proposal I2	0.5300	0.21	0.00	7.0000
Present SD proposal to the client	1.8900	0.28	1.0000	9.0000
Submit SD to the Agencies	1.2500	0.10	1.0000	3.0000
Update selected design alternative	1.3600	0.13	1.0000	4.0000
Update selected design alternative I2	0.5300	0.21	0.00	7.0000

Schematic Design Process

Replications: 100 Time Units: Hours

Queue

Time

Values Across All Replications

Schematic Design Process

Replications: 100 Time Units: Hours

Queue

Time

Waiting Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
1st review with the AHJs.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Asimilate and Analize info.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Batch Systems DA I2.Queue	0.7607	0.24	0.00	3.5044	0.00	7.9239
Batch Systems DA.Queue	11.3491	0.80	1.5831	20.5715	0.00	39.5247
Develop architectural design system I2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Develop architectural design system.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Develop MEP design system I2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Develop MEP design system.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Develop other design system I2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Develop other design system.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Develop site design system I2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Develop site design system.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Develop structural design system I2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Develop structural design system.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Establishing design goals.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Evaluating design alternatives I2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Evaluating design alternatives.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Perform prelimary studies I2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Perform prelimary studies.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Preliminary Code Compliance all systems.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Prepare and develop design alternatives I2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Prepare and develop design alternatives.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Prepare schematic design proposal I2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Prepare schematic design proposal.Queue	0.00	0.00	0.00	0.00	0.00	0.00

Schematic Design Process

Replications: 100 Time Units: Hours

Queue

Time

Waiting Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Present SD proposal to the client.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Submit SD to the Agencies.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Update selected design alternative I2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Update selected design alternative.Queue	0.00	0.00	0.00	0.00	0.00	0.00

Other

Schematic Design Process

Replications: 100 Time Units: Hours

Queue

Other

Number Waiting	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
1st review with the AHJs.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Asimilate and Analize info.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Batch Systems DA I2.Queue	0.01192970	0.00	0.00	0.1057	0.00	5.0000
Batch Systems DA.Queue	0.1696	0.01	0.02563714	0.3300	0.00	5.0000
Develop architectural design system I2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Develop architectural design system.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Develop MEP design system I2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Develop MEP design system.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Develop other design system I2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Develop other design system.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Develop site design system I2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Develop site design system.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Develop structural design system I2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Develop structural design system.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Establishing design goals.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Evaluating design alternatives I2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Evaluating design alternatives.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Perform prelimary studies I2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Perform prelimary studies.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Preliminary Code Compliance all systems.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Prepare and develop design alternatives I2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Prepare and develop design alternatives.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Prepare schematic design proposal I2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Prepare schematic design proposal.Queue	0.00	0.00	0.00	0.00	0.00	0.00

Schematic Design Process

Replications: 100 Time Units: Hours

Queue

Other

Number Waiting	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Present SD proposal to the client.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Submit SD to the Agencies.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Update selected design alternative I2.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Update selected design alternative.Queue	0.00	0.00	0.00	0.00	0.00	0.00

Schematic Design Process

Replications: 100 Time Units: Hours

Resource

Usage

Instantaneous Utilization	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
AHJs	0.1132	0.00	0.03711035	0.1693	0.00	1.0000
Architect	0.8565	0.01	0.7570	0.9589	0.00	1.0000
Civil Consultant	0.2306	0.01	0.1439	0.3388	0.00	1.0000
MEP Consultant	0.2661	0.01	0.1688	0.3852	0.00	1.0000
Other Consultant	0.2273	0.01	0.1288	0.3581	0.00	1.0000
Owner	0.3061	0.01	0.2072	0.3908	0.00	1.0000
Project Manager	0.03609528	0.00	0.01379128	0.06414547	0.00	1.0000
Str Consultant	0.2648	0.01	0.1655	0.4024	0.00	1.0000

Number Busy	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
AHJs	0.1132	0.00	0.03711035	0.1693	0.00	1.0000
Architect	0.8565	0.01	0.7570	0.9589	0.00	1.0000
Civil Consultant	0.2306	0.01	0.1439	0.3388	0.00	1.0000
MEP Consultant	0.2661	0.01	0.1688	0.3852	0.00	1.0000
Other Consultant	0.2273	0.01	0.1288	0.3581	0.00	1.0000
Owner	0.3061	0.01	0.2072	0.3908	0.00	1.0000
Project Manager	0.03609528	0.00	0.01379128	0.06414547	0.00	1.0000
Str Consultant	0.2648	0.01	0.1655	0.4024	0.00	1.0000

Number Scheduled	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
AHJs	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Architect	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Civil Consultant	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
MEP Consultant	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Other Consultant	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Owner	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Project Manager	1.0000	0.00	1.0000	1.0000	1.0000	1.0000
Str Consultant	1.0000	0.00	1.0000	1.0000	1.0000	1.0000

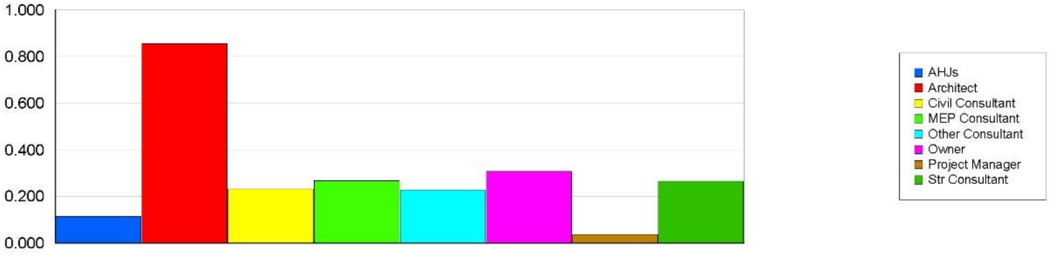
Schematic Design Process

Replications: 100 Time Units: Hours

Resource

Usage

Scheduled Utilization	Average	Half Width	Minimum Average	Maximum Average
AHJs	0.1132	0.00	0.03711035	0.1693
Architect	0.8565	0.01	0.7570	0.9589
Civil Consultant	0.2306	0.01	0.1439	0.3388
MEP Consultant	0.2661	0.01	0.1688	0.3852
Other Consultant	0.2273	0.01	0.1288	0.3581
Owner	0.3061	0.01	0.2072	0.3908
Project Manager	0.03609528	0.00	0.01379128	0.06414547
Str Consultant	0.2648	0.01	0.1655	0.4024



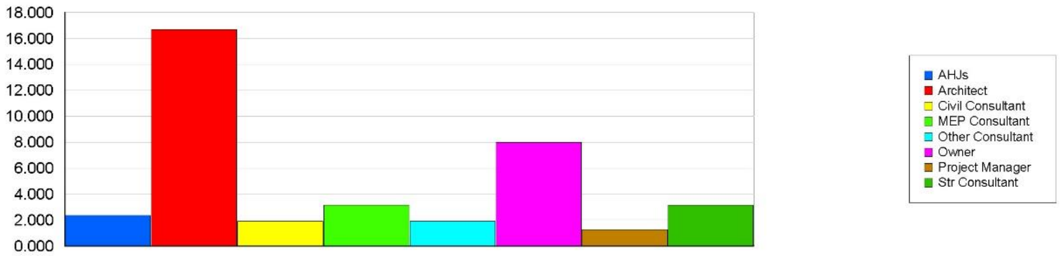
Schematic Design Process

Replications: 100 Time Units: Hours

Resource

Usage

Total Number Seized	Average	Half Width	Minimum Average	Maximum Average
AHJs	2.3600	0.13	2.0000	5.0000
Architect	16.6800	1.49	11.0000	45.0000
Civil Consultant	1.8900	0.28	1.0000	9.0000
MEP Consultant	3.1400	0.36	2.0000	11.0000
Other Consultant	1.8900	0.28	1.0000	9.0000
Owner	7.9900	0.77	5.0000	22.0000
Project Manager	1.2500	0.10	1.0000	3.0000
Str Consultant	3.1400	0.36	2.0000	11.0000



Values Across All Replications

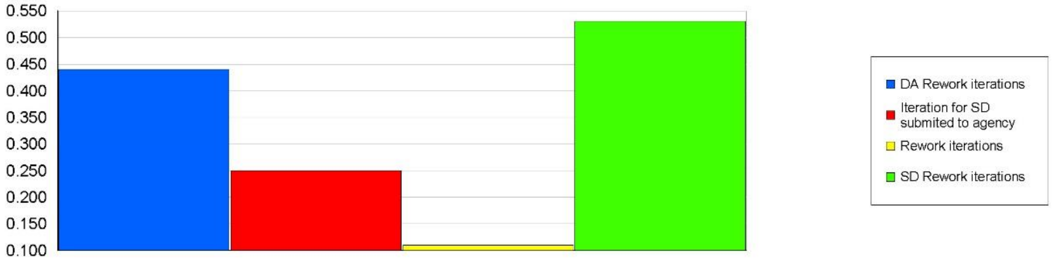
Schematic Design Process

Replications: 100 Time Units: Hours

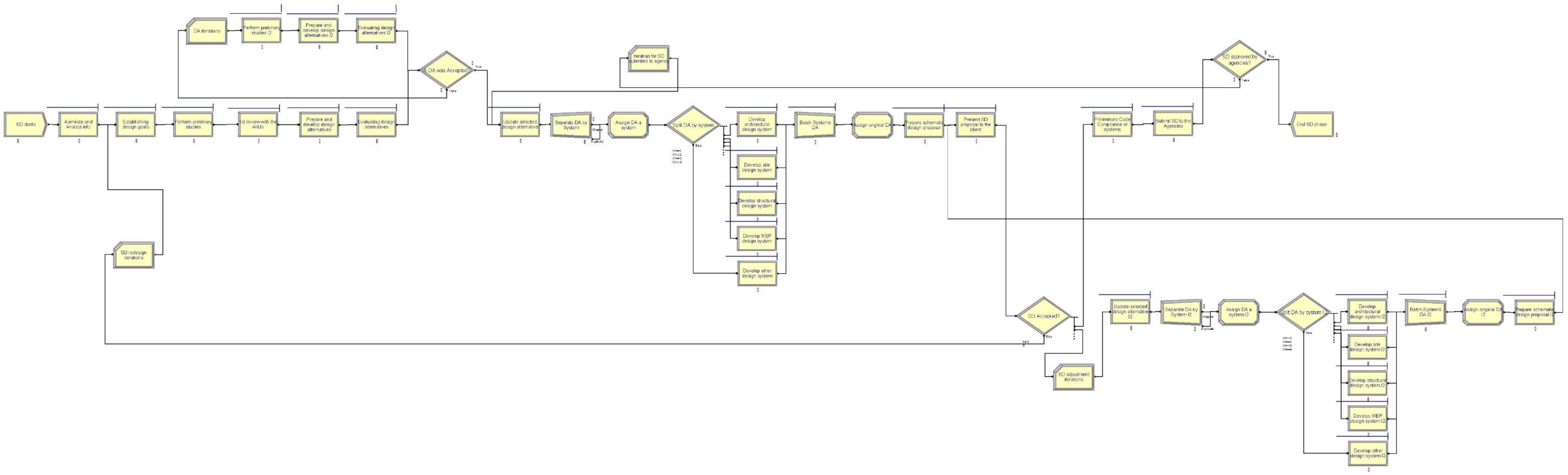
User Specified

Counter

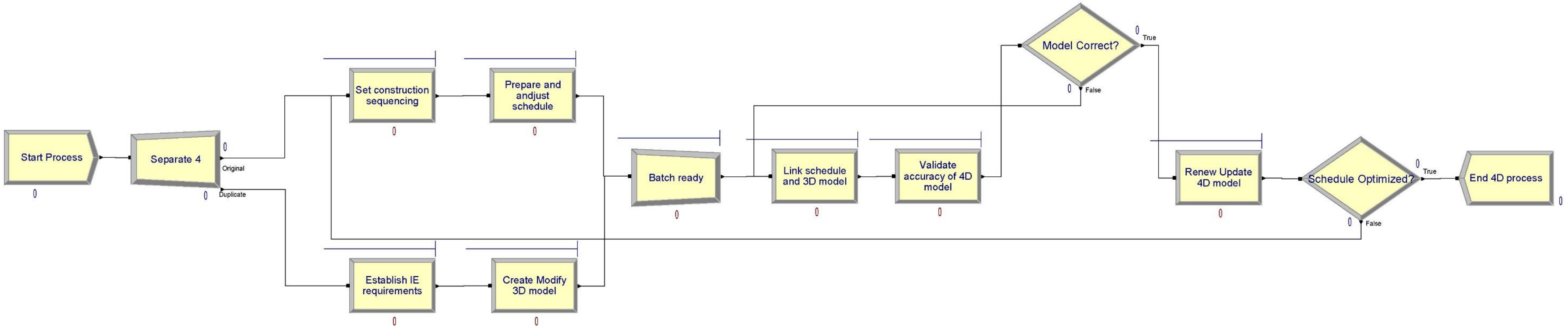
Count	Average	Half Width	Minimum Average	Maximum Average
DA Rework iterations	0.4400	0.13	0.00	2.0000
Iteration for SD submited to agency	0.2500	0.10	0.00	2.0000
Rework iterations	0.1100	0.07	0.00	2.0000
SD Rework iterations	0.5300	0.21	0.00	7.0000



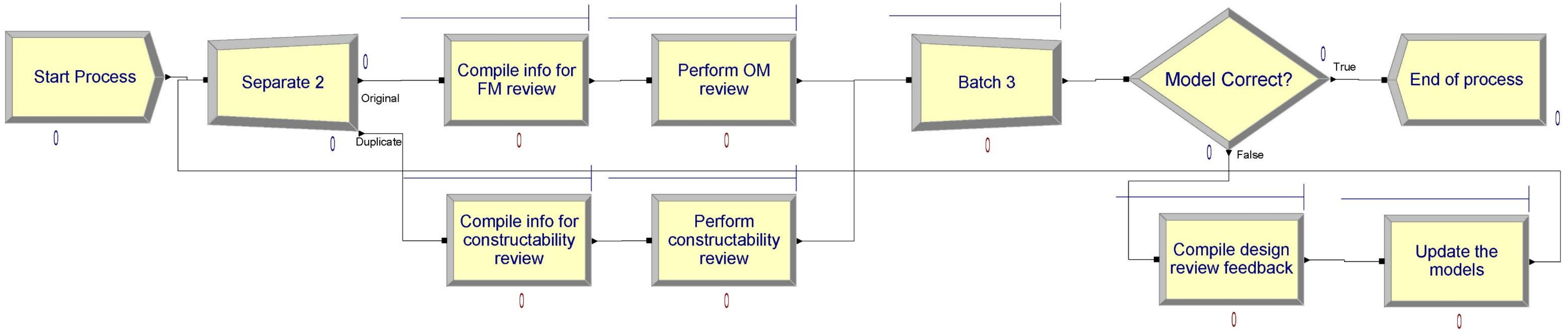
Appendix J. – BIM Processes maps in Arena®



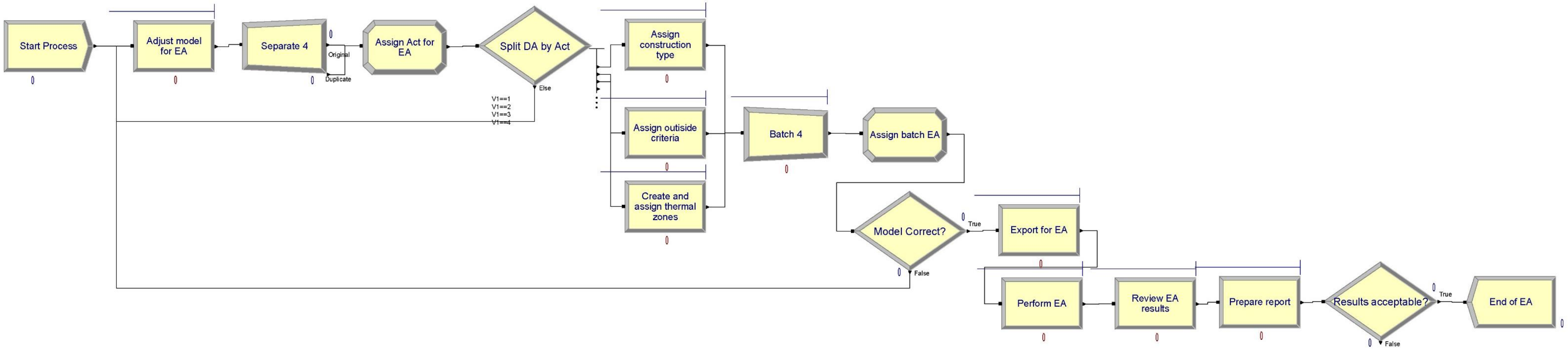
3D coordination process



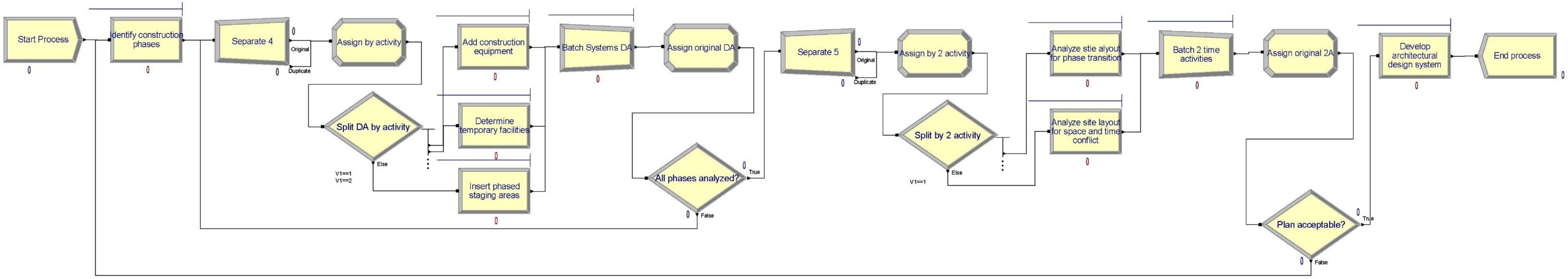
4D modeling process



BIM Design Review Process



BIM Energy Analisys Process



BIM Site Utilization Planning Process

This page has been intentionally left blank