PRODUCT MODEL EXCHANGE STANDARDS FOR CAST-IN-PLACE REINFORCED CONCRETE: IMPLEMENTATION METHODS, VALUE CONSIDERATIONS, AND APPLICATION TO DESIGN INDICATORS

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PRODUCT MODEL EXCHANGE STANDARDS FOR CAST-IN-PLACE REINFORCED CONCRETE: IMPLEMENTATION METHODS, VALUE CONSIDERATIONS, AND APPLICATION TO DESIGN INDICATORS

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To my mother

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LIST OF SYMBOLS AND ABBREVIATIONS

BIM	Building Information Modeling
CIP	Cast-in-Place
RC	Reinforced Concrete
ACI	American Concrete Institute
AISC	American Institute of Steel Construction
NBIMS	National BIM Standard
IFC	Industry Foundation Classes
IDM	Information Delivery Manual
MVD	Model View Definition
BPMN	Business Process Model Notation
ER	Exchange Requirement
EM	Exchange Model
EO	Exchange Objects
QTO	Quantity Take-off
ROI	Return on Investment
CO	Change Order
RFI	Request for Information
SD	Schematic Design
DD	Design Development
CD	Construction Documentation
PT	Post-Tensioned

SUMMARY

Building Information Modeling (BIM) has changed the way information in design and construction is communicated by allowing the possibility of exchanging project models and data together. To optimize the process, standards have been developed to define what is required in each exchange and how to represent it. For several years Cast-in-Place (CIP) reinforced concrete (RC), one of the most important construction materials worldwide, has been subject to considerable efforts toward the development of its standards. However, the monolithic nature of the material and its complex supply chain makes it difficult for this development to be efficiently carried out.

This dissertation presents the results of a study with four key aims: (1) identify how exchange standards for CIP RC fit into current engineering and construction practices, (2) develop the requirements and methods for implementation, (3) evaluate the value considerations of implementing the standards in practice, and (4) apply the information available in exchange standards to enhance the design and construction processes through the estimation of design indicators. This research is developed in the context of the undergoing efforts of the American Concrete Institute (ACI) to develop industry wide standards for CIP RC concrete.

To map the current engineering practices and challenges regarding CIP RC model exchanges, the dissertation presents the results of an ethnographic-action study performed to allow a description of current behaviors, the acquisition of qualitative data regarding the advantages of implementing BIM standards on a practical level, and to inform of potential additional requirements for standardization. To assist the implementation of standards in practice, this dissertation presents a set of methods for implementation that adapt to current

tools and practices. To identify the value considerations of implementing exchange standards, the same CIP RC processes captured in the ethnographic study are reproduced but using the methods developed for model exchange standards. Finally, the study presents the results of a logistic regression model developed to use the parametrized information made available through these exchanges, to estimate indicators that improve the design and construction processes.

The main conclusions of the dissertation include: a) although the value of using BIM has been studied and discussed in several publications and reports there is a gap in identifying the implementation methods and value considerations brought by using exchange standards; b) interoperability based on tool plug-ins is tied to software developers and versions, which has led to companies with high IT capabilities to develop in-house tools, and although automation and standardization require an increase in upfront work, the benefits are realized downstream; c) connectivity and boundary definition of overlapping structural elements remain a great challenge for CIP RC models, leading to some engineers developing their own in-house tools or starting the modeling in an analysis tool from scratch instead of importing it from a BIM tool; d) CIP RC has the additional challenges of communicating different views that change the boundary definition between objects based on the scope of the stakeholder performing the modeling, and representing data differently during different stages of the design and coordination process; e) to enhance the process of developing exchange standards for CIP RC special though should be given to the standardization of connectivity between physical and analysis models, standardization of concrete elements' volume interaction, full standard parametrization of representative information, alignment with standardization of reinforcement detail, and development of guidelines to use data-analytics techniques for processing of non-standardized scenarios;

f) implementation methods show the applicability of exchange standards to current design and coordination practices, and have the potential to serve both as guidelines for stakeholders to use as part of their processes, as well as a reference on how these guidelines could be developed for further interoperability and standardization efforts; g) the implementation of exchange standards may require an increase in implementation time, but derives in reductions in information production time, reinforcement detailing time, construction coordination time, as well as errors & omissions; h) logistic regression models are a suitable alternative to predict potential constructability issues based on parameters contained in exchange standards, as they properly fit datapoints representing typical congestion occurrences in CIP RC frame elements' intersections.

CHAPTER 1. INTRODUCTION

During the last few decades, Building Information Modeling (BIM) has earned its position as one of the most important trends in the design and construction industry. The possibility of exchanging project models and data together, while working in a collaborative environment has helped to increase the efficiency, decrease the number of errors, and support the representation of project complexities (Eastman, Teicholz, et al. 2011). However, these exchanges demand an increase in the interoperability capabilities since every discipline has a wide range of applications it can use and all of them should be able to interact with each other. This ability to exchange building models and data between different applications and during different project phases is something the industry has been working on for years, even before the term "BIM" was introduced, but remains the key barrier of BIM implementation (Sun, et al. 2017). The first interoperability attempts actually started in the manufacturing industry when parametric object-oriented modeling encountered exchanging problems between applications in the late 1980s. As for the Architecture, Engineering, Construction and Facility Management (AEC/FM) industry, several ISO-STEP based technologies started to be developed by the 1990s and have continued to evolve, resulting in product models such as AP 225, AP 241, ISO15926, CIS/2 and IFC (Eastman, Teicholz, et al. 2011).

1.1 Problem Statement

The most used standard in the AEC industry is the Industry Foundation Classes (IFC), which provides a digital data structure to describe relationships and properties of objects for a construction project. One of the most complete standards for interoperability within IFC is the one developed for the precast/prestressed concrete industry (Eastman, Sacks, et al. 2010). Similarly, the steel industry developed its own standard (CIS/2) and has worked on mapping this standard to IFC (Lipman 2009), and researchers in wood construction have made recent efforts in the standardization of mass and cross laminated timber (CLT) (Staub-French, et al. 2018) (Bermek, Shelden and Gentry 2019). Another industry segment, Cast-in-Place (CIP) Reinforced Concrete (RC), led by the American Concrete Institute (ACI), has standards under development using IFC but is far behind the steel and precast concrete developments, mainly due to the complexities of the materials and entities involved. and the late start of the process. According to the 2017 US Economic Census for Construction, when compared to the total categories of “foundations, super-structure and building exterior elements” cast-in-place concrete constitutes 29.5% of the revenue and 27.8% of the labor force. When the comparison is made only with respect to the other structural materials listed on the report (steel, precast concrete, framing, masonry), cast-in-place concrete constitutes 48.8% of the revenue and hires 44.1% of the labor (US Census Bureau 2017). This would indicate that the material with the greatest challenges and needs for exchange standards development is at the same time the most important construction material in the US in terms of revenue and labor.

The challenging task of developing such standards is being carried out by the ACI, who has already published two documents and is currently working to bring the CIP RC exchanges up to date with the development of another two documents. The first document, referred to as an Information Delivery Manual (IDM), includes a general description of the industry processes and exchanges, while the other three documents address three specific data exchanges required along the CIP RC supply chain described in the IDM (ACI

Committee 131 2015). These exchanges originated from a series of discussions from industry and technology professionals who identified their data exchange needs, constraints and methods. In the CIP RC industry, and in several others, some exchanges have been implemented by some tool suppliers, and have been tested and improved. The implementation and use of these standards in the AEC practice would not only increase the efficiency of the design process, but could also lead to a greater adoption and development of BIM exchanges, especially in the lagged CIP RC industry. (Grilo and Jardim-Goncalves 2010) argue that if true interoperability is to be achieved, the sector needs to realize the value it carries, and so the research should not focus only on the technology, but also on identifying the value proposition of interoperability at the business level. However, although there have been several publications that attempt to measure the value that BIM has on the industry across several dimensions, there is no actual study on the effects that the implementation of the aforementioned exchange standards has on the process. The data contained as part of the standards is sometimes conservative given that no major extra work wants to be done by any stakeholder, so some of the information is still transmitted using conventional methods. A value assessment on the exchange standards and all the data that can be incorporated within them can help incentivize the adoption and involvement in the development of the standards, thus improving the efficiency of exchange processes for CIP RC buildings. Furthermore, for stakeholders to adopt these standards, it is also relevant to identify the requirements, and develop the methods and procedures for implementation that align with current tools as well as design and construction coordination practices.

There are several methodologies to acquire data that reflects the current state of a system or community, as well as the potential improvements on a specific condition. Some of the most used include interviews, workshops and economic and time measurements. However, these approaches are based mainly on the opinions of experts and on data of finalized projects, and although such data can be valuable and it is often the approach used to develop exchange standards, it cannot describe how the exchanges are actually being performed or utilized and may not reveal dynamics that are only observable during the process (Ball and Ormerod 2000). Action research is a particularly well-suited approach for the development or testing of information systems because it proposes the integration of practice and research, particularly through cycles of observations of practice for problem identification, and development and implementation of technical solutions (Baskerville and Woodharper 1996). To complement this approach with the specific tools to gather the information from practice, (Hartmann, Fischer and Haymaker 2008) proposed combining action research with ethnography. Ethnography has been useful when applied to the Architecture, Engineering and Construction (AEC) industry because of its ability to capture processes and dynamics, which can be addressed in different ways and structured based on the context and purpose (Crabtee, Rouncefield and Tolmie 2012). Ethnographic studies consist of an immersive experience to characterize the context to be studied, and gather information based on field observations, interviews and/or available documentation. Usually, the researcher (ethnographer) gathers information firsthand by spending a considerable amount of time with subjects in the community under study within their own environment, while they continue with their activities and practices. Although qualitative in nature, it has also been applied on multiple studies to inform quantitative aspects of research if done at the beginning of the process (Bauman and Greenberg 1992). **Figure 1** shows these ethnographic-action research cycles proposed by (Hartmann, Fischer and Haymaker 2008) to support the development of technological solutions.

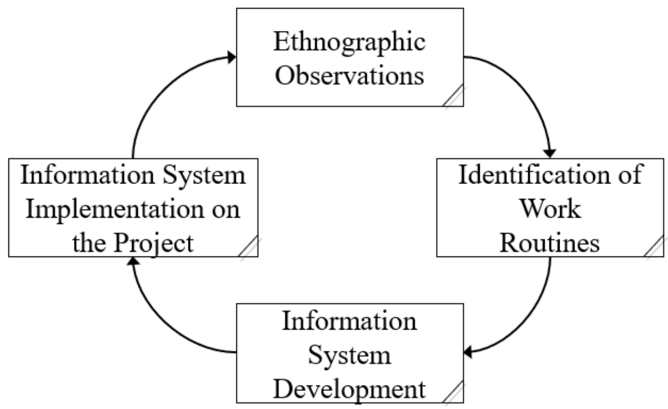


Figure 1. **Ethnographic-action research cycles (Hartmann, Fischer and Haymaker 2008).**

Furthermore, one of the main goals of interoperability is to allow each stakeholder to exchange the model both with specific analysis tools of its trade, and with tools from other stakeholders, which would allow them to perform analyses and coordination. Increasing the effectiveness and quality of the design process is a task of the uttermost importance to building designers, since the building environment directly affects the quality of life not only of the current generation of occupants, but also of the many generations to come. As defined in the book “The principles of design” by Nam Suh, the design process has four core steps: input (X), ideation process (G), analytical process (H) and desired output (Y) (Suh 1990) . The ideation process depends highly on the experience of the designer and is part of a loop with the analysis process, from which it receives feedback and performs modifications, as shown in **Figure 2**. If the analysis process to evaluate the performance and compliance with other disciplines’ requirements is richer and faster in the early stages, the process would require less loops to get to the desired outcome.

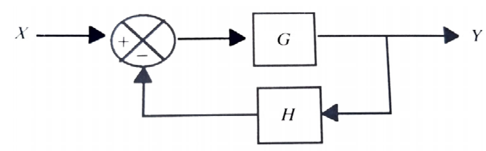


Figure 2. **Design process loop (Suh 1990)**

When a building model is exchanged and carried to an analysis or other stakeholder's tool, it has certain specific kinds of data that must be parsed, later allowing the user to model additional items, and finally performing the required analyses and informing the user of the behavior or compliance of the model. This capability of design checking constitutes in itself one of the greatest advantages of the use of BIM technologies (Eastman, Teicholz, et al. 2011). Most of the time, the data that can be carried from one tool to the other in an open format is not very rich, so the labor required in the receiving tool to bring the model to a point where it can provide valuable information is considerable. This panorama changes when exchange model standards are brought into the picture, and rich data in a specific format is required for the exchange. The exchange files in IFC that follow the standards for any tool to read, contain a vast amount of valuable data that can be accessed and potentially used for assessment and prediction before even going through the process of importing, processing, modifying, and analyzing in the target tools. Although there are multiple frameworks now available for design and code checking using model information and BIM tools, there has not been an exploration on how the data contained within an open exchange file can be used to predict indicators about the model. Particularly in the case of the ACI exchanges, how the design intent and construction planning exchanges could use the parametrized information to estimate potential issues that may arise once the model reaches further processes such as detailing or construction.

The purpose of this dissertation is fourfold: 1) to study the current practices of data exchanges for the CIP RC industry and provide further recommendations to the process, 2) to develop implementation methods of standard exchanges into practice, 3) to identify the value considerations of implementing current product model exchange standards on a practical level and identify which standardized data has the biggest impact on value, and 4) to use the data contained in such standardized exchanges to further improve the design process of CIP RC structures by identifying potential design issues during those exchanges. The following sections describe the specific research questions to be addressed, the goals and objectives of the research, and the research scope and structure proposed to be able to achieve the research goals.

1.2 Research Questions

The research questions this study seeks to respond are:

1. *What are the requirements to implement Cast-in-Place Reinforced Concrete exchange standards in practice and what would be the implementation methods needed to adapt them to current tools and capabilities?*

2. *What are the value considerations when implementing product model exchange standards in the complex industry of Cast-in-Place Reinforced Concrete and what is recommended for further standardization efforts?*

3. *Can the enormous amount of data contained in these standardized exchange documents be utilized to estimate design indicators during the exchanges in order to enhance the design process and make it more informed and efficient?*

In order to answer these questions, the dissertation is framed within the current development of exchange standards and the data contained within them, while analyzing the current exchange development practices and the way they respond on a practice level. The first question leads to the development of implementation methods that respond to the capabilities of commonly used tools and procedures. The second question leads to a study of the current practices and requirements in the workplace, and a comparison with a scenario where exchange standards are implemented. The third question leads to the development of a model to estimate indicators of the design process, by using the information available within the exchanges and the known characteristics of CIP RC structures.

1.3 Research Goals and Objectives

The main goal of this dissertation is to aid in the development, implementation and application of exchange standards for the Cast-in-Place Reinforced Concrete industry by identifying the value considerations of implementing them at a practice level, providing methods to implement them in practice and apply them to make the process more efficient. This goal requires a complete understanding and mapping of the exchange practices and exchange standards, the identification of the value they carry, and a study of the data usage. To achieve the goal, the following objectives are defined.

a. *Investigate the current exchange practices for CIP RC structures within their supply chain context and compare them to the current exchange standard's development processes.* This implies a refined observation of the current capabilities, practices, and dynamics of the different stakeholders as a part of a project that follows the supply chain.

b. *Develop the implementation methods necessary to apply the exchange standards in practice*, considering the tools commonly used for the different tasks and the requirements for design and coordination procedures.

c. *Identify the value considerations of implementing the current exchange standards for CIP RC as part of the process.* The definition of the metrics and dimensions is done by consulting different sources and through the observation described as part of the first goal. A replication of the same processes studied during the first phase is required, but this time using standard exchanges for CIP RC elements.

d. *Develop a regression model that allows using the rich data contained within the exchange standards to estimate design indicators that inform the design and coordination processes of potential design issues during the exchanges.* The focus of this application is identifying indicators that could be estimated from typical parameters available in the exchange files, create a database to train the model, and use it to inform the design process early on about issues that may arise during further phases.

1.4 Research Scope and Structure

This study is specific for the Cast-in-Place Reinforced Concrete industry, as it is one of the most used materials for construction in the US and in most parts of the world, and yet is still in the working stage of exchange standards development. The study itself is framed within the existing and under-development exchange standards by the American Concrete Institute as of 2022. Since a key aspect of this research is the study of the exchange practices and actual exchange behaviors within a CIP RC project, rather than the mere acquisition of post-project data or stakeholder interviews, the measurement of the value of implementation is characterized by the project selected for the ethnographic study. However, several triangulation and extrapolation efforts are made to obtain results that could apply to typical CIP RC projects.

The limitations of this study include those associated with the type of project(s) used for the study and the concrete elements within them. Although the most typical elements will be addressed and included in the study, there may be several more complex elements in practice that cannot be easily typified and standardized. The elements will mainly belong to concrete buildings and the approach may not have the same effect on other types of concrete structures. Furthermore, the dissertation is limited to the exchange standards published or under development by the ACI: reinforcement detail, structural design intent and construction planning. Finally, the application to estimate design indicators is limited to the indicators selected based on the data available for these exchange standards to further enhance the design process of CIP RC buildings.

The study starts with the study, mapping, and description of processes through an ethnographic-action study that allows the identification of data exchange behaviors for CIP RC models as well as the dynamics of the industry stakeholders themselves. This ethnographic-action study helps describe actual practices that may not always match typical interview responses from the individuals involved and helps create a series of recommendations for further development of the standards. To be able to create a scenario where standard exchanges are part of the process and to provide guidelines for practical usage, this study develops a series of implementation methods and procedures that allow the exchanges to be performed using the standards with specific examples on the most used tools in the industry. Subsequently, a comparison is performed by replicating the same process but with the use of CIP RC exchange standards, to identify the value considerations of their implementation on practice. The ethnographic study findings are also used to shape the implementation methods and adjusted procedures. To explore the application of the standards to enhance the design process, the study proceeds to select design indicators that may be estimated from the information available in the exchanges considered, based on a review of possible indicators and the context of the exchanges. Finally, the dissertation develops a database of typical situations that occur in CIP RC framed buildings from which the indicators may be estimated, to later create a regression model that allows these indicators to be estimated for further projects using the information available as part of the exchange standards.

1.5 Conclusion

The AEC/FM industry has leveraged the advantages of using of BIM for decades, but for those advantages to be fully achieved, the interoperability between all available applications needs to work seamlessly. The CIP RC industry is currently working in the production of exchange standards to transmit information for their type of structures, but due to the nature of the material and the complexity of the process has faced multiple challenges. The purpose of this dissertation, developed in the context of the development of these standards, is to provide further recommendations for standardization of CIP RC buildings based on current practices, to develop the implementation methods necessary to bring the standards into practice, to identify the value considerations of implementing these standards into the CIP RC practice, and to develop an application to use the information in the standards to estimate design indicators early in the process. These goals are achieved through an ethnographic-action study, the creation and testing of methods using test and real buildings, and a logistic regression model to predict the design indicators.

CHAPTER 2. LITERATURE REVIEW

2.1 Data Exchange Representation

The first interoperability attempts actually started in the manufacturing industry when parametric object-oriented modeling encountered exchanging problems between applications in the late 1980s. The attempt to solve those problems resulted in the creation of model exchange technologies in a standard known as the "Standard for Exchange of Product Model Data": ISO 10303, also known as ISO-STEP (Eastman, Jeong, et al. 2010), and that also provided the EXPRESS language, and its graphical version: EXPRESS-G, to achieve its goals (ISO 1994). As for the Architecture, Engineering, Construction and Facility Management (AEC/FM) industry, several ISO-STEP based technologies started to be developed by the 1990s and have continued to evolve, resulting in product models such as AP 225, AP 241, ISO15926, CIS/2 and IFC (Eastman, Teicholz, et al. 2011).

CimSteel Integration Standards (CIS/2) were developed to enhance the flow of information between the participants of the steel frame structures supply chain (Crowley and Watson 2000). They were promoted to be used in the United States for the design, analysis, planning and manufacturing process of steel framed structures, although they were not widely implemented for the design and analysis practice. Since they mainly provide integration within the process of steel structures, they lack interoperability with other disciplines of the industry. Therefore, some research was conducted to map the information contained in CIS/2 to the most used industry wide product data model, the IFC (Lipman 2009). Eventually, the American Institute of Steel Construction (AISC) moved its efforts to replace CIS/2 with IFC to allow communication and coordination within the steel supply chain as well as with other trades outside the steel industry, and even developed an exchange model called EM.11 to work with Numerical Control machines (Faulkner 2019). IFC has expanded progressively up to the point where it now supports not only geometry for steel structures, but also steel fabrication information (AISC 2019).

The Industry Foundation Classes (IFC) is an open standard flexible and comprehensive enough to allow the definition and representation of building objects, processes, relationships and other type of building related data through the project's entire lifecycle (Eastman, Jeong, et al. 2010), and has been so widely accepted that it is now an ISO standard itself: ISO 16739 ((ISO) 2013). Within IFC, further definition can be provided to develop standards specific for different areas in the design, construction, engineering and facility management fields. Regarding design and construction, one of the most complete standards is the one developed for the precast/prestressed concrete industry (Eastman, Sacks, et al. 2010). Cast-in-Place (CIP) Reinforced Concrete (RC) standards are also under development following the IFC schema but are far behind the steel and precast developments. The development of standards for CIP RC is a task on which the American Concrete Institute (ACI) 131 Committee is currently working on intensively (ACI 2020).

Since IFC is highly redundant and allows the same thing to be defined in different ways, the purpose of a BIM standard is to provide an extra level of specificity to the open and general IFC standard. The most accepted process to develop a BIM standard is the one proposed by the National BIM Standards (NBIMS) administered by buildingSMART, and it consists of identifying the practice workflows, the exchange of information demanded by each of them, and then defining proper model "views" that respond to the requirements of the workflow (Eastman, Jeong, et al. 2010). The process consists of four main phases:

Program, Design, Construct and Deploy and can be checked in detail in (Eastman, Teicholz, et al. 2011). The development can be seen from a case by case approach or from an integrated case approach (Georgia Institute of Technology; Precast Concrete Institute; Charles Pankow Foundation 2010), the latest being the one used by the ACI. The general approach relies on a group of experts in the field defining the process and the use cases (information flows) in a document called an Information Delivery Manual (IDM). The process is modeled using business process model notation (BPMN) and captures the stakeholders, the activities, the phases on which the activities take place, and the information exchange between activities known as exchange requirements (ERs) (Ouyang, et al. 2009). These exchange requirements are then classified in building model exchanges (exchange models) or non-building model exchanges, and are detailed in terms of what specific information is required to be transferred (exchange objects and their attributes and relationships), after which a group of information experts (IFC experts) implements a model view definition (MVD) based on it. Therefore, a MVD is a subset of the IFC schema that includes only the entities and relationships required in a specific information exchange (i.e., what is expected to be exported and imported), and that provides additional data or constraints to them. Finally, this allows software developers to write import and export translators that can read the standardized exchange data. A more detailed version of the process can be consulted in (Eastman, Jeong, et al. 2010) and in (Georgia Institute of Technology; Precast Concrete Institute; Charles Pankow Foundation 2010) with special application to the precast industry.

2.2 Product Model Exchanges for Cast-in-Place Reinforced Concrete

Regarding the standards specifically developed for concrete, considerable work has been published around the development and testing of precast/prestressed concrete standards. Several studies have been developed including the study of the requirements for parametric 3D modeling of precast concrete structures (Sacks, Eastman and Lee 2004), formal and ontological specifications for precast-model/building-information-model exchanges to provide an additional layer of specificity on top of IFC (Venugopal, Eastman and Teizer, Formal Specification of the IFC Concept Structure for Precast Model Exchanges 2012) (Venugopal, Eastman and Teizer 2012), the production of actual standards and model view definitions (Eastman, Sacks, et al. 2010), the development of benchmark tests to try the interoperability of the technology (Jeong, et al. 2009) and the creation of guidelines to develop BIM standards with specific examples of the Precast and Prestressed industry (Georgia Institute of Technology; Precast Concrete Institute; Charles Pankow Foundation 2010). However, although CIP and precast/prestressed are both concrete-based technologies, there is a huge difference between the monolithic nature of CIP versus the discrete nature of precast concrete. The two main reasons for the differences are: 1) The fact that steel and precast standards started their development earlier and therefore have had more time to advance, and 2) The fact that discrete structures such as those made from steel and precast have components that translate well and relatively easily to object-oriented modeling. On the other hand, CIP structures, monolithic in nature, can be divided in logical components but it is difficult to have clear physical delineation and break them into clearly defined objects (Barak, et al. 2009). At a practical level, CIP concrete structures are built as an aggregation of partial volumes of those logical components with several stakeholders involved in different parts of the process and elements, making it also a material with a very complex supply chain. For this reason, the research and standards development of CIP RC standards have taken longer and has not been as intensive.

Most of the research CIP-BIM oriented has focused on the reinforcement optimization of the elements using BIM models as noted in (Mangal and Cheng 2018), on the assessment and recommendations of BIM capabilities to handle the concrete reinforcement supply chain (Aram, Eastman and Sacks 2013) (Aram, Eastman and Sacks 2012) and on defining the unique requirements CIP RC has regarding its modeling and processes on BIM (Barak, et al. 2009). In the assessments performed for the BIM capabilities of current tools, from the evaluated categories of design and modeling, editing, project management and interoperability, interoperability proved to be the weakest because of the lack of a standardized way to document and translate the information (Aram, Eastman and Sacks 2012). Nevertheless, these assessments were performed before the release of the last ACI 131 documents which propose a standard way to exchange concrete reinforcement information (ACI Committee 131 2017). Furthermore, although in reality CIP RC is monolithic, during the modeling it has to be broken down into members, which means that the delineation between such members is conceptual and not physical. **Figure 3** shows the difference in model delineation and representation based on the particular stakeholder's interest and tasks. For example, the boundary for column and beam will be different for the detailer treating the node as a particular occurrence, whereas the structural engineer will give continuity to the column in the frames, and the construction planner will delineate based on planned pours and joints.

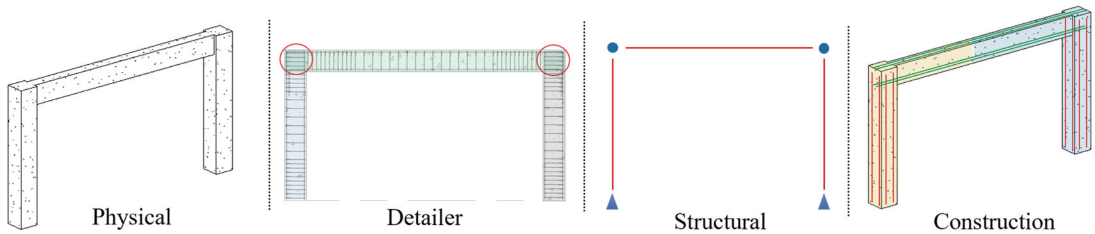


Figure 3. Concrete element delineation based on stakeholder view

Moreover, for structural modeling and detailing, objects must be divided depending on their function rather than their conceptual member definition and for fabrication the way elements are divided for modeling and for design differs from the way they are divided to be built. This creates three different mappings for the same exchange object (EO) (Barak, et al. 2009). Therefore, the main problem is that CIP RC structures can be modeled and divided into logical members, but they cannot be delineated in an unambiguous manner. (Barak, et al. 2009) proposed ways to handle this information within the modeling applications, but there is a lack of work regarding the way to represent this information using IFC for interoperability purposes.

With respect to the standards that have been developed by the ACI 131 committee, two documents have been published and two documents are under development. The first document that was published was the IDM for the CIP RC entire supply chain ACI 131.1R-14, including the process model and exchange requirements of the process (ACI Committee 131 2015). The second document published was an MVD for the exchange of reinforcement models (EM.15 in the IDM), which includes the IFC entities and property sets defined for the exchange of detailed reinforcement models (ACI Committee 131 2017). Finally, the on-going work of the ACI 131 committee is focusing on the development of the MVD for the exchange of the structural design model (EM.6 in the IDM), and on the MVD for the construction reference schedule (EM.20 in the IDM).

The purpose of the ACI 131.1R-14 document is to report the work of the ACI 131 committee in developing the IDM for the CIP RC industry, hence enabling efficient interoperability amongst the industry (ACI Committee 131 2015). The IDM was developed by industry professionals and defines the exchange requirements in the context of a CIP RC process model. This is a way to organize, identify and address ERs, not a prescriptive process to be followed by industry professionals. The main elements considered are footings, walls, columns, slabs, ramps, corbels, piles and piers. The main activities (and stakeholders) are formwork design and erection, reinforcement detailing, fabrication and placement, design of concrete mixture proportions, placing, testing, curing, and concrete finishing. The hierarchy of the IDM, as shown in **Figure 4**, include a process model, then detailed exchange models and finally exchange requirements definitions and tables (ACI Committee 131 2015). However, functional requirements are not defined in the report since an integrated use case approach was used. Only the exchanges are defined, and the detail is provided one by one as each of the MVDs is developed.

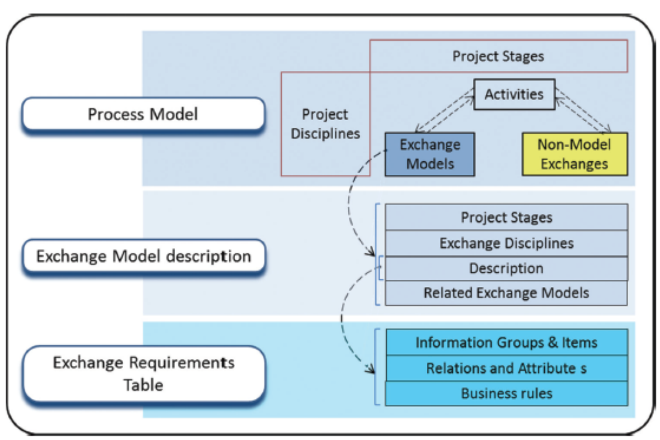


Figure 4. Hierarchy of IDM (ACI Committee 131 2015)

The value of the IDM is to provide a process model along with the tasks and information exchange descriptions. The whole process model can be reviewed in (ACI Committee 131 2015), but an overview of it is shown in **Figure 5**. A process model identifies the tasks (for example T1), stakeholders (for example Architect) and information flows throughout the duration of a project that have to be supported by BIM tools. The information flows can be building model data (such as EM.6) or non-model data (such as R.1). Things that go in the EM description are objects, processes, properties, relations and classifications that are relevant to the exporting and receiving application. EMs are described in more detail in the following sections. The information is transferred to information items and those information items might represent physical objects or non-physical objects.

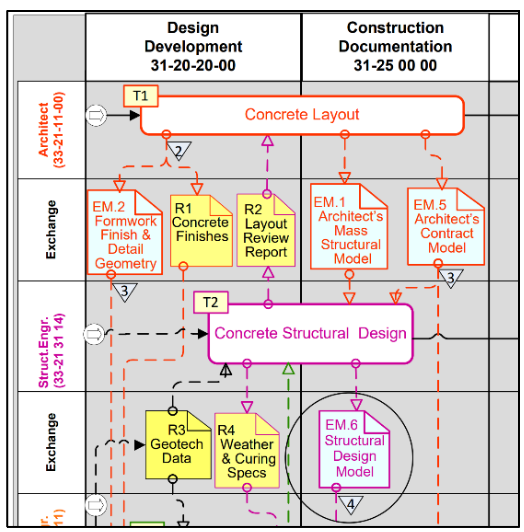


Figure 5. Zoom of ACI 131.1R process model (ACI Committee 131 2015)

The detailed representation of the steel reinforcement, named in the ACI 131.2R Reinforcement Placing Sequence or EM.15, is the only exchange model developed as an MVD so far, with its own published document (ACI Committee 131 2017). The purpose of the exchange is to transmit detailed models of the steel reinforcement along with information about the placement sequence and schedule. It is produced by the structural reinforcing detailer and imported by construction coordination applications (ACI Committee 131 2015). Therefore, in this exchange, the reinforcement is modeled as actual 3D objects and not represented just as a design intent as in the previous exchange.

MVDs cannot define new entities but can define what entities from the whole IFC schema are available and create some constraints or additional information for them, nor can they define new attributes but can constrain them or enforce them. However, there is an extensibility mechanism provided by IFC called property sets, which are sets of properties that are related to a certain entity. They are called IfcPropertySet and relate to an entity through IfcRelDefinesByProperties. In the ACI standards all physical components are a subtype of IfcProduct, and IfcTypeProduct (and its subclasses, for example IfcColumnType) act as templates for IfcProduct (and its subclasses, for example IfcColumn), to provide primary common attributes and geometry. This identifies commonalities and reduces duplication of information (for example between two columns of the same type but placed in different places) and also leads to smaller IFC files. IfcProduct represents actual instances of the type being used (ACI Committee 131 2017). Several property sets are defined for the different elements throughout the document (MVD). **Table 1** shows all the property sets developed, the entities each of them is related to and a short description.

Table 1. Property Sets Defined by ACI 131.2R (ACI Committee 131 2017)

Property Set Name	Entity Pset is related to	Description
Pset_ACI_ItemStatus	IfcElements	For all elements to use, to provide level of development
Pset_ACI_ReinforcingMaterial	IfcMaterial	Add information about grade, specifications and coating
Pset_ACI_ReinforcingBarType	IfcReinforcingBarType	Provide further detail to bar types
Pset_ACI_ReinforcingBarShape	IfcReinforcingBarType	Provide additional information regarding type shape
Pset_ACI_ReinforcingBar	IfcReinforcingBar	Indicate the type of element it belongs to (beam, column,etc), the use and relative position
Pset_ACI_ReinforcingMeshType	IfcReinforcingMeshType	Provide further detail regarding overhangs and surfaces
Pset_ACI_BarCouplerType	IfcMechanicalFastenerType	Provide more information regarding the coupler type
Pset_ACI_BarAccessoryType	IfcDiscreteAccessoryType	Provide more information regarding the accessory type
Pset_ACI_BarAccessory	IfcDiscreteAccessoryType	Provide more information regarding the accessory
Pset_ACI_BarCallouts	IfcElementAssembly	Provide more information regarding the callouts. Callouts are modeled as assemblies
Pset_ACI_BarCage	IfcElementAssembly	Provide more information regarding the cages. Cages are modeled as assemblies
Pset_ACI_BarBundle	IfcGroup	Provide more information regarding the bundles
Pset_ACI_BarRelease	IfcGroup	Indicate the release and other planning information

A special description is provided in the document for some entities. All objects in the MVD are a subtype of IfcRoot, and therefore inherit all its attributes. IfcPlacement is the way to place the objects, and they are placed relative to IfcSite or IfcBuilding. IfcRelContainedInSpatialStructure allows to implement hierarchy of spatial regions that contain items, mainly IfcSite or IfcBuilding. The geometry of the bar is defined by IfcRepresentationMap through a body representation of the type IfcSweptDiskSolid extruded through an axis, and the geometry of a reinforcing mesh is defined by IfcRepresentationMap through a body representation of the type IfcAdvancedSweptSolid which holds multiple IfcSweptDiskSolid extruded through an axis (ACI Committee 131 2017).

The design intent exchange, named in the IDM as Structural Design Model or EM.6, is one of the two exchanges currently under development. **Figure 6** shows the exchange model description provided by the ACI 131.1R. As it can be seen, the purpose is to communicate the design intent from the structural engineer to the concrete contractor, the site contractor and the reinforcing detailer. One of the biggest challenges in developing this exchange is capturing as much design possibilities as possible for every reinforced concrete member for which the IDM was developed (see previous section). The discussion on this matter is on-going and input from different professionals and committee members makes it as comprehensive as possible, but at the same time, difficult to resolve.

EM.6 - Structural design model

Project Stage

Construction documentation 31-25 00 00

Exchange Disciplines

Sender: Structural Engineer 33-21 31 14

Receiver(s): General contractor 33-41 11 11, Concrete contractor 33-41 11 14, Site contractor 33-41 11 14, Reinforcing detailer 33-41 11 14

Description

Purpose: Report of detail structural design to determine steel reinforcing sections, lap standard details, and special connections. Optionally provide early mill order for reinforcing and early
Major elements: Reinforced concrete members and reinforcing cross section layouts and spacing requirements; standard details; lap length; special connections; concrete strength; steel reinforcing and tendon specifications, including coatings, expansion joints, and post-tensiones tendon placement joints. Includes geophysical data and foundation spatial requirements.
Level of detail: Sufficient for determining detailing to realize project structural requirements, as defined by structural engineer.
Special attributes: Reinforcing bar layout for member sections, reinforcing lap requirements, required concrete joints, major embeds, and cutouts.

Software functionality: export and import

Export: Structural analysis application **Import:** Concrete detailing application

Figure 6. EM.6 description. (ACI Committee 131 2015)

One of the main challenges is that current engineering software can design steel reinforcement very fast (Mangal and Cheng 2018), but after this, there has to be human effort to draw the cross sections and even if this process is automated, the starting point for detailing and preliminary quantity take off (QTO) remains the 2D details or files in propietary software formats that don't allow optimal interoperability. **Figure 7** shows the typical rebar workflow as presented by (Castro-Lacouture and Skibniewski 2006), who developed a system to store and use rebar data through XML files, thus enhancing the collaboration and conflict resolution process. BIM has allowed further automation and integration of these tasks as discussed on the complex process model developed my Aram et al., but the overall process remains similar (Aram, Eastman and Sacks 2013).

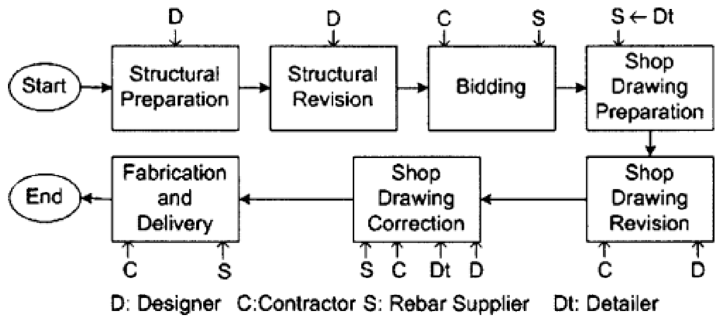


Figure 7. Typical rebar workflow. (Castro-Lacouture and Skibniewski 2006)

It is very important to note that a mixed parametric – 2D approach (providing basic design intent data for every element while still linking a file with the specific 2D detail for every element) is being considered by the ACI committee. However, a fully parametric approach when possible is preferred, because to achieve cost-efficient communication, software should allow designers the ability to express design intent parametrically in terms of dimensional constraints driven by equations or other types of relationships (Sacks, Eastman and Lee 2004).

The next exchange currently being considered by the ACI BIM Committee is the planning/construction exchange, referred to in the IDM as "Construction reference schedule" or EM.20. **Figure 8** shows the exchange model description provided by the ACI 131.1R. The purpose of this exchange is to coordinate layout of all systems, coordinate schedule of installation (including formwork and finishing), and optional 4D configuration. The challenge with this exchange consists of generating a model view that groups elements, or parts of them, into work packages that can allow the contractor to perform planning and coordination activities. However, as mentioned in the previous section, the physical model should not be modified for interoperability purposes so even if part of a slab is included in a certain pour activity and the rest of it in another pour, the slab itself should not be split in two since such division, although physical, does not imply the member now works as two separate members. This concept is illustrated in **Figure 9** for a slab with two construction joints that has to be built in three different pours.

EM.20 - Construction reference schedule

Project Stage

Concrete placement and resource planning 31-40 30 31

Exchange Disciplines

Sender: General contractor 31-41 11 11

Receiver(s): Concrete contractor 33-41 11 14, Finish contractor 33-41 11 14, Structural Engineer 33-21 31 14, Reinforcing contractor 33-41 11 14 17, Formwork contractor 33-41 11 14, Site contractor 33-41 11 14

Description

Purpose: Coordinate layout of all systems for clashes and coordinate schedule of installation, especially with formwork and finishing tasks; optionally a four-dimensional configurator, also used to verify coordination with mechanical systems and architectural intent.

Major elements: All major sustems: structure; mechanical, electrical, and plumbing; and architectural detailing interfacing with concrete work for clash detection and coordination. Concrete placement and discrepancy report

Level of detail: Full detail for concrete finishes and formwork

Special attributes: Concrete finishing spaces

Software functionality: export and import

Export: Concrete detailing application

Import: Construction management application, supporting detailed spatial coordination and scheduling of all project systems in an integrated building model

Figure 8. EM.20 description. (ACI Committee 131 2015)

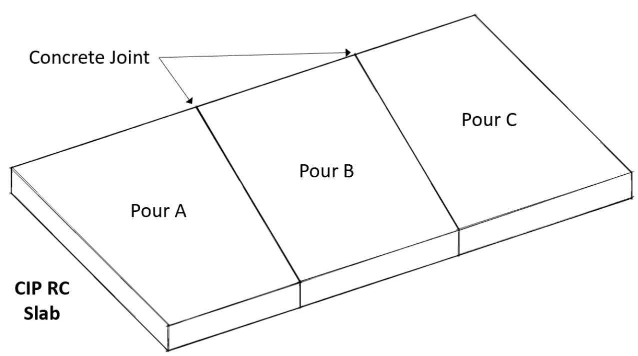


Figure 9. Example of physical model vs construction model for a CIP RC Slab

Discussion on this topic is also included on the table of the ACI 131 committee and the approach of creating "pour objects" proposed in (Barak, et al. 2009) is being followed. This approach consists of creating pour objects that contain a group of other objects, or part of them, and associate them to work packages. Property sets for schedule and formwork are being considered, but the issue of how to link them with actual objects in IFC without modifying the physical model remains a challenge. The mentioned association would have major applications, such as automatic pour QTO and schedule linking, automatic formwork QTO and schedule linking, and easier 4D preliminary simulation set-up. The creation of model views to break members and group them into pours is something several applications are capable of doing but that can't easily communicate the information through IFC.

Evidently, there has been considerable progress in the development of CIP RC BIM standards. However, the complexity of the supply chain also means that there is still a long way to go. An analysis on the current approach to develop the standards as well as on its alignment with real-world practices could help with providing recommendations for further standardization processes. Furthermore, since the implementation and usage phases haven't been studied yet, there hasn't been any analysis on the implementation methods necessary to bring the standards as part of the practice, and the value that these exchanges could provide to the daily design and construction practice of CIP RC buildings.

2.3 Ethnographic-Action Research in the AEC Industry

Ethnographic research seeks to identify predictable patterns within human interaction through careful observation and participation in those interactions (Angrosino 2007). From the multiple qualitative research approaches, this is the method best suited to gather information about a culture's (or group's) behaviors and dynamics. Since the target of this research is only partially qualitative in order to describe and compare the dynamics of the design stakeholders with respect to data exchanges in the CIP RC supply chain, this could be alternatively approached as a case study. However, several authors acknowledge the overlap between the two and identify ethnography as the broad qualitative method while the case study can be the particular topic or even one of the components of the ethnographic study (Hammersley 1992), (Silverman 2005), (Brewer 2000). Furthermore, ethnographic studies could be approached from a "pure" and "applied" perspective as suggested by (Ball and Ormerod 2000). Pure ethnography is the ethnography originated in the social sciences, particularly in anthropology, that has a holistic approach to describe the patterns of behavior within complex cultures, communities or organizations. Several authors have used ethnographic techniques to successfully study and describe design dynamics and processes, but when compared to the methods and techniques of "pure" ethnography, there are some discrepancies, thus leading to the concept of "applied" ethnography, best suited for contexts such as design behaviors and still referred to as "ethnography" (Ball and Ormerod 2000). The differences between the two types are the duration of the observation period, the not absolute independence of previous theories, and the requirement for some degree of verifiability. Such is the case of this study, which builds on top of previous developments and requires verification for implementation. The typical strategies ethnography uses and that will be used for triangulation in this research are: field observation, interviewing and analysis of resulting documents or product data (Yin 2003).

Action research is a particularly well-suited approach for the development or testing of information systems as well because it proposes the integration of practice and research, particularly through cycles of observations of practice for problem identification, and development and implementation of technical solutions (Baskerville and Woodharper

1996). To complement this approach with the specific tools to gather the information from practice, (Hartmann, Fischer and Haymaker 2008) proposed combining action research with ethnography, and worked on multiple cases and discussed how well suited ethnographic-action research is to assist in the development of information systems, particularly within AEC projects. Regarding AEC, early studies tried to understand and describe the professional practice and design as a profession (Cuff 1991), (Blau 1984), (Gutnam 1988), (Larson 1977). Although the studies are mostly qualitative, some of them incorporate measurable data to make comparisons or propositions based on their observations. (Demian and Fruchter 2006) studied the reuse of design knowledge in the AEC industry through an ethnographic study. (Emmitt 2001) used ethnographic observation to understand design teams while choosing building finishes, considering patterns of argumentation in the BIM environment, including data exchange patterns between different stakeholders and disciplines. (Abdelmohsen 2011) on his Ph.D. Dissertation did a detailed ethnographically informed study about the design intent communication into a BIM environment, focusing on the allowances and issues within the tools to represent and communicate such tacit knowledge. Although he considered the dynamics of the data communication, the perspective was mostly from an architectural standpoint and it was purely qualitative, with no measurable data reported.

Within the engineering practice, ethnographic research has proven immense value in studies concerned with engineering design dynamics and support tools (Jagodzinski, et al. 2000), with engineering design as a social process (Bucciarelli 1988), with the reuse of knowledge in the engineering design practice (Baird, Moore and Jagodzinski 2000), and with the support ethnographic research can provide for engineering design (Ball and

Ormerod 2000). Even within the construction realm, ethnography has proven to be valuable in studies including the research for knowledge, practices and design of potential interventions (Pink, et al. 2010), and the development of theories for research in the construction industry (Phelps and Horman 2010).

The applicability and value of implementing an ethnographic approach has been illustrated by multiple authors within architecture, engineering and construction. The value is particularly high at the beginning of the research, where it can inform on issues, special requirements and constraints early on as part of action research. This dissertation thus uses an ethnographic-action approach to understand the dynamics of the stakeholders and data exchanges within the AEC industry, to provide recommendations for further developments of the standards, and to better inform the implementation methods and the value they bring to the practice.

2.4 Measurement of Building Information Modeling Value

2.4.1 General Review

The value of BIM has been researched and studied since its beginning on different stages and dimensions. Within several of these researches, the authors are cautious about differentiating "actual" from "perceived" value. Perceived value usually comes from interviews and opinions, and although it can be "perceived" in the project it may not actually be measured. Actual value is typically derived from "actual" analysis and measurement of the benefits on the projects. On a study looking at the perceived value of BIM, a group of Swedish researchers showed that there are still a lot of users who think the investment on BIM is too big for the reward, and that there is a lack of actual measurements of the value BIM provides in several specific cases (Vass and Gustavsson 2015). Some authors use the concept of "BIM Maturity Model" to scaffold the implementation level of BIM, which requires a framework to measure the performance of BIM implementation on different levels and dimensions (Succar, Sher and Williams 2012).

In the BIM Handbook, (Eastman, Teicholz, et al. 2011) present an analysis of 10 case studies, each of which consisted of a project that implemented BIM in different levels and during different project stages. Although the study researched how the projects used BIM tools and didn't implement measurable metrics, it provided useful information about how BIM is used in practice, and showed that no project benefited from all the advantages BIM provides. The handbook also provides a comprehensive list of the benefits BIM brings to projects, which gives an initial indication of potential value measurement dimensions. From an owner's or project's point of view, the main applications for BIM contributions are to increase building performance, reduce financial risk, shorten project schedule, obtain reliable cost estimates, assure program compliance, and optimize facility management.

(Bryde, Broquetas and Volm 2013) studied the project benefits of BIM and used multiple criteria to evaluate the success of BIM use. The criteria included cost reduction, time reduction, communication improvement, coordination improvement, quality increase, negative risk reduction, scope clarification, organization improvement, and software issues. The research didn't actually measure parameters in any project, but did an analysis of 35 projects found in the literature that reported benefits or setbacks of BIM implementation and quantified, according to the defined criteria, the percentage of projects which reported benefits on each dimension. Similarly, in 2007 the CRC Construction Innovation group published the results of a research project that studied the business drivers to adopt BIM through a set of case studies. There were several BIM value propositions analyzed on the different cases such as reduced rework, improved efficiency (time vs. cost), ease of making changes, improved design performance, improved constructability, reduced risk, increased confidence in design outcomes, improved creativity and improved work flow and environment (CRC 2007). The data was based on experts' opinions and perceptions, rather than in actual measurements of project benefits. The study ends with the proposition of a business case framework to adopt BIM in practice, and proposes an after implementation analysis that includes financial benefits, financial costs, non-financial benefits, risk assessment, and impact assessment including opportunity costs. (Ghaffarianhoseini, et al. 2017) mentioned exchange standardization as one of the key benefits of BIM as part of their study of benefits, risks and challenges for BIM implementation. However, their research focuses mostly on the "perceived" value and on the study of previous literature.

Other authors, while they have considered both types of value, have focused more on the "actual" value of implementing BIM. This approach provides a more tangible measurement of the value of implementing BIM in a project. (Giel and Issa 2013) used metrics such as the Return on Investment (ROI), the number of Change Orders (CO), and schedule behavior to estimate the value of using BIM on a practice level. (Barlish and Sullivan 2012) developed a methodology to measure the benefits of BIM and applied it to several case studies where they divided their metrics in "Return Metrics": Requests for Information (RFI), CO, and schedule; and "Investment Metrics": Design costs, model creation costs and, construction cost. To define their metrics, they reviewed several references to find BIM benefits, amongst which the most referenced were schedule (11), sequencing coordination (7), rework (5), visualization (5), productivity (5), project costs (5), communication (4), design/engineering (4) and physical conflicts (4). From all their analysis they found only 4 which gave quantifiable results. One of the key aspects of this research is that the company they collaborated with had a BIM business process that implemented both BIM and conventional 2D technologies simultaneously, which allowed the researchers to measure the metrics on projects with both approaches. The research found differentials between BIM and Non-BIM, including RIFs, COs, schedule and design costs, that ranged from 30% up to 70%. Construction costs savings were around 5%. A similar approach was the one taken by (W. Lu, et al. 2014), who compared a BIM project with a non-BIM project of similar characteristics and identified a reduction of 6% of work time and 7% of total cost. The model they used is adapted from a previous publication where they mention several measurable parameters than can be used, such as staff-hours/cycle, cost/cycle, time/cycle and staff-hours/area (Lu, Peng, et al. 2013).

On the same line of measurement of "actual" value, a study performed around the benefits and obstacles of practice BIM implementation through a series of case studies reported benefits such as reductions of 0.5% of the project value in the workshop design stage, savings of 10% of time spent in supervision, and savings of 20% of time spent on drawing revision and redrawing (Migilinskas, et al. 2013). Another important research that measured the financial benefits of BIM through the analysis of case studies was the one published by (Azhar 2011). The study considered both the financial benefits and the costs of implementing the technologies, therefore aiming to estimate the Return on Investment (ROI) BIM had on each case. To illustrate the benefits the study presented four case studies, each one with a specific focus: The first case study measured the savings in construction costs by using clash detection technologies and assigning a value for each clash prevented; the second case measured the cost benefits of having multiple layouts and being able to select the most economical and workable one; the third one measured the benefit of implementing BIM to keep the project on schedule; and the fourth studied the benefits of providing multiple skin options and performing sunlight analyses. After the analysis of the cases the research presents a summary of the ROI of 10 projects from the same construction company that considered the BIM cost, the direct and the net BIM construction savings. The values of the ROI were extremely high and varied from 140% to 1,633%. The study did not consider indirect, design, and administrative benefits.

Recently, in 2018, PwC published the BIM Level 2 Benefits Measurement Methodology (PwC 2018). This sophisticated methodology is used to estimate the financial benefits of using BIM in the UK and considers measurements across eight dimensions: time savings, material savings, cost savings, improved health & safety, reduced risk, improved asset utilization, improved asset quality for end-user, and other intangible benefits. The methodology considers several pathways (or actions), 117 in total, through which a measurable benefit can be achieved, based on specific activities and BIM implementations. For each specific benefit dimension, the methodology gives processes and equations to monetize the benefit, examples of calculations from previous projects with positive values, and reference values from the UK for some calculations. The time benefit can be monetized through a reduction in direct labor cost, a reduction in time-dependent recurring preliminary costs, and through acceleration in asset delivery. The material benefit can be monetized through a reduction in the amount of material, a change in the type of materials used and the consequential environmental benefit. The cost benefit can be estimated through a change in the number of instances of a particular event (i.e. clashes, changes, litigation claims, rework) or a reduction of the cost associated with a particular instance of an event. Improved health and safety can be monetized through the financial and human costs. The risk can be monetized by applying the opportunity cost to the change in value of the contingency. Most of the measurements either required two projects of very similar characteristics, or projected information about the project, before BIM was implemented.

Clearly, there has been extensive research on methodologies and metrics to measure the benefits and costs of BIM usage in AEC projects. These reported benefits have incentivized owners to impose the use of BIM in projects through contract clauses, thus leaving no choice to many of the AEC stakeholders but to implement it. This situation switches the discussion from “Should I implement it?” to “How do I implement it better than my competitors?”. The use of exchange standards arrives as one of the main industry proposals to enhance the BIM process, but the value it poses is something yet to be addressed. This research aims to use some of the value dimensions from previous studies, and those identified during the ethnographic study, to evaluate the value considerations of implementing exchange standards on a practice level for CIP RC structures.

2.4.2 Review of BIM value measurement metrics and dimensions

A thorough review was conducted to assess the dimensions and metrics that have been used in previous studies to measure the benefits of BIM, across different project stages. After the review, 30 sources were selected because they had clearly defined qualitative and/or quantitative metrics used to determine or define the value of implementing BIM. **Appendix A** presents all the 30 sources selected, including a short description, the metrics identified in each of them, and the calculation method used for each of the metrics. This metrics were then grouped and classified in “Dimensions and Categories”. The four dimensions identified were Cost, Time, Performance, and Qualitative. The metrics related to Cost were grouped in the categories Design Cost/Benefit, Direct Technology Cost, and Other Related Costs. The metrics related to Time were grouped in the categories Time Loss/Benefit and Productivity. Finally, the metrics related to Performance, were grouped in the categories Request for Information(RFI), Change Order (CO), and Rework/Errors. **Table 2** presents the metrics in each category, and the references where each metric was considered or estimated. Regarding the qualitative metrics, there was a vast number of approaches, so the summary was limited to those applicable to the design intent production and coordination phases.

Table 2. Metrics for BIM Value Measurement in Literature

Dimension	Category	Metric (Measurement Source)	Reference
Cost	Design Cost/ Benefit	Design cost	(Barlish and Sullivan 2012)
		Labor	(Khanzode, Fischer and Reed 2008)
		Costs	(Abdirad 2016), (Lu, Peng, et al. 2013), (W. Lu, A. Fung, et al. 2014)
		Cost benefit/savings	(Azhar 2011), (Kuprenas and Mock 2009), (PwC 2018)
		Reduced costs of engineering	(R. Sacks 2004), (Gilligan and Kunz 2007)
		BIM Contribution Value (BCV)	(Kim, et al. 2017)
		ROI	(Azhar 2011), (Walasek and Barszcz 2017), (Lee, Park and Won 2012), (Giel and Issa 2013)
		Enhanced cost estimating accuracy	(R. Sacks 2004)
	Direct Technology Cost	3D Background Modeling Cost	(Barlish and Sullivan 2012)
		Investment cost	(Walasek and Barszcz 2017), (Giel and Issa 2013)
		BIM cost to project	(Azhar 2011), (Gilligan and Kunz 2007)
		Direct costs of 3D BIM stations	(R. Sacks 2004)
		Replacement cost: existing systems	(R. Sacks 2004)
		BIM Utilization Value (BUV)	(Kim, et al. 2017)

Table 2. Continued

Dimension	Category	Metric (Measurement Source)	Reference
Cost	Other Related Costs	Construction cost	(Barlish and Sullivan 2012), (Dodge Data and Analytics 2015), (Azhar 2011)
		Project cost	(Khanzode, Fischer and Reed 2008)
		Prefabrication	(Khanzode, Fischer and Reed 2008), (Kuprenas and Mock 2009)
Time	Time Loss/ Benefit	Time savings	(Barlish and Sullivan 2012), (Azhar 2011), (Giel and Issa 2013), (Gilligan and Kunz 2007)
		Time	(Khanzode, Fischer and Reed 2008), (Abdirad 2016), (Lu, Peng, et al. 2013), (Kaner, et al. 2008)
		Construction duration	(Kuprenas and Mock 2009)
		Accelerated project completion	(Dodge Data and Analytics 2015)
		Time savings in design	(PwC 2018)
	Productivity	Documentation productivity	(Sacks and Barak 2008)
		Productivity	(Lu, Peng, et al. 2013), (Kaner, et al. 2008)
		Productivity gain: design/drafting	(R. Sacks 2004)
		Modeling Productivity	(R. Sacks, C. Eastman, et al. 2005), (Dodge Data and Analytics 2015)
Performance	RFIs	RFIs	(Barlish and Sullivan 2012), (Khanzode, Fischer and Reed 2008), (Giel and Issa 2013), (Abdirad 2016)
		RFI Reduction	(Dodge Data and Analytics 2015)
	COs	COs	(Barlish and Sullivan 2012), (Cannistraro 2010), (Giel and Issa 2013), (Abdirad 2016), (Kuprenas and Mock 2009).
		CO Processing Time	(Francom and Asmar 2015)
	Rework/ Errors	Rework	(Kuprenas and Mock 2009), (Khanzode, Fischer and Reed 2008), (Abdirad 2016)
		Errors & Omissions	(Abdirad 2016)
		Error reduction: design & drafting	(R. Sacks 2004)
		Completeness of Information	(Abdirad 2016)
		Illogical design	(Lee, Park and Won 2012)
		Discrepancies	(Lee, Park and Won 2012)
		Missing Items	(Lee, Park and Won 2012)
		Cost: Warranty & Latent Defects	(Francom and Asmar 2015)
		Material savings in design	(PwC 2018)
		Risk savings in design	(PwC 2018)
		Conflict Checking	(Kuprenas and Mock 2009)
		Coordination	(Khanzode, Fischer and Reed 2008)
	Safety	Safety	(Khanzode, Fischer and Reed 2008)
		Reduction in Safety Incidents	(Dodge Data and Analytics 2015)
Qualitative	General	Improved project definition	(R. Sacks 2004)
		Enhanced estimating accuracy	(R. Sacks 2004)
		Streamlined logistics	(R. Sacks 2004)
		Production automation	(R. Sacks 2004)
		BIM Sensible Value (BSV)	(Kim, et al. 2017)

2.5 Design Indicators

One of the first structured approaches to the concept of design indicators' measurement was the "design quality indicators" approach, developed in the UK two decades ago for the purpose of assessing the degree of compliance of public projects with the project's requirements (Gann, Salter and Whyte 2003). The methodology does not imply that all designs that satisfy the indicators are "good designs" since this is at least partially subjective, but it provides ground rules that all good designs must satisfy thus filtering during revision those "good designs" from a project's requirements perspective.

The main approach for the "Design Quality Indicators" was developed in the United Kingdom by the Construction Industry Council and a research group. They created a toolkit known as Design Quality Indicator to assess the performance of a building's design based on the Vitruvian Principles, a set of indicators and peer review techniques (Whyte and Gann 2003). The tool was also adopted by New York City in 2008 and included into the Design and Construction Excellence Program (The City of New York 2008). However, relating the indicators to the Vitruvian principles creates a confusion between what is subjective and objective, and between aiding the process and assessing the result, which leaves the tool with some issues (Prasad 2004) (Markus 2003). Similar approaches have been taken for specific purposes, including procurement (Office of Government Commerce 2004), healthcare facilities (National Health Service 2004), defense buildings (Defence Estates 2007), housing projects (National Afforable Homes Agency 2007), and architectural design quality (Harputlugil 2009). Since then, not much research has been done on the design quality topic given that the tool has been operating for several years with more than 1,300 projects evaluated.

Recently, some indicators were developed by a group of researchers to measure the design quality of buildings (Suratkon, Chan and Jusoh 2016) and the satisfaction towards design quality (Suratkon and Jusoh 2015). The research does a good job at researching a number of indicators available and summarizing them. **Table 3** shows a summary of the indicators proposed classified in three categories which combined constitute, according to the reference, a design of quality: functionality, impact and build quality or performance.

Table 3. Design Quality Indicators (Suratkon and Jusoh 2015)

Functionality	Build Quality	Impact
Use	Engineering System	Design
Layout	Security System	Colour
Access	Energy	Form & Material
Space	Green energy & sustainability	Comfort
Lighting	Finishes	Internal environment
Open Space	Structure element	External environment
Pedestrian Walkway	Road width	Character & Innovation
Service	Building stability	Urban & social integration
Natural Lighting	Landscape	Location
Natural Ventilation	Building Maintenance	Visual effect
		Security
		Noise

The measurement of such indicators in the reviewed resources is based on existing designs or models. Although those indicators are great to inform the compliance of the design after the process is completed, and allow the design to make corrections when something doesn't behave as expected, there is a gap in the research about how to anticipate some of those indicators based on the information contained during early model exchanges. The research of (Sanguinetti, et al. 2012) explored how to analyze and check processes such as energy analysis, cost estimation, spatial validation and circulations using simple schematic models to provide some feedback. The study shows great propositions on how to early inform the design of future issues but is focused on architectural aspects of the building and lacks access to rich exchange data information about the concrete structure.

2.6 Conclusion

This chapter presented the literature review of the topics related to the purpose and methods used in this dissertation. It started by performing an exhaustive review of what has been done regarding data exchange representations in the industry, as well as in other industry segments' developments, and relating it to the research and developments focused on CIP RC concrete. The review illustrated the particular challenges of CIP RC for standardization such as the boundary definition between elements as a function of the scope of the stakeholder interested, representation of partial elements for construction processes, the possibility of a wide variety of reinforcement configurations, and the engagement of a complex supply chain involving multiple stakeholders. It also explained the documents that have been published and that are under development by the ACI Committee 131, which have started the process of standardization. While a very good starting point for CIP RC standards' development, when compared to other developments, it was shown that there is still a long way to go. The review also presented a comprehensive revision of how the value of using BIM has been studied and discussed in several publications and reports, but showed the gap in identifying the value considerations brought from using exchange standards. Finally, it introduced the concept of design indicators and presents a review of how they have been researched in previous publications and reports, and how they may be a good application for the information now available in a standard manner.

CHAPTER 3. METHODOLOGY

The methodology is a combination of qualitative and quantitative methods, adapted from the ethnographic-action research methodology, where ethnographic observations serve as the data acquisition method and action research is used to integrate practice and research for the development and implementation of technical solutions. Aligned with this method, the methodology is divided in three phases: 1) the ethnographic study including observations, data acquisition and processing, 2) the development of the implementation methods and the identification of the value considerations of implementing CIP exchange standards and 3) the application of the information contained in CIP RC exchange files to estimate design indicators. **Figure 10** shows an overview of the methodology and specific activities, and the following sections explain each activity in detail.

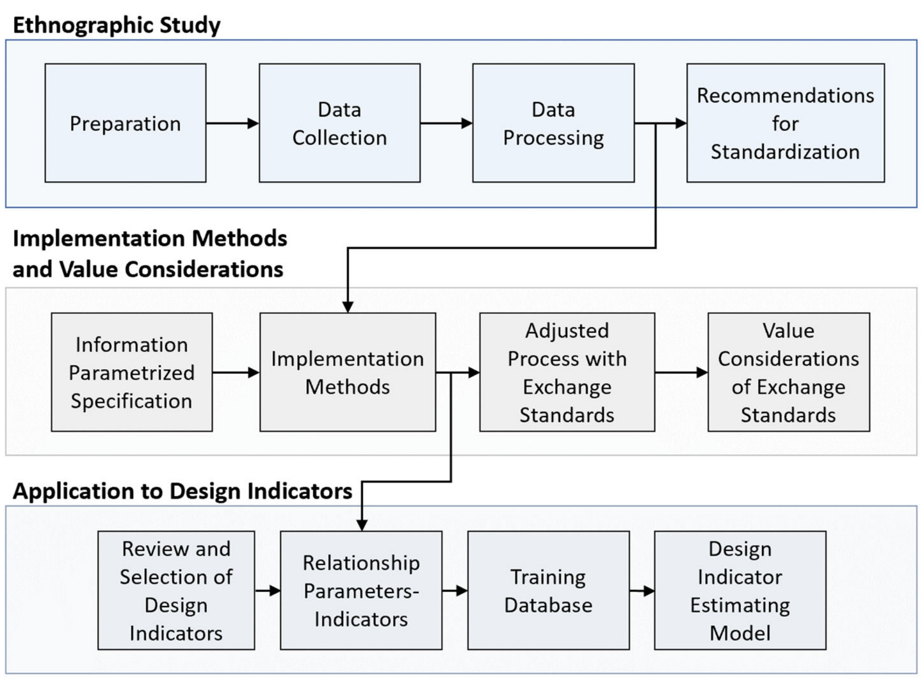


Figure 10. Methodology

3.1 Ethnographic Study

The first step is to plan and perform the ethnographic study in the field. This part of the methodology has been divided into four different stages: preparation, data collection, data processing, and standardization recommendations.

3.1.1 Preparation

The study is performed in a structural engineering company that has CIP RC exchange practices with detailers and contractors, given that this type of company is the one that benefits the most based on the scope of the ACI exchanges under consideration: EM.6, EM.15 and EM.20. The preparation part includes the selection of the engineering company where the study will be performed and the selection of the project.

The criteria for the selection of the company are the following:

- Acknowledged in the "Building Design + Construction Giants Report" and the "Atlanta Business Chronicle Book" of lists.
- Must have existing BIM practices implemented for inter-company and intra-company activities regarding CIP RC buildings.

The criteria to select the project is:

- The project has not started or is on its early design stages at the time of the study.
- The project is a CIP RC building which includes several of the elements covered by the exchange standards.

- The project is representative of typical practices for CIP RC structures as defined by the IDM developed by the ACI.

3.1.2 Data Collection

There are three main methods used to collect data: Observations, Interviews and Project Documentation. For the observation phase, all the actors are informed of the methods and purpose of the thesis, and informed consent is obtained from the company and team (Approved by Georgia Tech IRB, Study H21047). Afterwards there are three focuses, and consequently three forms: field observation, process, and exchange.

The first form, field observation, collects observations about the dynamics and behaviors of the actors during the design, planning and exchange processes. This is used to generate conclusions of the process itself and the accuracy of the BIM exchange standards' creation process to represent them. **Figure 11** shows a sample of this form.

Document No.	FO - SE1 - 001
Document Type	Field Observation
Company/Discipline	Structural Engineering
Subject/Actor	Structural Engineer 1
Recording Method	Visual
Date	5/14/2020
Duration	4 hours
Observations	

Figure 11. Sample form for field observations

The second form records information about the different specific design processes and interactions including tools, theories, and procedures. This information is essential to be able to later replicate the process while using the exchange standards reducing the assumptions to a minimum. **Figure 12** shows the structure of this form.

Document No.	PO - RD1 - 001
Process	Detailing of Column Rebar
Company/Discipline	Reinforcement Detailer
Subject/Actor	Detailer 1
Recording Method	Visual/Interview
Date	5/14/2020
Duration	4 hours
Tools Used	Tekla Structural Detailing
General Considerations	
Theories and Methods	
Steps and Processes	

Figure 12. Sample form for process observations

The last form for observations is the form to register the actual data exchanges between tools and between actors. The form follows the standard structure used to detail exchange requirements for standards' development. **Figure 13** shows a form used to describe certain exchange requirements.

Exchange Requirement	Geometric Frame Model		
File Type	IFC		
Producing Actor(s)	Revit		
Consuming Actor(s)	SAP2000		
Project Stage	6 - Coordinated Design	20 20 21 - Engineering Analysis Test Phase	
Description	The purpose of this exchange is to transfer geometry and material of a simple frame from the architect (Revit) to the Engineer (SAP2000). The exchange was done using an IFC file only capable of translating these properties.		
Information Units	Building	Placement	Building Location
		Storey	Number of Storey
	Beam	ID	Beam ID
		Type	Type of Beam
		Placement	Relative Location (to Building)
		Cross Section	Element Cross Section
		Length	Element Length
		Material	Material Type
	Column	ID	Column ID
		Type	Type of Column
		Placement	Relative Location (to Building)
		Cross Section	Element Cross Section
		Length	Element Length
		Material	Material Type
	Material	ID	Material ID
		Type	Type of Material
		Strength	Material Strength

Figure 13. Sample form for data exchanges

The second type of data collection are the interviews, which are conducted with the team members based on the observations and processes. **Figure 14 Error! Reference source not found.**shows a proposal for the form used to conduct or transcribe interviews. Other interviews were conducted with structural engineers and construction professionals outside of the design team, in order to validate and complement the results and conclusions. These interviews were more informal and based on the research results rather than on the observations. Finally, available project documentation and models are stored to be used during the testing and replication process.

Document No.	IN - SE1 - 001
Document Type	Interview
Company/Discipline	Structural Engineering
Subject/Actor	Structural Engineer 1
Recording Method	Voice Recording
Date	5/14/2020
Duration	4 hours
Description	
Question	
Answer	
Question	
Answer	

Figure 14. Sample form for interviews

3.1.3 Data Processing

The most standard way to process qualitative data is through "coding". Essentially, coding is the process of assigning attributes to pieces of data, such as a word, a sentence or a paragraph. Coding can be either inductive, which looks for emerging patterns through an iterative process and builds a theory from the ground up (grounded theory), or deductive, which provides answers to a theory or research question. Due to the nature of this study, the coding is mostly deductive since the field, purpose and target of the study is relatively specific. However, since part of the analysis is revealing dynamics not captured by the standards' development process, there is room for the introduction of new categories through the course of study. Every attribute and category can be given a meaning or a description. After processing, these codes can be analyzed both from a frequency point of view, based on statements and behavior, and from a sequence point of view, looking for causation within the context.

The storing of the transcripts and gathered data, as well as the coding and processing is done using the tool MAXQDA. The tool allows storing all the transcripts, labelling the information and aids in the process of creating the coding system and final categories, as well as the correlations that might exist amongst them. This output allows to draw conclusions from the dynamics, supply chain, and data exchange practices for CIP RC.

The analysis and classification of this information allows the author to map typical processes and workflows, as well as identifying challenges, requirements, and issues for each of the coding categories. To ensure the consistency of the coding and classification, two methods are use: triangulation and validation. Triangulation is the process of using alternative sources of information to ensure the consistency of the coding system used. This is done by comparing the codes and conclusions obtained from the field and process observations with the interviews and questionaries. The validation is done through interviews and consultation with engineers and construction managers from other firms, who revise the codes or categories, the coding of the information and finally the conclusions. Two structural engineers and two construction managers from different firms and not related to this project were consulted for this purpose. This validation also allows the conclusions to be extrapolated to other projects and contexts beyond the specifics of the projects within the scope of the ethnographic observations.

3.1.4 Recommendations for standardization

The final step of this phase compares the results from the ethnographic observations both to the current IDM for CIP RC developed by the ACI and to the current methods and tools capabilities. Here, the information about the general process dynamics, behaviors, and requirements is compared to what is proposed in the IDM. This allows the generation of recommendations on whether the current approach and standards under development respond to the needs of the industry and what additional practices might be incorporated to enhance this standardization of CIP RC modeling and exchanges.

3.2 Implementation Methods and Value Considerations

3.2.1 Information Parametrized Specification

The first step to be able to develop the implementation methods and identify the value considerations of the standard, is having all the parametric information required for the exchange available. Given that the two exchange standards considered are still under development, namely the structural design intent and the construction planning, the author bases the specifications on the current development stage and definitions, but additional definitions and IFC mapping is required. Furthermore, to accomplish maximum automation and efficiency, additional parametrization of the information typically contained in the exchanges is proposed. This additional parametrization can also serve as a reference for a second phase on the ACI exchange standards development.

The physical model, which contains the actual CIP RC members, should not be modified for interoperability purposes, and serves as the basis for the different functional views, which are views of the object depending on the purpose or activity, such as structural analysis or Quantity Take-Offs (QTOs) (Barak, et al. 2009). For this reason, the parametrization is implemented through the creation of property sets rather than through intervention of the actual geometry. **Figure 15** shows an example of the instance diagram of a beam, and how a property set with multiple property values is related to the beam. This is the typical way to represent instance diagrams in IFC.

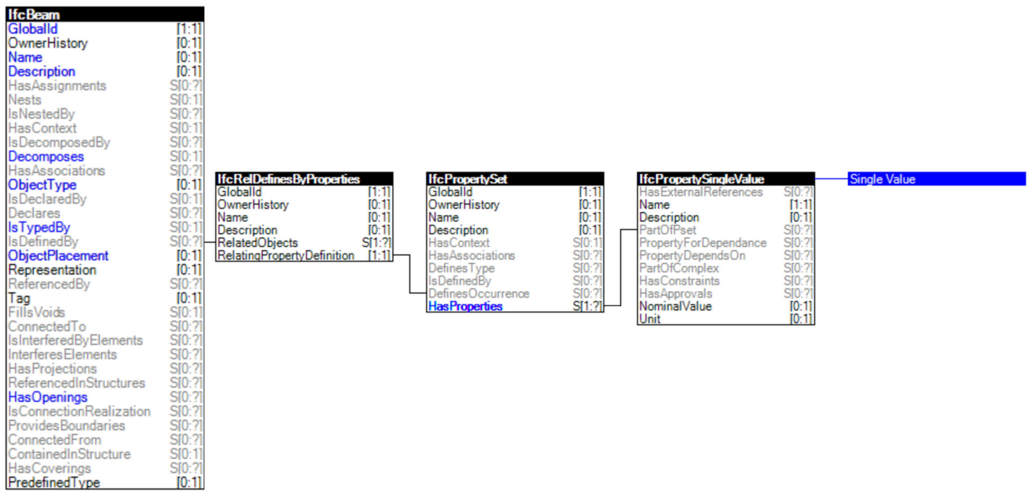


Figure 15. Example of instance diagram for a beam

3.2.2 Implementation Methods for Standards

One of the main arguments against the use of BIM is that it requires additional work from some professionals, who might not be compensated for the time it takes to move that information to a BIM environment (Azhar 2011). Similarly, the standardized parameters in the proposed format cannot be required from the structural engineer or construction coordinator as straight data for the property sets. For this reason, a key part of the methodology and an important contribution of this dissertation are the implementation methods that allow the standards to be taken into practice. The methods are step by step guides for implementing the standards into current tools and practice and are supported by the coding and conclusions from the ethnographic study. To be applicable and serve as guidelines for practice, methods are developed to consider the transformation requirements of the information into the standardized parameters, the interaction processes with software tools, the visualization and usage of the information, and the communication using the IFC open standard. The dissertation also develops specific examples for implementation in commonly used tools.

To facilitate the process and be able to tackle different issues that arise at different levels of building complexity, four successive levels are considered for testing:

1. Level 1: Isolated elements with a limited number of parameters.
2. Level 2: Single-story structure with a few key elements and their interactions.
3. Level 3: Two-story structure including all considered CIP RC elements.
4. Level 4: Multi-story structure including several CIP RC elements in several floors.

3.2.3 Adjusted Process with Exchange Standards

Most of the projects that measure the value of implementing BIM, either compare a pool of projects or follow projects on which they measure similar aspects. However, this method cannot be directly implemented in this study since it would require implementing the standards as part of the workflow of all the stakeholders involved in the project, including practical user interfaces, user training, and user willingness. This would not only be extremely time consuming but would also require a lot of additional effort from the participants that is most likely not going to occur. Therefore, this dissertation presents the usage procedures of the implemented exchanges, and replicates the same exchange processes observed during the ethnographic study but applying the methods developed.

The procedure uses the information collected during the ethnographic study, where specific processes and exchanges were documented.

3.2.4 Value Considerations of Exchange Standards

Finally, the value considerations of implementing CIP RC exchange standards, as part of the professional practice, are addressed. **Figure 16** shows an example of a specific dynamic and data exchange where the process is evaluated. Afterwards, the process is repeated replacing the conventional procedure with the exchange standards and implementation methods proposed. This procedure, combined with the comprehensive literature review on BIM value dimensions and metrics, allows the identification of value considerations and the potential value proposition of implementing exchange standards for CIP RC models and data.

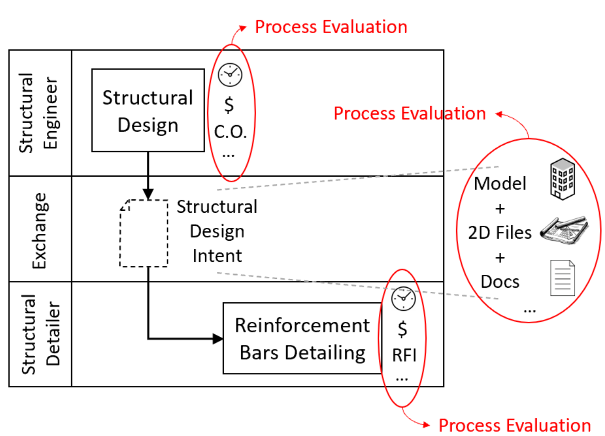


Figure 16. Example of exchange to evaluate value considerations

3.3 Design Indicators Estimation

This part of the dissertation applies the information contained within the exchange standards to predict indicators of design performance early in the design process. The methodology followed to achieve this includes the review and selection of the design indicators applicable to the standards considered, a determination of the relation between those indicators and the parameters inside the IFC files, the development of a database of occurrences where the indicator is determined, and the implementation of a model to estimate the parameter in new projects.

The problem in question, identifying when a design indicator will be triggered based on model parameters, can be seen as a binary classification problem (trigger or not). The most common methods to address these kinds of problems are called "supervised machine learning algorithms", since they sort data and predict future behavior based on existing data. The method selected is Logistic Regression, which is a modeling approach that is used to describe the relationship between independent variables (parameters) to a binary dependent variable (the indicator) (Kleinbaum and Klein 2010).

3.3.1 Review and Selection of Design Indicators

The selection of the indicators starts with the revision of the indicators available in literature that apply to CIP RC structures. The selection of the indicator(s) is done applying the rule that they have to be related to the exchange standards that fall under the scope of this study: EM.6, EM.15 and EM.20 in the ACI IDM. This indicator should be able to be classified with a binary approach (one or zero), meaning that it is either satisfied, or not.

3.3.2 Relationship Parameters-Indicator

The next step is to determine the relationships that exist between the parameters included in the standard exchanges, and the chosen indicator(s). The study identifies within the data structure the properties that are needed to estimate the indicator(s) for each of the concrete elements considered in the scope of the method, and how they are used to calculate the parameter used to estimate the indicator.

3.3.3 Training Database

With the indicator(s) and the defining parameter(s) determined, a database to build the estimating model is created. The database considers multiple occurrences where the indicator can be determined, based on the objects' properties and the selected parameter(s). The properties are obtained from the parametrized properties available during the different exchange standards considered.

3.3.4 Design Indicator Estimating Model

The final step is building a model capable of estimating the design indicators using the training database. The method selected, logistic regression, is shown in **Figure 17**. The method fits a sigmoid curve between the training database points (green) where the dependent variable Y varies from 0 (for some values of the independent variable X) to 1 (for the rest of the values of X). When a new point is introduced only knowing the independent variable X (the parameter), the method estimates the probability that the point will comply with the dependent variable (the indicator). The threshold allows the definition of different decision boundaries with different weights, or the value at which the point is considered to satisfy, or not, the indicator.

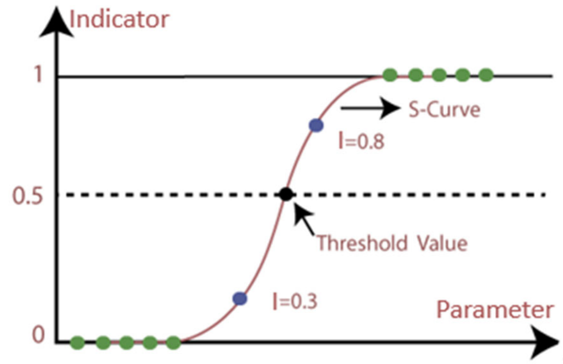


Figure 17. Visualization of logistic regression

3.4 Conclusion

This chapter presented the methodology used for the dissertation, and the specific methods applied for each of the tasks. To gather information about current practices and behaviors of stakeholders involved in the CIP RC standards, an ethnographic-action study was described, and the requirements for the company, project and data collection were established. The results of this study along with the development of parameterized specifications for CIP RC elements allow the development of implementation methods of CIP RC exchange standards in practice. These exchanges are tested using models with varying levels of complexity and finally an adjusted process with exchange standards is carried out using the model of one of the projects studied during the ethnographic observations. These tests along with the findings of the ethnographic research are used to identify the value considerations of applying these standards in practice. Finally, a revision and selection of design indicators that may apply to the scope of these exchanges is done, and after establishing the relationship between indicators and parameters and developing a database, a regression model is developed and revised.

CHAPTER 4. ETHNOGRAPHIC STUDY

4.1 Preparation

The company where the ethnographic study was conducted is one of the biggest and well-known structural and construction engineering companies in the United States (Building Design+Construction 2021). The company was selected because of their vast experience in structural and construction engineering, because the size and relevance of the projects the company conducts, and because of the very advanced BIM practices in the company, evidenced in their project's documentation and models, capabilities of in-house tools, and constant involvement in developments and research conducted around BIM and modeling. This company also became a great candidate for the ethnographic-action study, because they have implemented several interoperability solutions for in-house practices and tools, thus illustrating most of the benefits and challenges of an integrated process for CIP RC structures.

Regarding the projects, the company, and particularly the design principal, were extremely generous and eager to collaborate, and allowed the author to observe and interact during the development of two different projects. Each project had its own team working on it. Both projects have confidentiality agreements, so the information provided for each of them in this document is somewhat generic and has been authorized for publication by the company. The first project, a section of which is shown in **Figure 18**, is a ten-story healthcare building with a three-story podium and an Intermediate Moment Framing (IMF) structural system, consisting mostly of slabs, beams and columns, with a foundation system composed of piles caps, and piles.

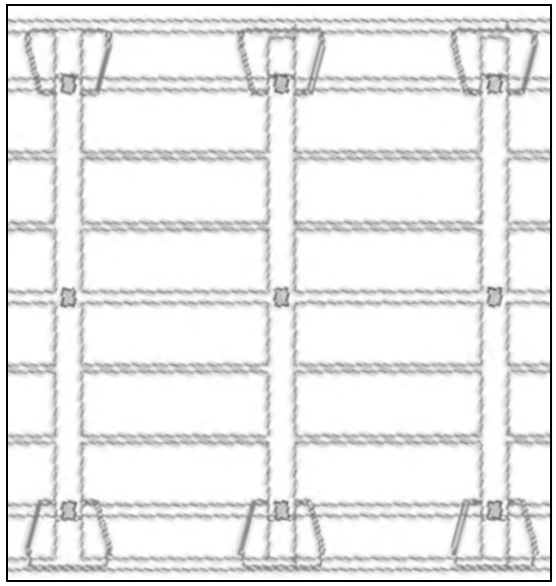


Figure 18. Revit model view of project 1: healthcare building

The second project is a three-story commercial building with an Ordinary Moment Frame (OMF) structural system, consisting mostly of slabs, beams, post-tensioned (PT) beams, with a foundation system composed of pile caps and piles. This is an approximately 575,000 SF of elevated CIP structure building using an estimated 25,000 CY yards of concrete, and a section of it is shown in **Figure 19.** The loading criteria for the projects varies between 15 psf to 20 psf for floor superimposed dead load, 100 psf to 125 psf for floor live load, 25 psf to 200 psf for roof superimposed dead load, and 60 psf to 100 psf for roof live load. By the time the author came to the projects, they were on a schematic design (SD) - early design development (DD) stage, which allowed the observation of most of the dynamics and processes involved in design, modeling and construction planning of the CIP RC buildings. Considering the design phases observed, the type of buildings, and the elements in them, both projects satisfy the three criteria set forth in the methodology and constitute representative projects for the scope of this research. Furthermore, being able to conduct the study in two different projects, with different teams and design considerations, contributes to the extensibility of the results found during the ethnographic observations. During the time of the study, company processes took place almost exclusively online, through videocalls and work sessions. Therefore, the field observations were planned as observations of meetings and work sessions between the different participants. The total duration of the ethnographic study was 12 months. During this time the author observed multiple meetings, processes, work sessions and conducted interviews.

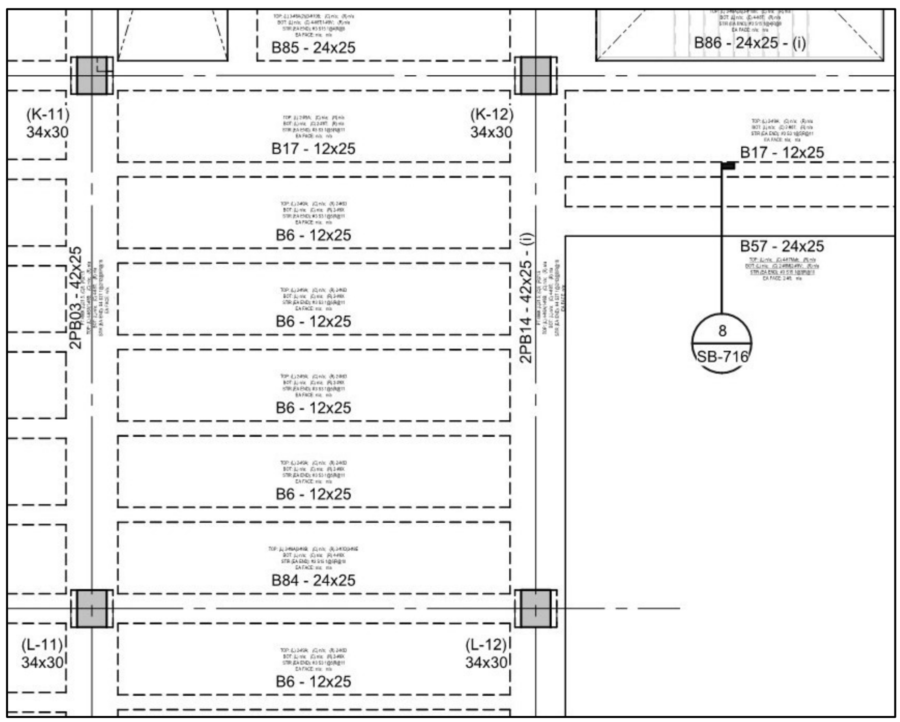


Figure 19. Revit model view of project 2: commercial building

4.2 Data Collection

4.2.1 Field Observations

During the work sessions the team members discussed multiple topics regarding the modeling, design, visualization, interoperability, and document production of the CIP RC buildings. Furthermore, since continuous field observations were not possible, the team members generously and thoroughly described to the author the processes they had worked on to advance between meetings. **Figure 20** shows a section of one of the field observation forms, with the notes taken during the work session. **Appendix B** shows two complete examples of these forms for specific work sessions, one for each of the projects studied.

Document No.	FO – 001 – SE/M
Document Type	Observation
Company/Discipline	Structural Engineering + Construction Coordination
Subject/Actor	Structural Engineer
Recording Method	Videocall
Date	4/15/2021
Duration	1.5 hours
Project	Healthcare Facility
Participants	Principal, Project Manager, Design Manager (responsible for project technical oversight), Lead Engineer, Lead Modeler, Technical Designer 1, Technical Designer 2, Director of Digital Practice.
Observations	The goal of the work session is to discuss the concrete matrix and using it as a live schedule to track the material information on the concrete elements, and go beyond the conventional "dumb" text methods. The goal is to have live tracking of concrete properties and quantities. The building is a new patient tower and emergency podium made of Cast-in-Place Reinforced Concrete Building that will serve as an expansion to an existing healthcare facility. There is a small metal building and a pre-cast concrete parking deck outside of the scope of the meeting. The project is on the early design development (DD) phase, still dealing with schematic design (SD) decisions. The building is a Cast-in-Place reinforce concrete intermediate moment frame (IMF) building, with no shear walls. Foundations consist of piles and pile-caps. This is standard for many framed projects made of CIP RC. The process wants to go beyond referencing the strength of the concrete, and wants to be able to track the details of the mix used, and its association with the corresponding elements made of that mix. The concrete matrix wants to be able to associate to each element the concrete material parameters, or types of concrete mix. (This is closely related to the intent to transmit material information during the EM.6 and EM.20 exchanges).

Figure 20. Sample of observations of work session in form FO-001-SE/M

4.2.2 Process Observations

During some of the work sessions the team members took time to thoroughly describe their processes and procedures, with specific examples of actual usage on the projects they were working on. These processes were registered by the author step-by-step, both to be able to understand workflows for replication, and to draw conclusions and recommendations. This was extremely important since the company had already implemented company-wide standards for modelling and exchanges, that shed a light on how some of the new workflows using industry-wide standards may look like, and what specific differences and additional recommendations may exist. **Figure 21** shows a section of one of the process observation forms, with the notes taken during the work session. **Appendix B** shows the complete form of this process registered.

Document No.	PO - 002 – SE/M
Process	Framing Structural Design
Company/Discipline	Structural Engineering
Subject/Actor	Structural Engineer + Modeler
Recording Method	Videocall
Date	8/26/2021
Duration	1.5 hours
Tools Used	ETABS, Autodesk Revit, Kodiak
General Considerations	The process intents to model and design CIP RC framing elements, particularly beams for vertical loads and deflections.
Steps and Processes	- Generate an analytical model in a structural analysis tool, to revise and correct the connectivity between the elements. Sometimes modeling starts in BIM tool, in which case the model is later pushed into the analytical model for connectivity revision and analysis. - Push model to BIM tool to add information and hold a structural BIM model for coordination. If modeling starts in BIM tool, model CIP RC elements in BIM tool (Revit), ensuring proper dimensions and 3D interactions. - Export the model with the proper connectivity to a central database or neutral file, that can be used to retrieve the geometry and connectivity. - Import the geometric model in the design tool and verify consistency in relationships and connectivity. - Assign loads and load patters to the different elements based on the use of the facility. - Run the analysis and design program. - Verify force diagrams for logic, consistency. and output of design results. Note potential necessary connectivity and geometry adjustments.

Figure 21. Sample of procedure in form PO-002-SE/M

4.2.3 Data Exchanges

The company has developed multiple tools that allow communicating models and information between tailor-made design applications, modeling applications, and BIM tools. For specific exchange procedures, the team illustrated step-by-step these exchanges, detailing the information required and the way it was structured, written, and parsed. This allowed the identification of specific data exchange requirements, including the purpose, the information units, and the type of information. **Figure 22** shows a section of one of the data exchange forms, with the information units and data. **Appendix B** shows the complete form of this data exchange registered.

Exchange Requirement	Concrete Material		
File Type	PDF		
Producing Actor(s)	Structural Designer / Revit		
Consuming Actor(s)	General Contractor / PDF		
Description	The purpose of this exchange is to transfer concrete material information from the structural engineer to the contractor. Information is produced by a tool, but communicated through conventional 2D schedules. The concrete material is associated with the relevant concrete elements		
Information Units	Concrete Element	ID	Concrete Element ID
		Type	Concrete Element Type
		Dimensions	Concrete Element Dimensions
		Material	Concrete Mix Assignment
		ID	Unique identifier of the Mix
		Material Class	Class of material classification
		Name	Name of the mix
		Description	Description of the mix

Figure 22. Sample of information exchange requirements in form ER-001-CC

4.2.4 Interviews

Finally, multiple interviews were conducted for triangulation purposes to ensure the consistency of the information gathered and compare the opinions and insights of the team members with the observations. The questions in the interviews varied slightly depending on the role of the team member interviewed, but in general followed a certain pattern focused on CIP RC modeling and data exchanges. Some questions asked the team members to correlate some of their answers and the observations, with their experience in other projects, in order to discern typical challenges and project-specific challenges. **Figure 23** shows a section of one of the interviews with a structural engineer and modeler. **Appendix B** shows this complete interview.

Document No.	IN - 002 – SE/M
Document Type	Interview
Company/Discipline	Structural Engineering
Subject/Actor	Structural Engineer 1
Recording Method	Videocall
Date	3/25/2022
Duration	1 hour
Description	This interview was intended to gather information from one of the key actors involved in the processes observed, and gain information on his perspective and approaches. This information is also used for triangulation with the information acquired during the observations.
Question	How do you typically communicate design intent information to the detailer or contractor?
Answer	*Luckily we do have some tools internally. Let's talk about columns. We have a tool internally which lets us take the results from ETABS, and then process those results, because ETABS only yields area reinforcement, not number of bars, so we process that into number of bars and spacing. Then we push it to Revit which Is the important part, Once it is in Revit we can create a column schedule from that…. The out of the box family does not have a lot of things that we want to populate, we have created parameters in the family… and our tool can populate that.* *For beams we also have an internal tool, Kodiak, which basically does design, and pushed that design into Revit. The design is pushed and also the labels are pushed, I mean the beam types, so if you do a beam schedule, its already there.* *We also have tools to create foundations. We have a tool that does that and then pushes it to Revit. The one that is a little bit green is shear walls, and link beams, we don't have any sophisticated tool that helps us push from ETABS to Revit. Let's say it's yellow. The design of a two-way slab has always been a challenge for any company, we do have an internal tool that has been developed. I think it's at 75%. It's pretty good but still needs some tweaks. Most of the times it's schedules.*

Figure 23. Sample of interview to structural engineer and modeler

4.3 Data Processing

4.3.1 Coding

After all the information is digitalized, the first step to process the data is the definition of the coding categories and the process of coding itself. Due to the nature of this study, the coding is mostly deductive since the field, purpose and target of the study is quite specific. Based on the review from previous ethnographic studies within the field, particularly (Abdelmohsen 2011), and on the goal of this study, the base coding categories are the following:

- Design/planning practice or method
- Communication pattern
- Modeling of CIP RC elements
- Representation of CIP RC elements information
- Data requirements from others
- Exchange affordances
- Exchange constrains or limitations
- CIP RC Particularities
- Correctness of exchange data
- Confidence on exchange data
- Partial use of exchange data

Figure 24 shows a view of MAXQDA with the coding done on one of the interviews. The tool allows storing the transcripts, labeling the information, and aids in the coding procedure, which in turn facilitates the analysis and the process of drawing conclusions from the great amount of information. There were multiple field observations, process observations and interviews that needed to be revised and coded which derived in 454 code assignments, varying from sentences to paragraphs. To reduce the possible bias in assigning codes to particular ideas, two independent reviewers were asked to revise the coding system, strategy, and specific assignments to certain forms. Both reviewers agreed with the coding system and strategy. Each reviewer was asked to code one sample of each of the forms, and the code assignments were extremely consistent with the coding performed by the author. The main difference occurred in what the reviewers considered to be an “Exchange affordance” or an “Exchange constraint and limitation”, mainly because of the different level of exposure to advanced interoperability strategies, so the coding of these categories was revised to ensure it fit the scope of the current study.

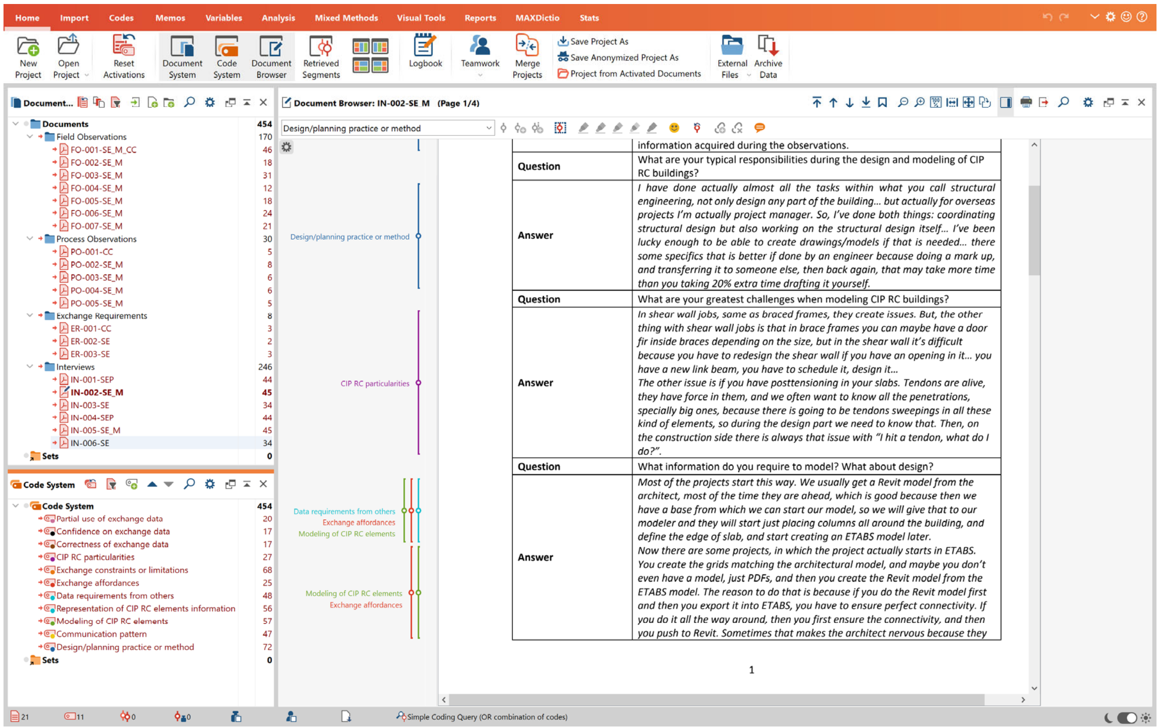


Figure 24. View of MAXQDA coding for field observations IN-002

Table 4 shows all the categories used for the coding process, along with a short description of each of them, and the total number (count) of coded segments for the category. Furthermore, an example of segments coded for each of these categories is provided, for the reviewers to understand the criteria and type of information retrieved. Each segment indicates the format from which it was retrieved, which vary from field observations, process observations, and interviews.

Table 4. Description, Occurrences and Examples of Each Category

Category	Description	Count	Examples
Design/planning practice or method	Specific methods or procedures used in design or planning of CIP RC structures	72	**FO_003_SE_M** Typically, the model is created in ETABS or in Revit, then it is pulled into the tools, loaded, and load and deflections checks are done to analyze and design the beams. Afterwards the bars are scheduled using standard details or bar diagrams and bar types. The information is also pushed back to Revit. The tool was created because current analysis tools are not great at designing beams

Table 4. Continued

Category	Description	Count	Examples
			IN_002_SE_M *Our program that we told you about the columns, will essentially process reinforcement, but you have to tell it the bar size you want, and it will say how many bars you need. It will check that it fits and all that. However, if you mis- click a button it will instead of No. 8 lets say schedule No. 5, and it will fit, and it will be code compliant and all that. But, you don't want a job where you have No. 8 and No. 5 and all kinds of crazy combinations of bar sizes.*
Communication pattern	Repetitive or standard patterns in the communication of information, models, or processes	47	**FO_003_SE_M** Columns are typically analyzed and designed inside of ETABS because that module does work more consistently. The team uses a different program to schedule the columns, which pulls the required areas from the analysis tool, converts it to bars and fits a standard detail and distribution to it based on the specific requirements. Some SMF specific requirements such as strong column/weak beam are still performed "manually" because of the separation in design procedures. **IN_001_SEP** *Specifically for joints we have a rough idea of where the contractor may want to put those, but we usually handle it through some generic details saying "it has to be kind of in these zone"*
Modeling of CIP RC elements	General discussion regarding the modeling of CIP RC elements, including challenges, tools, and procedures	57	**FO_001_SE_M_CC** The initial definition of materials in Revit comes from a selection of options of a database, which has over 60 alternatives for concrete mixes. The database considers requirements for material based on location, exposure, etc. This is the baseline, or out- of-the-box option, and then the material can be individually tailored within the model for the project. **IN_001_SEP** *So, coming up with that framework for how we are going to keep a BIM model connected for analytical purposes. However, even after we have that framework spelled out it was still an issue. Saying "hey we want to implement it this way", but we have a bunch of framing in there, and it looks okay right now, but just getting over that hump of "a deliverable looks this way, so we want the deliverable to look that way" and the modeling may not be happening for the interoperability to map out.*
Representation of CIP RC elements information	Representation techniques or procedures for information regarding CIP RC structures, such as reinforcement, details, joints, and drawings	56	**FO_001_SE_M_CC** Most of the time the materiality definition in the model is done so that there is proper joining between intersecting concrete elements. Conventionally, the reference to materiality, is done through an element parameter that has a code to a scheduled mix. The new approach is to name the material based on the element type it will be used on, so that if the resistance is changed in the schedule, it is not inconsistent with the name of the material. Essentially based on material usage. **IN_001_SEP** *Connectivity. We developed a whole page dedicated to connectivity. So, this took a lot of back and forward and discussions about what are we expecting the design program to receive, so we just run through all these types of scenarios… sometimes we use the analytical lines and sometimes we don't. That was a part of it, but also enhancing our Revit families…*

Table 4. Continued

Category	Description	Count	Examples
Data requirements from others	Required input/data from previous processes or stakeholders before starting a design, planning, or modeling task.	48	**FO_004_SE_M** There is an effort to develop a tool that takes an architectural model, and based on pre- established keys assigns live and specific dead loads to the model, instead of going through the manual assignment process. **IN_003_SE** *To the geometry we later apply the load of the design criteria, based on the architect use. At the beginning the architect just gives you rooms, and gridlines. We then decide, sometimes architect location for columns may not work, so we coordinate.*
Exchange affordances	Affordances of applied exchange methods or mechanisms, that successfully achieving the required data exchange.	25	**FO_001_SE_M_CC** The initial definition of materials in Revit comes from a selection of options of a database, which has over 60 alternatives for concrete mixes. The database considers requirements for material based on location, exposure, etc. This is the baseline, or out- of-the-box option, and then the material can be individually tailored within the model for the project.
Exchange constraints or limitations	Limitation of applied exchange methods or mechanisms, that pose a challenge to successfully achieve the required data exchange.	68	**FO_006_SE_M** A very big step that also took some time for the modeler was ensuring that the model is properly connected and checked for consistency before going into the analysis model. The connectivity does not have to be precise to the millimeter since the analysis tool has some tolerances built into it, but it should be as clean as possible to avoid connectivity issue during the analysis that may require re-import and re-processing.
CIP RC Particularities	Unique features, requirements, and challenges of CIP RC structures, related to design, planning, and modeling.	27	**FO_004_SE_M** The BIM standard has documentation how to properly create CIP RC models and how to assign and connect their analytical lines. This part of the standard is essentially a list of scenarios, where detailed attention is typically needed and how to solve the connectivity on it, so the models are consistent across the company. Examples of these scenarios are interior girders on interior columns or spandrel girders near perimeter columns. **IN_002_SE_M** *But the other thing with shear wall jobs is that in brace frames you can maybe have a door for inside braces depending on the size, but in the shear wall it's difficult because you have to redesign the shear wall if you have an opening in it… you have a new link beam, you have to schedule it, design it*
Correctness of exchange data	Fidelity of the data and data structure during export, import and exchange procedures.	17	**FO_003_SE_M** For structural reasons, most of the times it is better to make the analytical lines coincide with the outer boundary of the element or the slab. This is because in that case the load is applied all the until the end which is what would happen in the building. If the center line was taken, then there would be the need to add loads for the weight of the slab, dead loads and live loads applied between the center line and the edge of the element **IN_002_SEP** *The framework itself is like a language translator between the human and the computer. It's like "these are the guidelines we are going to follow" so the computer is expecting a certain input and we are providing it that way. When we don't follow that we get a bunch of errors. When things were not modeled the way the program is expecting it to be coming in, it catches that and we have a lot of errors because of connectivity, and then we have to go back and fix those. That is very common.*

Table 4. Continued

Category	Description	Count	Examples
Confidence on exchange data	Degree to which the information exchanged is considered correct by the exporting or importing stakeholder.	17	**FO_003_SE_M** Furthermore, with other software the teams had to wait for vendors to implement their own bridges, whereas if the work within their own environment, they have full control of interoperability developments and troubleshooting.
Partial use of exchange data	Limited use of all the usable data in an exchange file, due to various limitations, correctness, or confidence.	20	**FO_001_SE_M_CC** Special care needs to be given when relying on information reported by the tools. Some tools do not report information about all the objects or considerations included. For example, Revit does not schedule slab edge quantities(slab turn down),so the team had to implement a plug-in for that **IN_002_SE_M** *Most of the time when they send a PDF and it's colored, and they have clouds it's understandable. What gets hard is when the don't send any of that and it's just a narrative. Then it is impossible to understand… so we do ask them to give more context.*

4.3.2 Summary of findings and conclusions by category

All the information for each category was then analyzed to extract findings and conclusions that may be used to identify the value of implementation, to assist in the development of implementation methods, and to provide guidance on recommendations for further standardization efforts. To complement and validate the findings in this part of the study two further steps were taken. First, a targeted review of publications and resources was conducted to identify previously addressed or mentioned challenges. This review is part of a publication currently under revision, which assessed the requirements for CIP RC modeling and standardization, performed tests in current tools considering the requirements, and provided further recommendations to target each of these challenges (Garcia and Castro-Lacouture . Under Review). Some of the proposed recommendations for further research listed in the paper are tackled by the present dissertation. **Table 5** presents a summary of the key requirements identified, which align with most of the findings from the ethnographic observations regarding modeling and interoperability.

Table 5. Requirements for CIP RC Modeling and Interoperability (Garcia and Castro-Lacouture . Under Review)

Requirement	Sources
i. Boundary definition of overlapping objects	(Barak, Jeong, Sacks, & Eastman, 2009), (Muller, et al., 2017)
ii. Representation during phases prior to the creation of rebar shop drawings	(ACI Committee 131, 2015)
iii. Representation of partial geometry for construction processes	(ACI Committee 131, 2015), (Barak, Jeong, Sacks, & Eastman, 2009).
iv. Consistency between geometric and analysis models	(Hu, Zhang, Wang, & Kassem, 2016), (Liu, Zhang, & Zhang, 2016), (Muller, et al., 2017)
v. Increased focus in constructability from the engineers	(Aram, Eastman, & Sacks, 2013)
vi. Usage testing, examples, and new workflows	(ACI Committee 131, 2017), (Aram, Eastman, & Sacks, 2013)
vii. Value of implementation	(Grilo & Jardim-Goncalves, 2010)

Afterwards, interviews were conducted with two engineers (a senior structural engineer at a firm in Atlanta, GA and a senior engineering coordinator at a firm in Bogota, Colombia) and two construction managers (an assistant project manager and a BIM/VDC coordinator at a construction company in Atlanta, GA). During these discussions, the challenges of modeling and exchanging CIP RC models were discussed. All findings from the ethnographic study were found as consistent with the challenges they face with CIP RC building in their practice, and they all acknowledged on the advantages standardized exchange could bring to their practice. **Table 6** presents the findings and conclusions for each of the categories and dimensions defined for the ethnographic study and that are used to identify the value of implementation, to assist in the development of implementation methods, and to provide guidance for recommendations for further standardization efforts.

These conclusions were drawn from an analysis of key ideas and the frequency of their appearance in the field observations, interviews, and previous publications. Every element that was considered as fundamental because of its importance for the success of further tasks, or whose frequency of discussion stood out, is addressed in the table. Some aspects such as "model connectivity" had a frequency of discussion as high as 35 occurrences.

Table 6. Summary of Findings and Conclusions per Category

Category	Findings and conclusions
Design/planning practice or methods	• Setting up automated or enhanced processes typically demands an increase in upfront work. However, this investment is compensated by great benefits realized downstream when the time comes to generate outcomes or communicate information to other stakeholders. • Design and planning processes are never unidirectional, where there is an input and an output. Processes are usually iterative, where there may be several alternatives generated at once, or where a considerable number of changes in short periods of time may occur. The room for error and waste of time is exponentially increased because of these dynamics. • Specific stakeholder processes vary heavily in their intensity based on the degree of automation and interoperability implemented in the company. The steps required to complete certain tasks is reduced dramatically as automated and interoperable workflows become stronger. The processes observed in the company, which are extremely automated and interoperable, are considerably more efficient than conventional approaches seen by the author and interviewed engineers in other projects.
Communication patterns	• Heavy coordination happens during design with the architect and systems engineers. Every time an element varies in size, communication and coordination is required with other stakeholders to ensure conflicts will be prevented. The capability of effectively communicating such information relies on the capability of the stakeholder to receive and use the information provided. The more advanced this capability, the least stakeholder-to-stakeholder advanced coordination is required. • Key communication patterns include architect-structural engineer (iterative), structural engineer-systems engineers (need-basis), contractor-structural engineer (construction methods approval), and contractor-subcontractors (iterative).
Modeling of CIP RC elements	• The boundary definition of overlapping objects for CIP RC structures remains a challenge and is still something subjectively defined. Defining these interactions can be an extremely time-consuming task, and companies with advanced IT capabilities have chosen to develop algorithms to automate most of this process. • The connectivity of the structural model and the consistency with the analysis model is one of the greatest challenges when modeling CIP RC elements. This problem has led practitioners to either start their modeling from scratch in analysis tools, where connectivity can be ensured but losing the advantage of having a BIM model, or to develop in-house interoperability mechanisms and tailor-made design and planning software applications. • Concrete is unique not only on the way it is modeled (overlapping volumes) and the need for multiple visualizations depending on the stakeholder, but also on the geometric and material possibilities. While several structural systems mostly use a "catalog" approach, for example steel where sections are pre-defined and the material is standard with some small room for modifications, CIP RC is highly subjective, allowing user definitions about shape, dimensions, and concrete mix composition.
Representation of CIP RC elements information	• A common idea shared by multiple team members and stakeholders interviewed, is the understanding that most of current efforts for representation of CIP RC information focus in the capability to transform design intent and construction planning information into 2D documents and drawings. They acknowledge this process while necessary, will no longer be necessary in 5 to 10 years, when the industry switches to model and data-based communication.

Table 6. Continued

Category	Findings and conclusions
	• Concrete has a particular approach towards material assignment to different elements. While several elements may share the same design strength, the concrete mix itself may vary considerably based in the specific requirements of the element type, such as a beam vs a column. Even within the same element type, concrete mix properties of the same strength and limitation, may vary due to situations such as exposure or location. Therefore, representation of concrete material information for CIP RC should be usage-based, depending on the specific element where the mix will be applied. • The representation of CIP RC elements during phases prior to the detailed structure is fundamental for the design and coordination processes of these type of structures. Common representation of this design intent is done through schedules of element types and bar types (size and distribution) assignment, using graphical keys to reference typical or specific 2D details. While companies with advanced IT capabilities can embed this information into their models, it is almost never used by receiving stakeholders, who still rely exclusively on the 2D documentation and details, mostly because of their capability to parse the information. • Most companies have standard 2D details they may use an adapt to every project as necessary. These details and representation may vary widely between companies, and may even be subjective depending on the engineer's approach to tailoring it to the project. Consequently, detail assignment, referencing and tailoring is still a time-consuming task for many engineers, regardless of the level of automation implemented.
Data requirements from others	• The requirements for the structural design process vary based on the project, the architect's proficiency with BIM tools, and the approach to modeling taken by the engineer. For geometric considerations, input may involve a BIM model from which to start modeling a structural system in BIM, or it may be based on drawings from which a model is created from scratch. Depending on connectivity challenges and the engineer's preferences, the modeling may start on the analysis or on the BIM tool. When a model is provided by the architect, engineers are more inclined to start the process in a BIM environment. Sometimes grid lines or potential column locations are also part of the input. There is also a requirement for a usage narrative or room-use assignments to establish a load pattern for the building. • To perform structural design, modeling and calculations, the engineer requires from the modeler a geometric model with IDs, locations, and dimensions, which has been revised for connectivity. If there are connectivity issues, the engineer will have to go back and fix them. • To communicate design intent information, the modeling tool or stakeholder requires the bar types (sizes and distribution) mapped to the corresponding elements using the unique identifiers. Standard details for these bar types are also required to create schedules. If the exchange is model based, the receiving application must have a mapping mechanism where element parameters are populated based on design results. • To perform tasks at a subcontractor level the modelers or designers require from the subcontractor construction planning information including concrete volumes, concrete pours, joint locations, loading, and other particular requirements. • To develop a construction coordination model, the contractor requires planning or design results from the subcontractors associated with particular elements or pours by a unique identifier. If the exchange is model based, the receiving application must have a mapping mechanism where element parameters are populated based on design and planning results.
Exchange affordances	• Interoperability can be achieved through central databases or standard data exchanges, but one thing in common and to pay special attention to, is preserving a unique indexing approach, consistent across all the tools involved in the process. Central databases have become standard for companies with high IT capabilities, while other stakeholders without such capabilities heavily rely on tool affordances. • Exchanges based on tool plug-ins developed by software vendors are common in any company with BIM practices, and the exchanges typically carry all the information contained by default in the exporting tool, and that the exporting application considers relevant to be communicated to the receiving application. These non-standard proprietary exchanges include information such as geometry, locations, and basic naming and material properties. Depending on how advanced the exchange has been implemented, the users may be able to exchange connectivity information, proper element type mapping, and more advanced program or user-defined properties.

Table 6. Continued

Category	Findings and conclusions
	• Companies with high IT capabilities have developed tools where the exchange affordances are defined by their own developments and are therefore very comprehensive and responsive of all the exchange requirements and processes within the company. These affordances are what open exchanges seek to achieve at an industry level.
Exchange constraints or limitations	• Exchanges based on tool plug-ins developed by software vendors are common in any company with BIM practices, but the exchanges are limited to the information contained by default in the exporting tool, and that the exporting application considers relevant to be communicated to the receiving application. These non-standard proprietary exchanges constrain the user to communicating exclusively with the pre-defined tool and exporting the data in a certain manner, which most of the times derives in the user manually correcting and adjusting everything that was not exchanged as expected, or exchanged at all. Furthermore, the process is limited by software versions and releases, forcing the user to update, or not update, versions until the compatibility has been properly resolved by software vendors. • Standard exchanges are always limited by the type of situations they are capable of representing. Whenever a situation occurs where the information to be represented does not fit into that standard representation, the exchange is limited in communicating the CIP RC structure information to what was defined in the exchange methods. • For companies with high IT capabilities, the exchange of information becomes much more effective when using the applications developed for such a purpose. However, when interacting with other stakeholders, given that they lack the ability to parse this information, the exchange is constrained to conventional methods of representation and the need to transform the data into these conventional methods appears.
CIP RC Particularities	• Although the connectivity of the models for analysis purposes is certainly a focus that needs to be given to all structural model, it is certainly a particular focus for CIP RC structures for two reasons. First, the monolithic nature of the material leaves room for interpretation of where analysis lines should be located and where one element ends and the other begins. Second, CIP RC elements are typically larger and more robust, leaving more room for potential location of nodes and connectivity points. This issue is also linked to the volume interaction challenge, which requires the definition of what element takes precedence over the other at every intersection or node. • The diverse views a model requires based on the scope of the stakeholders is one of the greatest challenges and particularities of CIP RC. Particularly, the representation and exchange of partial geometries to allow the communication of concrete pours and construction coordination information without affecting the integrity of the model elements, is a great challenge. Conventionally, for coordination purposes, this information is communicated using 2D documents, and the modeling is used for QTO and scheduling, where the pours are typically treated as a whole volume, instead of as an aggregation of structural elements. • The need for coordination given the wide range of options for dimensioning, reinforcing and material properties is a notable particularity of CIP RC. This also derives in the requirement for more complex constructability analyses, in order to ensure that the dimensions, amount of reinforcing and overall disposition facilitate the construction process, or make it even possible. • The detailing of several structural elements, such as steel connections, needs to be very precise given that the behavior of the connection can vary greatly if all design assumptions are not satisfied. Conversely, CIP RC typical details seem to live in an abstract manner in the mind of all those involved in the process, so that the use of typical details expressing the design intent may be sufficient for detailing and construction. When very specific cases arise, the engineers do feel the need to spend extra time creating their details to ensure proper communication of the design intent.
Correctness of exchange data	• One of the most repeated comments and sentences is “it depends in how it is modeled”. The capability to successfully exchange models and information depends on successful elements and properties mapping, which depend on proper modeling methods and techniques. Having standard procedures becomes vital to achieve the consistency in the success of the exchanges.

Table 6. Continued

Category	Findings and conclusions
Confidence on exchange data	• The capability of parsing the data received by other stakeholders is not the only argument against fully utilizing the data provided in the models. Several team members and professionals consulted agree that it is also a matter of confidence in the model information since, although provided, there is no guarantee given by the providing stakeholder about the reliability of that information, and focus is given mainly to the 2D documentation. The lack of industry standards causes the representation to vary so widely, that the room for error in interpretations is enough to encourage receiving stakeholder to prefer spending man-hours dedicated to transforming 2D information to their own structure and tools. • Oftentimes the modeling approach focuses on modeling the structure so that the 2D documentation generated seems correct, rather than modeling it "properly" based on the specific producing stakeholder's requirements. This process, while aiding the clarity of 2D documents, undermines the reliability of the model and data exchanges. • For some companies and projects, particularly those that involve less BIM-capable stakeholders, BIM deliverables represent a requirement rather than a tool to leverage. When the motivation is purely contractual, the confidence in the deliverables is usually questioned given that the exchange data was put in place to satisfy a requirement rather than to aid in the process of communication and coordination.
Partial use of exchange data	• Study participants agree that the consideration of what constitutes "complete information" changes over time. It depends on how detailed the modeling and exchange processes get on the exporting and importing side. Therefore, it becomes important to provide the vehicle to exchange as much data as possible in a standard manner and allow the user to define the degree to which the standard serves its communication goals. • Several exchanges occurring outside of the company teams derive in the use of partial data. Receiving applications and stakeholders take what they can parse or import from the incoming model and parameters, and rely on documentation and drawings for everything else, regardless of whether it was available or not in the exchange, since they could not use it. This is mainly due to the lack of standard methods for data exchange.

4.3.3 Workflows

In order to complement the author's experience with CIP RC modeling, design, and coordination workflows, as well as the workflow proposed in the ACI IDM, the workflows from the ethnographic study were mapped as a reference. This proved very useful since the fact that the company has several developments for modelling and interoperability within their tools, made it possible to identify how interoperable workflows may look like, and how industry-wide standards may contribute to the overall process when more than certain specific tools are used. **Figure 25** shows a summarized version of the ACI IDM, adapted to show the design intent exchange (EM.6) and the construction coordination exchange (EM.20). Although it does not show the level of detail for specific processes carried by the stakeholders working around the exchanges of interest, is does provide a good reference for validation. Most of the workflows for specific processes identified in the ethnographic observations, although far more detailed for particular procedures, are found to be consistent with the ACI IDM workflow.

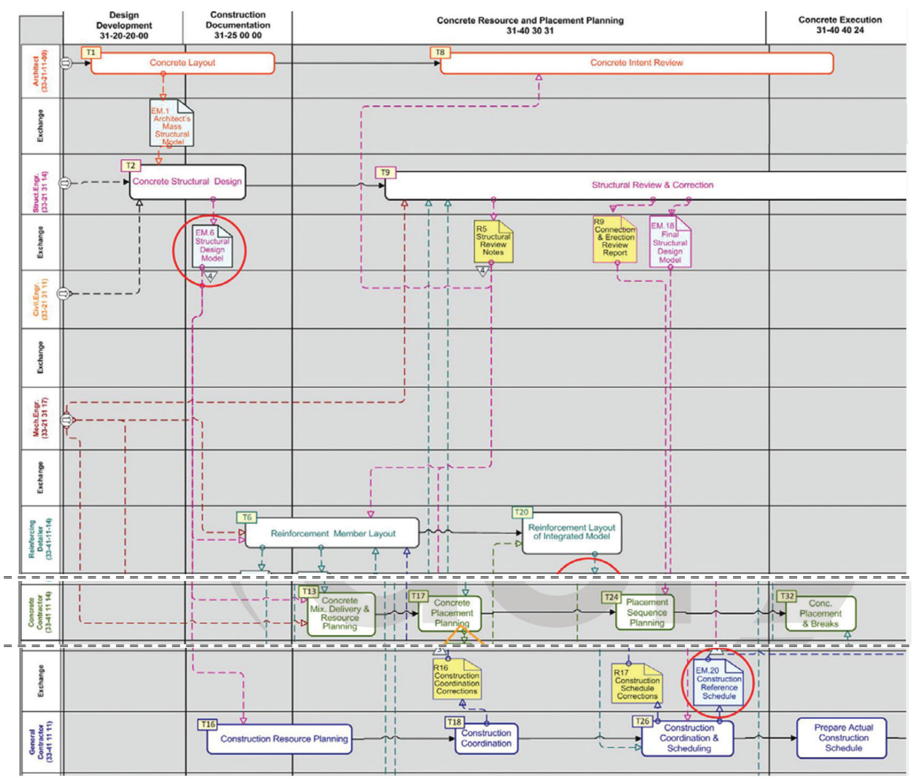


Figure 25. Adapted ACI BPMN with EM.6 and EM.20 (ACI Committee 131 2015)

There are four key workflows derived from the ethnographic observations that help guide the creation of exchange implementation methods in the next sections of this dissertation. The first and second workflows deal with the modeling, analysis, design, and rebar scheduling of CIP RC elements. The key difference between the workflows is that in workflow one, **Figure 26**, the workflow starts in the BIM tool, while in workflow two, **Figure 27**, the workflow starts in the structural analysis tool. As mentioned during the previous section, one of the biggest challenges for CIP RC models is connectivity. Therefore, some workflows start in the structural analysis tool where connectivity is much better dealt with from the beginning, while other start on the BIM tools using as a baseline an architectural model. Identifying these exchanges and procedures during a particular task, and that do not necessarily constitute exchange models in the IDM, is what guides the development of the implementation methods required to take the standards to practice. Based on these workflows, the implementation methods will need to gather design intent information as produced by the engineers and transform it into the standardized forms, as well as automatically map the information to the corresponding elements in the modeling tool, and populate pre-defined element parameters created to hold such information.

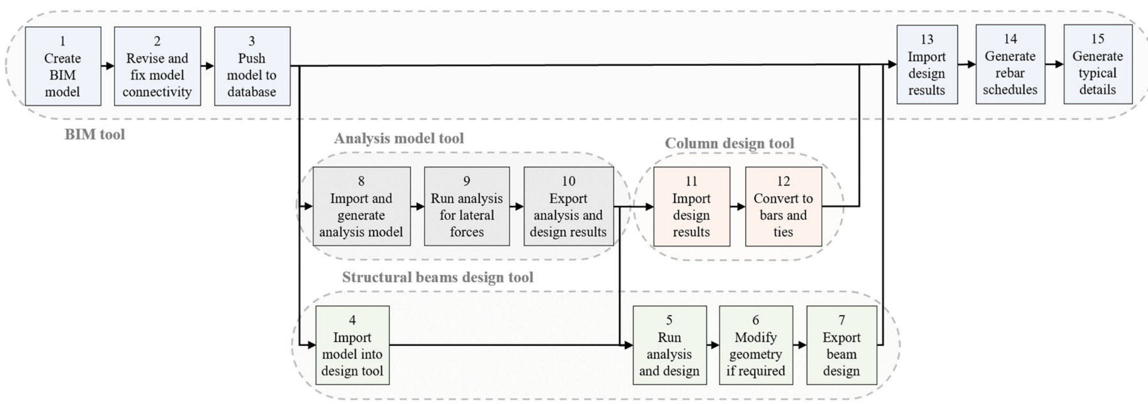


Figure 26. Workflow for design intent preparation – based on BIM

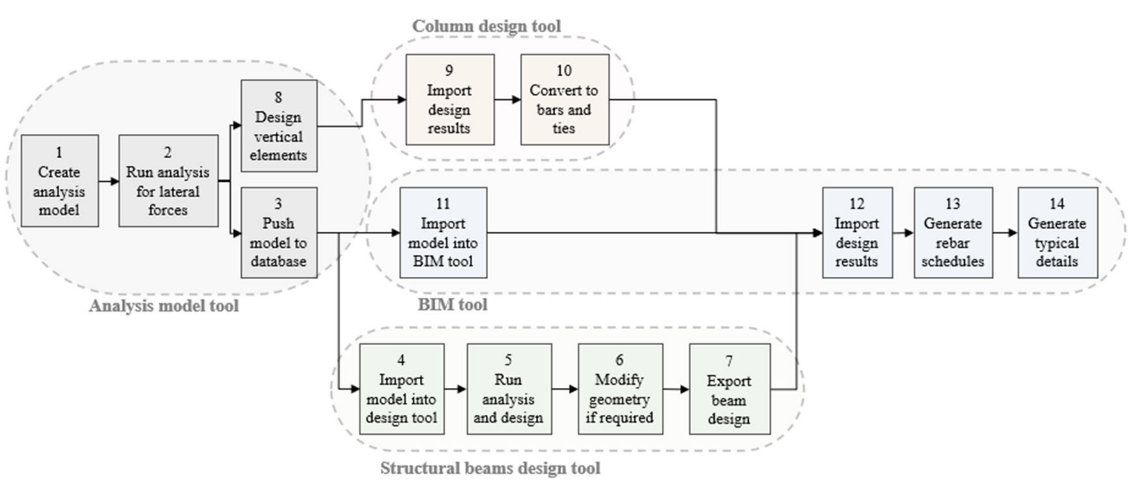


Figure 27. Workflow for design intent preparation – based on analysis model

The third workflow identified, **Figure 28**, is the preparation, assignment, and communication of the concrete mix information. The company had a special approach under development referred to as the live concrete matrix. The observations of these processes and developments allowed the identification of three key requirements for the implementation methods: the selection of applicable mixes from a database that can be assigned to elements, element types, or pours, automatic mapping of the properties to model elements, and the automatic population of such information into pre-defined parameters in the CIP RC model elements.

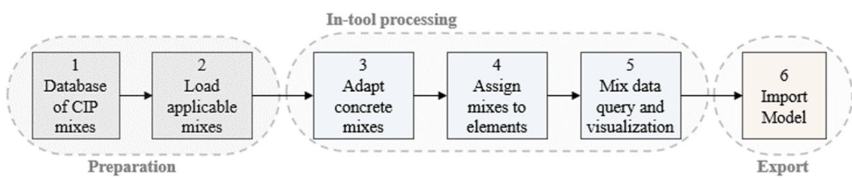


Figure 28. Workflow for concrete mix information preparation

Finally, **Figure 29** shows the fourth workflow, which maps the information flows to generate the construction coordination information exchange model. This workflow was based on conversations with the structural engineer as how the process works with the contractor, and with one representative of the contractor. The main requirements identified for the implementation methods include the selection of applicable mixes from a database that can be assigned to elements, element types, or pours, the mapping of information provided by specific subcontractors with the corresponding pours or pour objects, and finally the communication and automatic population of the corresponding model parameters.

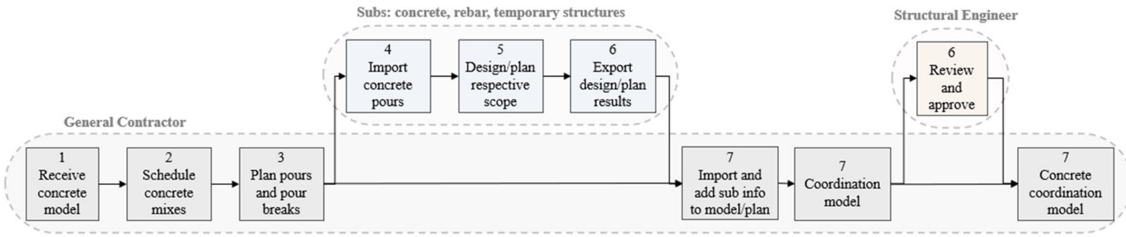


Figure 29. Workflow for construction planning information preparation

4.4 Recommendations for Standardization

The review of exchange standard developments for CIP RC structures, the review of challenges and requirements for CIP RC modeling and standardization, and the findings and conclusions from the ethnographic observations and discussion with industry professionals serve as the basis for generating recommendations for further standardization efforts of CIP RC structures. It is important to note that the work performed by the ACI has been exhaustive and the Committee 131 has made notable progress towards standardization, so these recommendations are intended for further developments and efforts. The recommendations are concerned not only with the exchanges, but also with modeling techniques, which as shown in the ethnographic findings, have a direct effect on the successful exchange of the model information. The following sections list and explain the recommendations proposed as well as implementation guidelines for some of them.

4.4.1 Standardization of connectivity between physical and analysis models

The connectivity of the model was the biggest point of discussion during many of the work sessions observed. That is because, although modeling tools have made attempts for consistent exchange between a physical and an analysis model, when the model originates in a BIM tool, there needs to be a big effort in revising and ensuring proper connectivity. Furthermore, when the exchange happens using an open standard and without the use of a proprietary plug-in, providing and preserving such consistency becomes even more challenging. The issue is particularly important for CIP RC elements, since these elements are typically larger and more robust, leaving more room for interpretation in the location of nodes and connectivity points. Therefore, it is recommended that a standard approach for the required transformations between the two representations be developed, that accounts not only for the geometric modifications, but also for the structural loading consequences of the transformation. This would allow the consistent exchange of physical and analytical models in an open format, making the modeling and exchange processes much more efficient. The BIM standards used in companies for consistent modeling may serve as a guideline in identifying typical situations and best practices, along with testing and export/import evaluation, as done in the publication under review (Garcia and Castro-Lacouture . Under Review). **Figure 30** shows an example of an occurrence of a connectivity issue due to the notable size of a CIP RC column with an eccentric beam, that requires certain modifications and load transformations to achieve a consistent model.

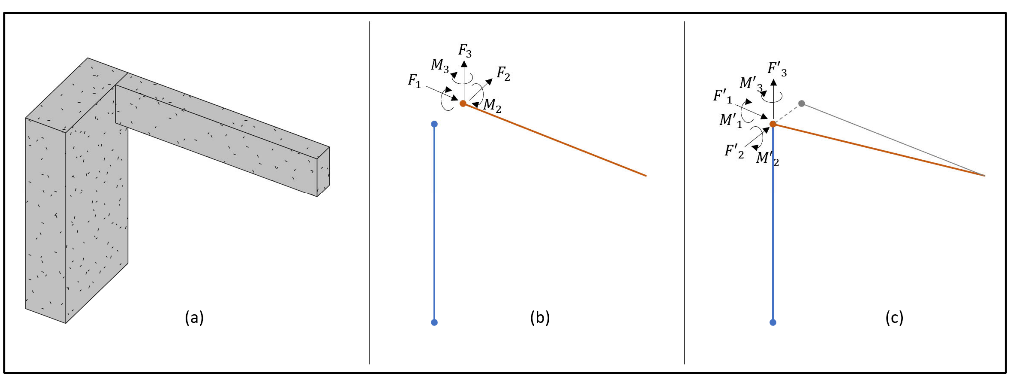


Figure 30. Recommended standard translation. (a) physical model, (b) initial and (c) corrected analytical model (Garcia and Castro-Lacouture . Under Review)

4.4.2 *Standardization of concrete elements' volume interactions*

While software applications have considerably increased their capability to handle the volume interactions between CIP RC elements, this is mostly a process done node by node, which can become extremely time consuming for the modeler or the engineer when the situation is not automatically defined. In practice, several of the rules that give priority to an object over another are a standard practice or a project-defined approach. Consequently, the next recommendation is to standardize the volumetric interaction definition between object types, to follow a pre-defined set of rules based on the standard practice and that can be modified by the user based on project-specific requirements. As proposed in (Garcia and Castro-Lacouture . Under Review), **Table 7** shows an example of this rule definition, which determines which object is given priority when intersected with another, and in case they are the same element type, which priority criteria is used to give precedence to either of them. **Figure 31** shows how a model applies the predefined set of rules from **Table 7** to standardize and automate the approach to defining CIP RC element interactions. The automation was achieved using the routine from **Figure 32**, which was implemented in Dynamo and illustrates how this process may be taken into practice.

Table 7. Rule Definition for Automatically Joining Elements (Garcia and Castro-Lacouture . Under Review)

	C Column	B Beam	J Joist	S Slab
C Column		Column	Column	Column
B Beam		*Priority	Beam	Beam
J Joist			*Priority	Slab
S Slab				

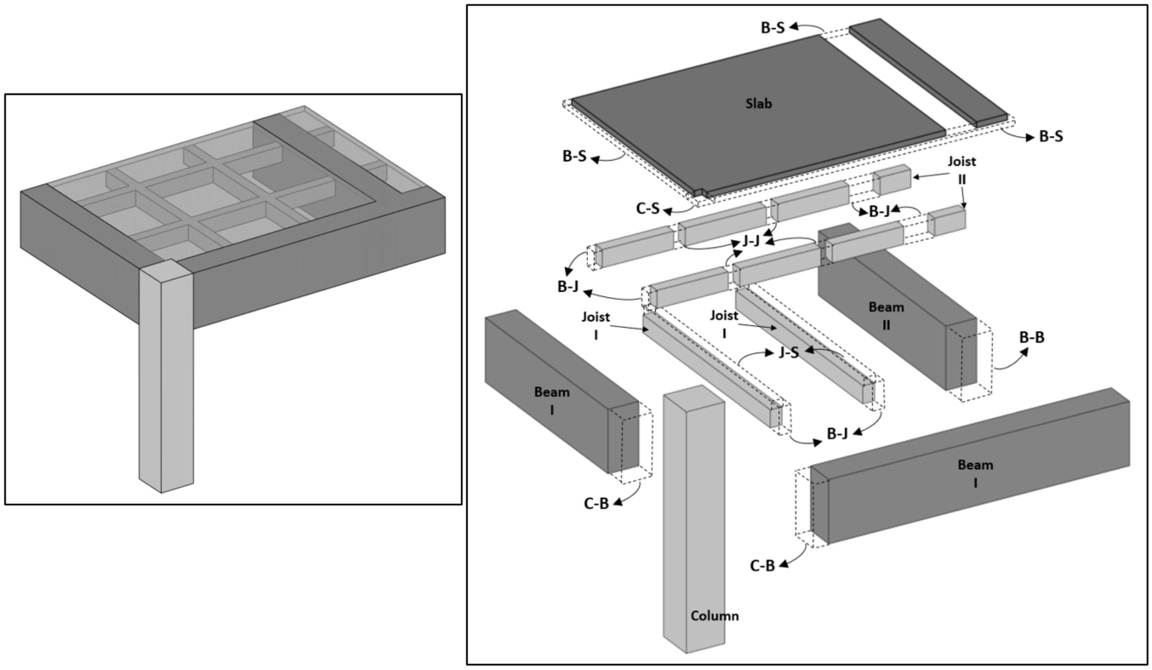


Figure 31. Model with detailed automatic interaction definition (Garcia and Castro-Lacouture . Under Review)

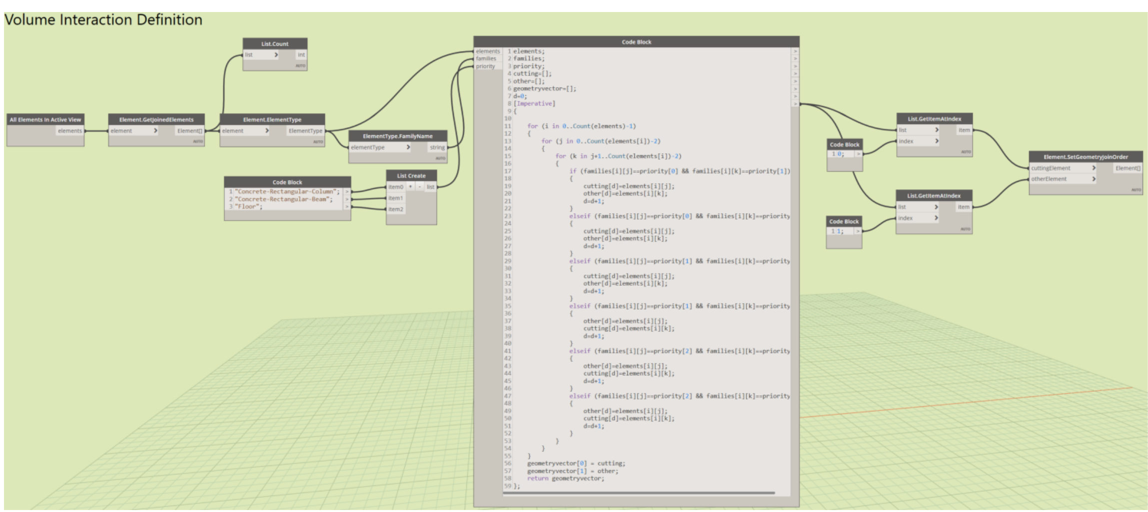


Figure 32. Dynamo code for automatic definition of volume interactions

4.4.3 Full standard parametrization of representative information

As mentioned in the findings, the consideration of what constitutes “complete information” changes over time. It depends on how detailed the modeling and exchange processes get, both on the exporting and on the importing side. Therefore, it becomes important to provide the vehicle to exchange as much data as possible in a standard manner, and then allow the user to define the degree to which the standard serves its communication goals. While the current approach of carrying the information typically contained in standard details is a notable first step towards standardization, for future iterations a fully parametric approach is recommended, because to achieve cost-efficient communication, software should allow designers the ability to express model and properties parametrically in terms of dimensional constraints driven by equations or other types of relationships (Sacks, Eastman and Lee 2004), which include design intent and construction coordination information. A fully parametrized approach is developed in the “Parametrized Information Specification” of this dissertation (Chapter 5), to provide a baseline for this recommended approach to the standardization of CIP RC information.

4.4.4 Alignment with standardization of reinforcement details

Most companies have standard 2D details they may use and adapt to each project as necessary. These details and representations may vary widely between companies and may even be subjective depending on the engineer’s approach to tailoring it to the project. Consequently, the assignment, referencing and tailoring of details is still a time-consuming task for many engineers, regardless of the level of automation implemented. To enhance standard practices in the CIP RC industry, the ACI Committee 315 is constantly working in the production of guidelines to represent reinforcing steel details, and is consistently working the production of standard representations that respond to common practices and constructability concerns (ACI Committee 315 2018). Some of the people interviewed agree that one of the reasons detailed concrete modeling might not be concern, is because several of the details live in an abstract manner in the minds of the stakeholders involved, which may lead to errors and omissions. The recommendation is for companies to embrace and implement the industry-wide standards whenever applicable to situations in their practice, and for the exchange standards to adopt these standard details and representations as part of their communication mechanisms. Referencing standard detail representations at an industry level could considerably facilitate the representation of design intent information, the early planning of reinforcing bars, and reduce errors by considerably reducing the number of parameters required to represent a certain design intent.

4.4.5 Data analytics techniques for processing of non-standardized scenarios

As comprehensive and inclusive as the development of exchange standards may strive to be, the nature of CIP RC will always generate scenarios where the design intent and the construction planning information may not be represented by the standard parameters. This is a recognized limitation, and in such cases the receiving applications and stakeholders may take whatever they can parse or import from the incoming standardized file and rely on documentation and drawings for everything else. It would be impractical to attempt to enhance the standards to capture these types of situations, since they may be so unique that it would require the creation of parameters that may never be used again, overcomplicating the exchange process of typical buildings which happen much more often. Lately, the use machine learning techniques within software applications has greatly improved and had allowed several processes to be much more efficient and informed. Therefore, the recommendation is to develop guidelines to use data analytics and machine learning techniques to identify and parse non-standardized information, based on historically successful parsing and import of standardized situations that may share similarities with the non-standardized scenarios.

4.5 Conclusion

This chapter presented the preparation, procedures and results of an ethnographic study performed at an engineering company with strong BIM practices for CIP RC structures. The design and coordination processes of two buildings were observed for a one-year period, and information including field observations, process observations and interviews was obtained. A coding system was proposed to organize and analyze the data gathered, which proved to be extremely useful to draw findings and conclusions from the large amount of information available. To complement and validate the findings, they were compared with previously researched challenges for CIP RC modeling and interoperability, as well as consulted with four different professionals from different companies. The ethnographic approach was extremely useful to provide multiple sources of information, and the findings were consistent and very valuable to identify typical practices for CIP RC modeling, design, planning and coordination, as well as affordances and limitations. Some key findings include: a) automation and standardization require an increase in upfront work, with several benefits realized downstream; b) the required intensity to perform design and planning tasks, as well as the room for error, vary depending on the level of automation in the processes; c) the connectivity and boundary definition of overlapping structural elements remain a great challenge for CIP RC models, leading some engineers to develop their own in-house tools or start the modeling in an analysis tool from scratch instead of importing it from a BIM tool; d) interoperability based on tool plug-ins is tied to software developers and versions, which has led to companies with high IT capabilities to develop in-house tool; e) CIP RC has the additional challenge of communicating different views that change the boundary definition between objects based on the scope of the stakeholder performing the modeling; f) current BIM efforts for CIP RC focus on translating the information to be represented using conventional methods (drawings), which stakeholders believe will need to change within the next few years; g) CIP RC has the particularity of requiring material assignment (concrete mixes) based on the usage; h) standardizing typical details for CIP RC reinforcement would have great value in simplifying communication and reducing the number of errors and room for interpretation, and; i) there is a lack of confidence in the exchange of model data due to the lack of commitment or interest in proper modeling and data assignment. The findings of the ethnographic observations were used to provide a description of current and potential modeling and exchange practices, map workflows of design and planning processes, as well as to provide recommendations for future standardization, including the standardization of connectivity between physical and analysis models, standardization of concrete elements' volume interaction, full standard parametrization of representative information, alignment with standardization of reinforcement detail, and development of guidelines to use data analytics techniques for processing of non-standardized scenarios.

CHAPTER 5. IMPLEMENTATION METHODS AND VALUE CONSIDERATIONS

5.1 Parametrized Information Specification

The challenge for the reinforcement design intent exchange resides on parametrizing as many design alternatives as possible, while the geometry remains the same. The challenge for the construction coordination exchange resides on representing partial geometries and associating them in groups based on work packages, while the properties can simply be added to property sets as necessary. Therefore, the parametrized specifications for the reinforcement design intent focuses on proposing parameters that represent as many design alternatives as possible, while the specifications for concrete and construction information represent examples of the type of information that may be transmitted, and the focus for this exchange is given to representation.

5.1.1 Reinforcement Design Intent Information

To accomplish maximum automation and efficiency in the exchanges, additional parametrization of the information typically contained in the reinforcement design intent is proposed. This additional parametrization can also serve as a reference for a second phase on the ACI exchange standards development. More complex shapes are not considered in this method, and in such cases, the mixed approach taken by the ACI committee, which considers attaching 2D details, is recommended (ACI 2020). Further advantages of this increased parametrization include the potential application to perform tasks such as automatic preliminary Quantity Take-offs (QTOs) or generation of basic detailing models for the detailer to have a starting point from which to continue detailing the structure.

Objects from five projects with different characteristics were analyzed to define the parameters for each object. The parameters were obtained for each object type to represent as many of the alternatives that result from the design phase as possible. **Table 8** and **Figure 33** show the parameters obtained for a beam, along with a description and an example of how that parameter can be represented. Linear elements (e.g., beams) are generally split in three zones along their axis (start, middle, and end), and the parameters considered include length of each zone, longitudinal reinforcement, transversal reinforcement, rebar strength and concrete cover. Area elements (e.g., slabs) generally define a main direction, zones parallel and perpendicular to that direction, and the parameters considered include reinforcement with spacing and cover. The complete results of the parametrization process can be found in **Appendix C**. For slabs, the reinforcement specifications are additional to the uniform mesh, which may or may not exist.

Table 8. Parameters Obtained for Beams

Element	Parameter	Description	Example
Beam	Longitudinal Bars - Start Beam	Comma separated values, with each value containing information of a reinforcement row. Each value contains 5 parameters of the row: Number of bars, diameter of the bars, distance of row from bottom (local y=0), bar spacing and first bar distance from left face (x=0). There can be 3 different lists: one for the start, one for the middle	5#6-630-95-55, 3#5-580-190-55, 2#5-350-380-55, 5#6-630-95-55
	Longitudinal Bars - Mid Beam		3#6-630-95-55, 2#5-350-380-55, 3#6-630-95-55
	Longitudinal Bars - End Beam		5#6-630-95-55, 3#5-580-190-55, 2#5-350-380-55, 5#6-630-95-55
	Stirrups - Start Beam	There are 4 parameters for the stirrups: Number of closed stirrups, diameter of closes stirrups, horizontal length of each closed stirrup, separation of closed stirrups. There can be 3 different values, one for the start, one for the middle and one for the end of the beam.	1#4-420-100
	Stirrups - Mid Beam		1#4-420-200
	Stirrups - End Beam		1#4-420-100
	Stirrups S - Start Beam	There are 3 parameters for the ties: Number of ties, diameter of ties, separation of ties. There can be 3 different values, one for the start, one for the middle and one for the end of the beam.	1#4-100
	Stirrups S - Mid Beam		1#4-200
	Stirrups S - End Beam		1#4-100
	Fy - Long. Bars	Steel Strength for Longitudinal Bars (Units by file)	420
	Fy - Stir & Ties	Steel Strength for Stirrups and Ties (Units by file)	420
	Cs	Top Cover	50
	CL	Lateral Cover	40
	Ci	Bottom Cover	60
	Lz	Length of zones. 3 values: start, middle, end length	1000,4000,1000

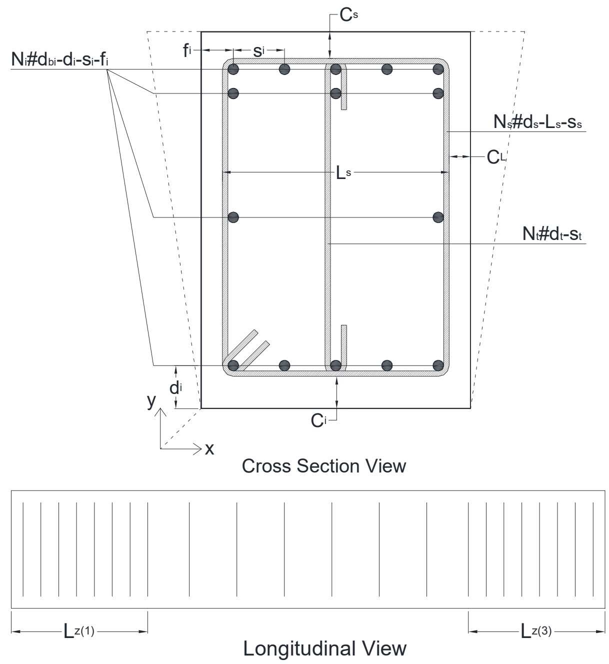


Figure 33. Visualization of parameters for beams

Table 9 shows how many objects were analyzed from each project, the total number of elements analyzed, and the number and percentage of how many of them could be represented using the proposed parameters. For each object type, the compliance of the main reinforcement categories was analyzed. For example, for beams the table shows the capacity of the parameters to represent the longitudinal reinforcement, stirrups, ties and zones (i.e. seismic zones). As it can be seen, in all cases more than 85% of the objects' design can be represented using the proposed parameters. In the case of slabs, the main weakness of the method is that it lacks the capability to carry data for thicker slab edges if they exist. However, incorporating them as part of the parameters would be counterproductive since it would make the result much more complex and such data can still be manually input by the receiving stakeholder should it be required. For the rest of the objects, the reason why some elements could not be represented is that they have details too specific for the project, which makes it impractical to parametrize and standardize them. Nevertheless, a minimum of 80% is a good number considering the number of objects that were reviewed.

Table 9. Percentage of Objects Described with the Proposed Parameters

Percentage of Objects Described with Parameters																			
Parameter Groups		Project 1			Project 2			Project 3			Project 4			Project 5			Total		
		A	D	%	A	D	%	A	D	%	A	D	%	A	D	%	A	D	%
Beams	Long. Reinf.	14	14	100%	18	18	100%	15	15	100%	20	20	100%	15	15	100%	82	82	100%
	Stirrups - Shape		12	86%		18	100%		15	100%		16	80%		15	100%		76	93%
	Stirrups - Single		12	86%		18	100%		15	100%		16	80%		15	100%		76	93%
	Reinf. Zones		14	100%		16	89%		15	100%		20	100%		13	87%		78	95%
Columns	Long. Reinf.	10	10	100%	12	12	100%	12	12	100%	16	16	100%	10	10	100%	60	60	100%
	Ties - Shape		8	80%		12	100%		12	100%		14	88%		9	90%		55	92%
	Ties - Single		8	80%		12	100%		12	100%		14	88%		9	90%		55	92%
	Reinf. Zones		10	100%		9	75%		12	100%		15	94%		10	100%		56	93%
Walls	Long. Reinf. B.E.	8	6	75%	4	4	100%	10	8	80%	4	4	100%	8	8	100%	34	30	88%
	Ties - Shape B.E.		6	75%		4	100%		8	80%		4	100%		8	100%		30	88%
	Ties - Single B.E.		8	100%		4	100%		10	100%		4	100%		8	100%		34	100%
	Wall Reinf.		8	100%		4	100%		10	100%		4	100%		6	75%		32	94%
Slabs	Reinf. Direction	6	6	100%	10	10	100%	8	8	100%	12	10	83%	6	6	100%	42	40	95%
	Unif. Reinf.		6	100%		10	100%		8	100%		12	100%		6	100%		42	100%
	Add. Reinf.		6	100%		8	80%		8	100%		8	67%		6	100%		36	86%
	Col. Zones		6	100%		8	80%		8	100%		8	67%		6	100%		36	86%
Spread Footing	Top. Reinf.	10	10	100%	12	12	100%	0	0	0%	16	16	100%	0	0	0%	38	38	100%
	Bottom Reinf.		10	100%		12	100%		0	0%		16	100%		0	0%		38	100%
Strip Footing	Top. Reinf.	8	8	100%	4	4	100%	10	10	100%	4	4	100%	8	8	100%	34	34	100%
	Bottom Reinf.		8	100%		4	100%		10	100%		4	100%		8	100%		34	100%
Pile Cap	Top. Reinf.	0	0	0%	0	0	0%	12	12	100%	0	0	0%	10	10	100%	22	22	100%
	Bottom Reinf.		0	0%		0	0%		12	100%		0	0%		10	100%		22	100%
	Ties		0	0%		0	0%		10	83%		0	0%		10	100%		20	91%
Piles	Long. Reinf.	0	0	0%	0	0	0%	12	12	100%	0	0	0%	10	10	100%	22	22	100%
	Ties		0	0%		0	0%		12	100%		0	0%		10	100%		22	100%
	Reinf. Zones		0	0%		0	0%		12	100%		0	0%		10	100%		22	100%

5.1.2 Concrete Mix and Construction Coordination Information

Since for the exchange of material and construction related information the challenge is on representation and not on parametrization, the properties defined for the exchange of information regarding the concrete mix and construction coordination are not intended to be exhaustive, but rather a representation of typical properties for the purpose of having them available during the development of implementation methods and testing. A comprehensive list of the properties required for these exchanges requires the participation of multiple professionals with broad experience in the construction industry, and it is currently being produced by the ACI Committee 131.

The parameters identified as key for this scope are shown in **Table 10** and can be grouped under three categories: Concrete mix information, concrete pour logistics information, and temporary structures information. At any point during the implementation these groups can be modified, or properties can be added, to include more complex or comprehensive information. These parameters were selected since they were all present in the documents reviewed as part of the specifications for design or construction. Since concrete information is typically communicated by the structural engineer as part of the design intent as well, this group of properties is also considered as part of the design intent exchange.

Table 10. Parameters Obtained for Concrete Mix and Construction Logistics

Group	Parameter	Description	Example
Concrete Mix	Mix Identifier	Unique identifier of the concrete mix	Mix A
	Strength	Mix design strength in psi	4000
	Strength Age	Day at which the mix design strength is expected	28
	Min E	Elasticity mudulus in psi	4400
	Cement Type	Type of cement	Portland I
	Aggregate Type	Type of aggregate (normal, lightweight)	Normal
	Slump	Mix slump in inches	2"
	Max Aggregate Size	Maximum size of aggregate in inches	1"
	W/C Ratio	Water/cement ratio limit	0.45
	Durability Requirements	Requirements for durability and protection	Corrosion Protection
Concrete Pour Logistics	Activity ID	Unique identifier of the pour	CT002 - Footings
	Start Date	Planned start date of the activity	8/25/2022
	End Date	Planned end date of the activity	8/30/2022
	Duration	Expected duration of the activity	5 days
	Crew	Code of the crew assigned to the task	B-33F
	Equipment	Code of the equipment assigned to the task	E-02
	Method	Placement method	Pump
	Vibration	Vibration method	Standard External
Temporary Structures	Form Type	Material and type of formwork required	Timber- Standard
	Form Weight	Weight per LF or SF of the formwork specified	10 lb/SF
	Shoring	Material, section and spacing of shoring required	Timber - 2"x4"@ 2'
	Walkways	Width/specification of walkway required	Timber - 3'

For the Construction Coordination exchange the ACI approach is to create “Pour Objects”. A Pour Object is an aggregation of elements, or parts of them, that are poured (grouped) altogether as part of the same pour activity. This group can be assigned properties and behaviors that would be inefficient to assign to each object individually, but there are challenges with its representation and the process to add the properties. The implementation methods tackle both. When only a part of an element is considered to be grouped as part of a certain pour object, then a proxy element that holds that part of the geometry is created. **Figure 34** shows the proposed data structure to relate the parts of the element to the whole.

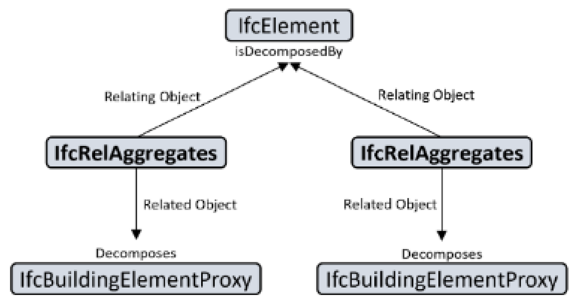


Figure 34. Proposed data structure for split objects using proxys

The geometry of each part is defined within the proxy element, and the geometry of the element as a whole is the sum of the geometries of the proxy elements. The geometry is defined through the "Representation" attribute inherited from IfcProduct and using IfcProductRepresentation. The properties of the element itself are defined in the entity IfcElement to provide consistency with the element type. An example of the grouping using parts of an element is shown in **Figure 35**. In case only part of an element belongs to the Pour Object, then only the proxy element that is part of that pour is associated. **Figure 36** graphically illustrates how the elements would look like in a real-object situation. Only the left side of the slab belongs to the pour. Therefore, the proxy element that represents the left part of the slab is the one that is associated to the Pour Object. Since a group does not have semantic meaning, the semantics and geometry are still within every object that is part of the Pour Object. However, the standard properties for the pour or work package can be associated with the group and either preserved as part of it or propagated to all of its elements.

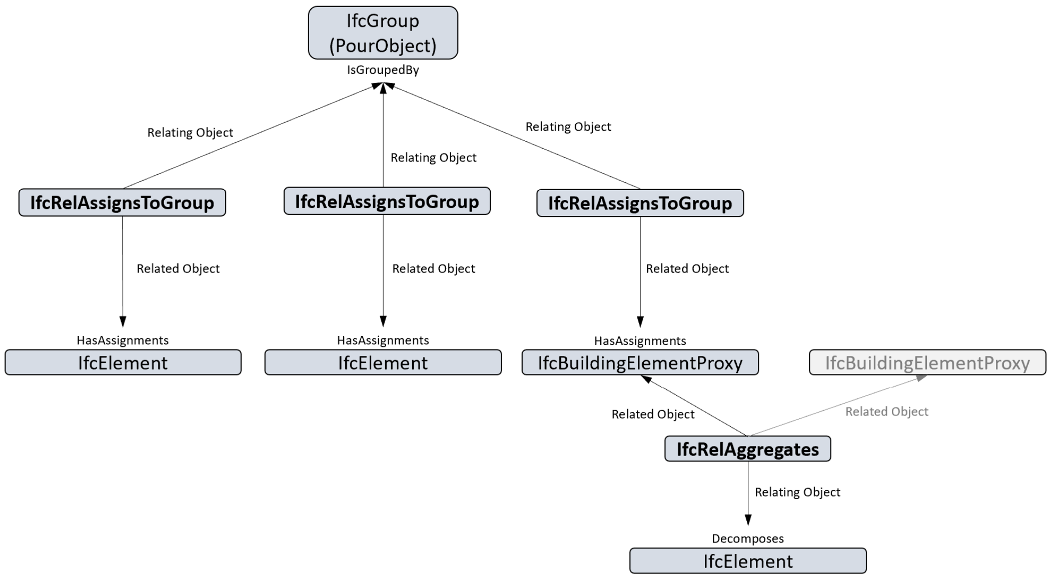


Figure 35. Proposed data structure for pour objects

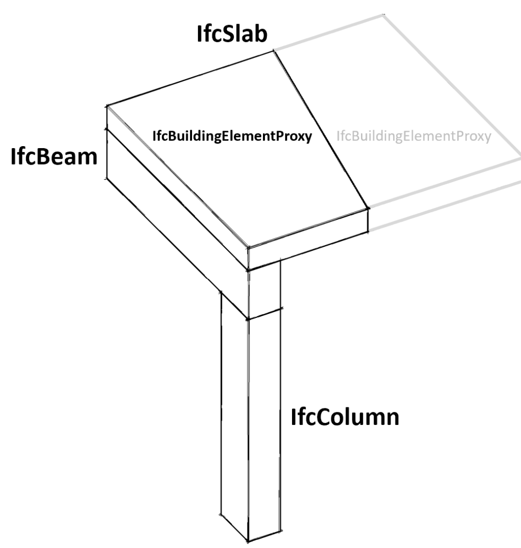


Figure 36. Example of pour object with split element

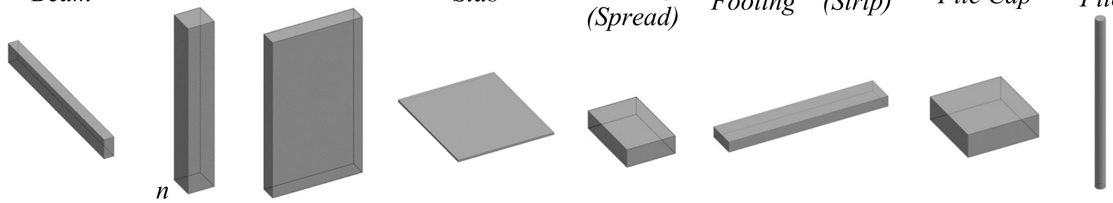
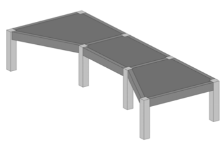
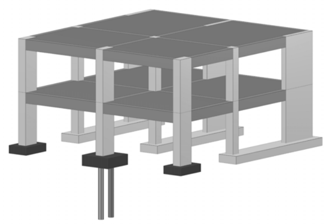
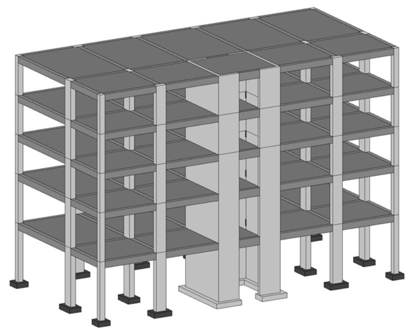
5.2 Implementation Methods

This section of the dissertation presents the implementation methods developed to take the exchange standards to practice, after studying the applicability and requirements. These implementation methods may be used both as guidelines for stakeholders to use as part of their processes, and as a reference on how these guidelines could be developed for further interoperability and standardization efforts. This subchapter first presents the testing models used during the development of the implementation methods, and then proceeds to present the methods for each exchange and an illustration of how the implementation works for one of the models tested.

5.2.1 Testing Models

After each implementation method is explained, the dissertation presents the results of some of the tests performed to ensure the applicability of them on current tools as well as providing an example of how they could be implemented. **Table 11** shows the models used for testing of the implementation methods, with increasing levels of complexity that which allowed the progressive identification and resolution of challenges. To serve as an example for future use, the overall testing results and implementations are shown for the level 3 model, since this model included all the elements considered within the scope of the study.

Table 11. Models Used for Implementation Testing

<table>
<tr><th colspan="8">Level 1 Models</th></tr>
<tr><td>Beam</td><td>Colum n</td><td>Wall</td><td>Slab</td><td>Footing (Spread)</td><td>Footing (Strip)</td><td>Pile Cap</td><td>Pile</td></tr>
<tr><td colspan="8"></td></tr>
<tr><th>Level 2 Model</th><th colspan="3">Level 3 Model</th><th colspan="4">Level 4 Model</th></tr>
<tr><td></td><td colspan="3"></td><td colspan="4"></td></tr>
</table>

5.2.2 Structural Design Intent Exchange

This section presents the implementation methods, testing and examples for the structural design intent exchange.

5.2.2.1 Implementation Methods

The implementation method to communicate and use the structural design intent is shown in **Figure 37**. The method considers a preparation phase, tasks on the exporting side, tasks on the importing side, and a testing phase. Most of the tasks may be performed either through advanced plug-ins and programs for interested parties with advanced IT capabilities, or through simplified methods.

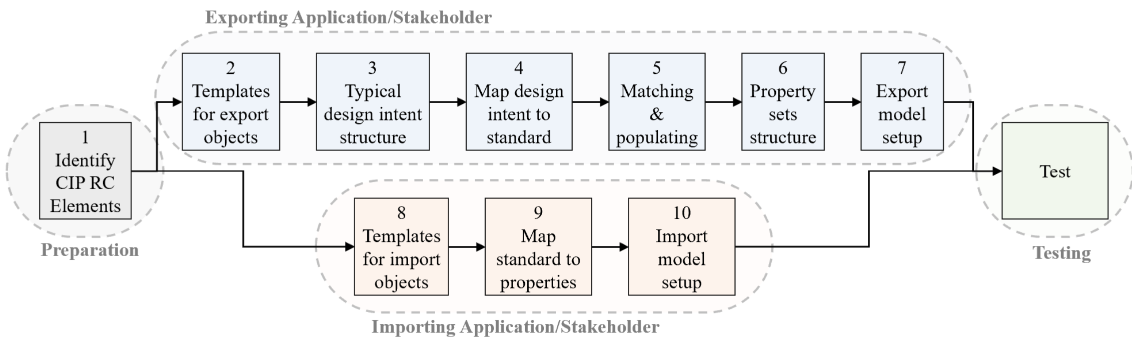


Figure 37. Implementation method for design intent exchange

1. Identify the CIP RC elements that should be included in the standard exchanges. It may be all the elements included in the standard, or just the ones the implementing party is interested on.
2. In the modeling BIM tool, create model templates for each of the CIP RC elements, which include the new standard properties. When modeling a new structure, these templates will be used when creating a corresponding CIP RC element.
3. Gather typical design intent results or schedules for each CIP RC element, and identify the typical structure of the information as it comes from the design phase.
4. Create a template/code/spreadsheet to map the typical information structure for each of the CIP RC elements as it comes from the design phase to the standard properties for each of the elements.
5. Implement a matching and populating algorithm to populate the parametrized design intent information in the corresponding model objects. The matching can be done using a specific property of the model object, or through the "Type Mark" property proposed. The process may be achieved using a guide for manual input, through a plug-in, or through intermediate platforms provided by the tool.
6. Define the property sets for IFC export. The following property sets are recommended:

- PropSet_DI_Beam (Applicable to beams)
- PropSet_DI_Column (Applicable to columns)
- PropSet_DI_Wall (Applicable to walls)
- PropSet_DI_Slab (Applicable to slabs)
- PropSet_DI_Footing-Spread (Applicable to spread footings)
- PropSet_DI_Footing-Strip (Applicable to strip footings)
- PropSet_DI_PileCap (Applicable to pile caps)
- PropSet_DI_Pile (Applicable to piles)
- PropSet_DI_ConcreteMix (Applicable to all elements)

7. Set up the IFC file export by assigning the properties to the corresponding property set to be exported.
8. In the importing BIM tool, create model templates for each of the CIP RC elements, which include the new standard properties.
9. Map the standard properties to native tool properties as required depending on the application of the importing tool. This parsing may be done directly inside of the tool, through a plug-in, or through a mapping template applied after import.
10. Set up the IFC file import and population of the properties for each CIP RC element accordingly

Finally, this process should be tested using existing projects where the imported and exported results are known and can be used for comparison.

5.2.2.2 Testing - Example

All the level 1 to level 4 models were tested following the implementation and usage procedures. Since the level 3 model includes all the CIP RC elements under the scope of the dissertation, this section illustrates the entire process for this model to be used as an example for future implementations. **Figure 38** shows the 3D model, while **Figure 39** and

Figure 40 show the structural floorplans. The elements were designed for average occupancy loads and a moderate seismic hazard zone.

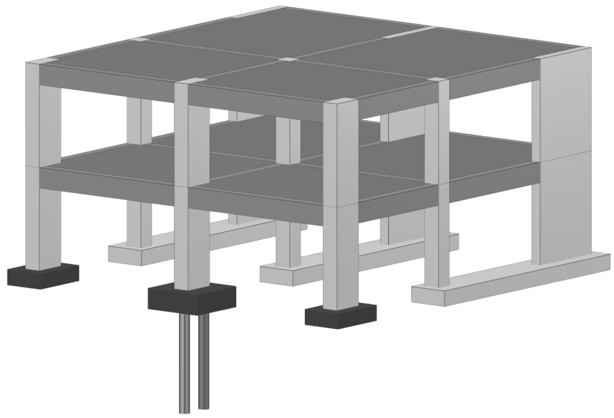


Figure 38. 3D view of level 3 model

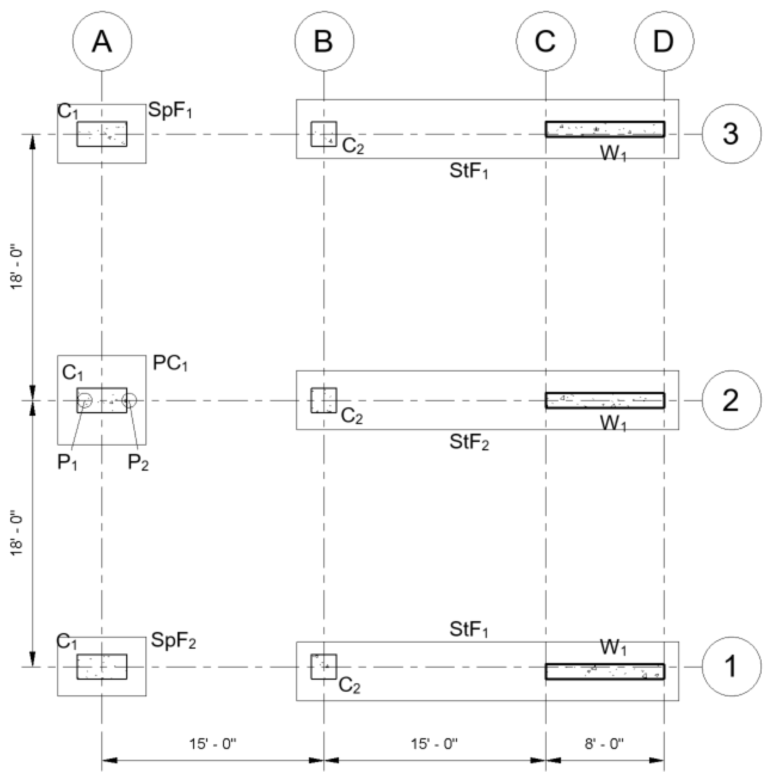


Figure 39. First floor structural plan for level 3 model

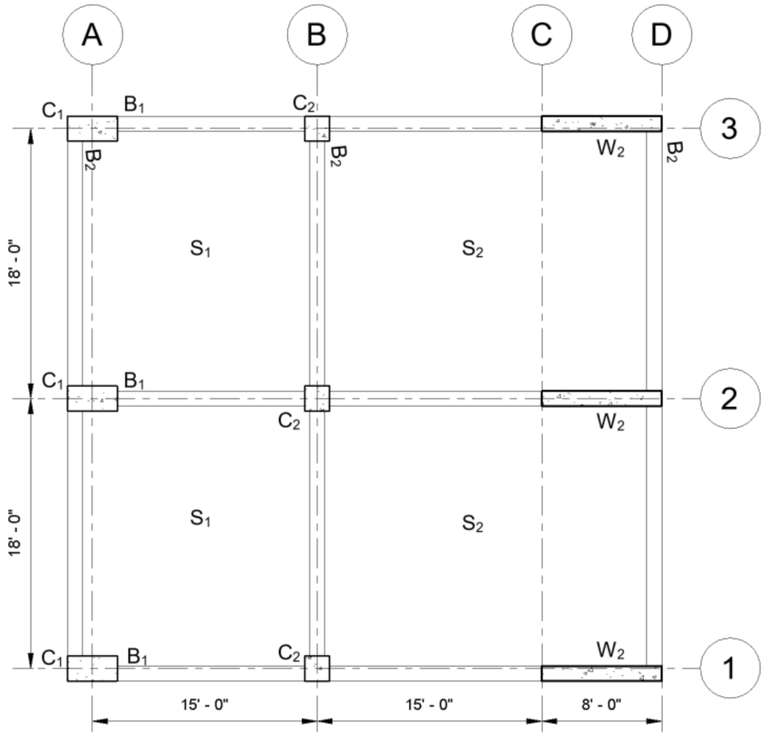


Figure 40. Second floor structural plan for level 3 model

Each of the tasks performed in this test indicates the step number on the proposed implementation method. The test considered all the objects defined for level 1 (step 1). Templates that included all the defined standard properties to communicate the design intent (reinforcement and concrete mix information) were created for each of the objects (step 2). **Figure 41** shows an example of the template created for beams. The selected modeling tool is Autodesk Revit, given that it is one of the most used tools for BIM modeling of CIP RC structures.

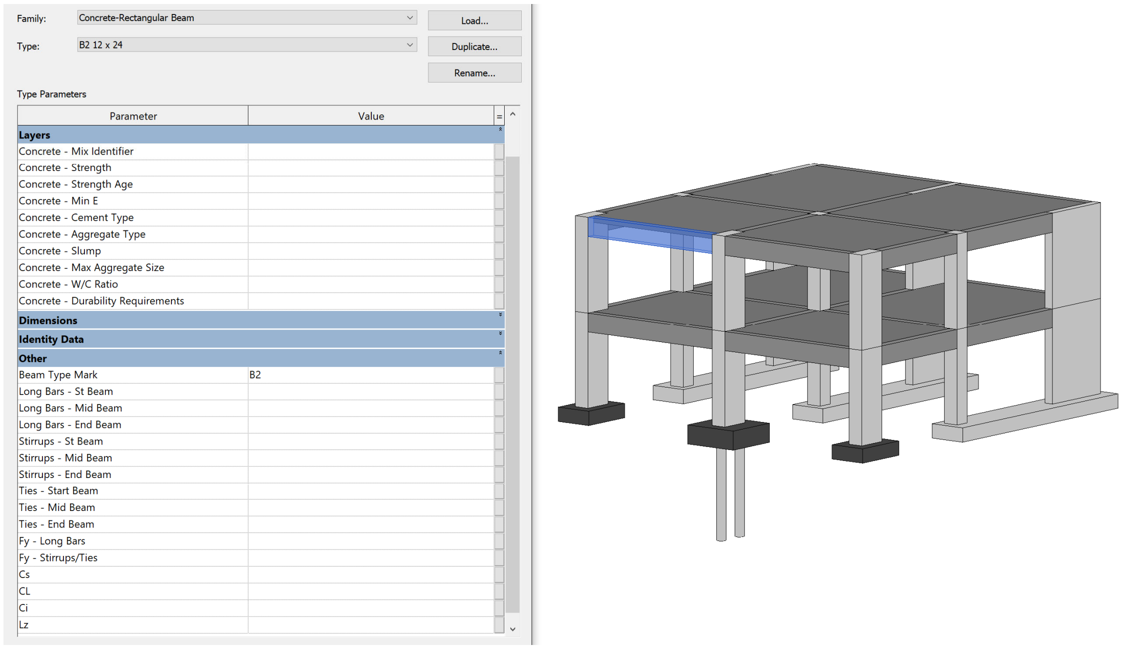


Figure 41. Template for beam design intent including standard properties

A spreadsheet was developed to input the design intent information for each of the CIP RC elements as it comes from the design phase (step 3) and to automatically convert it into the defined standard structure for the parameters, depending on the specific CIP RC element (step 4). **Figure 42** shows the sheet for beams, with all the design result variables that could be parametrized, and the resulting parametrized values. The sheet allows the user to define the spacing of the reinforcement, or if no value is provided automatically spreads the reinforcement in the width of the section. The concrete mix is selected from a list generated from a database that includes all the concrete mixes specified for the project. Each of the sections specified is stored to be loaded later into de model. The mapping between the properties and the model elements is done through the "Type Mark" parameter, so this is the only value that will need to be populated in the model by the designer to be able to perform the property mapping. **Appendix D** presents the templates used for each of the CIP RC elements.

Beam	
Type Mark	B2
Concrete Mix	C-28-Beam-A
Width	300
Height	600
Length	5500
Top Cover	40
Side Cover	40
Bottom Cover	40
Left Zone Length	800
Right Zone Length	800
Fy Long Bars	420
Fy Stirrups & Ties	420

Store Type

Stirrups								Parameters
	Diameter	Number	Width (Auto)	Width (Input)	Width	Separation		
Start Beam	3	1	220		220	150		1#3-220-150
Middle Beam	3	1	220		220	300		1#3-220-300
End Beam	3	1	220		220	150		1#3-220-150
Ties								
	Diameter	Number	Separation					
Start Beam	3	1	150					1#3-150
Middle Beam	3	1	300					1#3-300
End Beam	3	1	150					1#3-150
Top Reinforcement								
	Diameter	Number	d'	Spacing (Input)	First (Input)	Spacing	First Bar	
Start Beam	5	3	57			93	57	3#5-543-93-57
						-201	50	0
Middle Beam	5	2	57			185	57	2#5-543-185-57
						-201	50	0
End Beam	5	3	57			93	57	3#5-543-93-57
						-201	50	0
Middle Reinforcement								
	Diameter	Number	d	Spacing (Input)	First (Input)	Spacing	First Bar	
Start Beam	4	2	300			188	56	2#4-300-188-56
						-201	50	0
Middle Beam	4	2	300			188	56	2#4-300-188-56
						-201	50	0
End Beam	4	2	300			188	56	2#4-300-188-56
						-201	50	0
Bottom Reinforcement								
	Diameter	Number	d	Spacing (Input)	First (Input)	Spacing	First Bar	
Start Beam	5	2	57			185	57	2#5-57-185-57
						-201	50	0
Middle Beam	5	4	57			62	57	4#5-57-62-57
						-201	50	0
End Beam	5	2	57			185	57	2#5-57-185-57
						-201	50	0

Concrete Mix Parameters	
Concrete Mix Row Location	2
Concrete - Mix Identifier	C-28-Beam-A
Concrete - Strength	4000
Concrete - Strength Age	28
Concrete - Min E	4350
Concrete - Cement Type	Portland I
Concrete - Aggregate Type	Normal
Concrete - Slump	2"
Concrete - Max Aggregate Size	1"
Concrete - W/C Ratio	0.45
Concrete - Durability Requirements	N/A

Long Bars - St Beam	3#6-541-91-59,2#4-300-188-56,2#6-59-182-59
Long Bars - Mid Beam	2#6-541-182-59,2#4-300-188-56,4#6-59-61-59
Long Bars - End Beam	3#6-541-91-59,2#4-300-188-56,2#6-59-182-59
Stirrups - St Beam	1#3-220-100
Stirrups - Mid Beam	1#3-220-200
Stirrups - End Beam	1#3-220-100
Ties - Start Beam	1#3-100
Ties - Mid Beam	1#3-200
Ties - End Beam	1#3-100
Fy - Long Bars	420
Fy - Stirrups/Ties	420
Cs	40
CL	40
Ci	40
Lz	800,3900,800
Beam Type Mark	B1
Concrete - Mix Identifier	C-28-Beam-A
Concrete - Strength	4000
Concrete - Strength Age	28
Concrete - Min E	4350
Concrete - Cement Type	Portland I
Concrete - Aggregate Type	Normal
Concrete - Slump	2"
Concrete - Max Aggregate Size	1"
Concrete - W/C Ratio	0.45
Concrete - Durability Requirements	N/A
Long Bars - St Beam	3#5-543-93-57,2#4-300-188-56,2#5-57-185-57
Long Bars - Mid Beam	2#5-543-185-57,2#4-300-188-56,4#5-57-62-57
Long Bars - End Beam	3#5-543-93-57,2#4-300-188-56,2#5-57-185-57
Stirrups - St Beam	1#3-220-150
Stirrups - Mid Beam	1#3-220-300
Stirrups - End Beam	1#3-220-150
Ties - Start Beam	1#3-150
Ties - Mid Beam	1#3-300
Ties - End Beam	1#3-150
Fy - Long Bars	420
Fy - Stirrups/Ties	420
Cs	40
CL	40
Ci	40
Lz	800,3900,800
Beam Type Mark	B2
Concrete - Mix Identifier	C-28-Beam-A
Concrete - Strength	4000
Concrete - Strength Age	28
Concrete - Min E	4350
Concrete - Cement Type	Portland I
Concrete - Aggregate Type	Normal
Concrete - Slump	2"
Concrete - Max Aggregate Size	1"
Concrete - W/C Ratio	0.45
Concrete - Durability Requirements	N/A

Figure 42. Template to convert the beam design intent into standard parameters

To automatically map the properties to the corresponding elements inside of Revit, a Dynamo code was created (step 5). The matching criteria is the "Type Mark" Parameter, previously populated inside each model element in Revit. **Figure 43** shows a screenshot of the dynamo code, with zoomed views of the data import part and of the processing code for beams. **Appendix E** presents the codes to map all the CIP RC objects considered. All properties are assigned to the type, except for the slabs, since for these elements it is more practical to map at an instance level. **Figure 44** shows a beam in the model after the information has been populated using the algorithm developed.

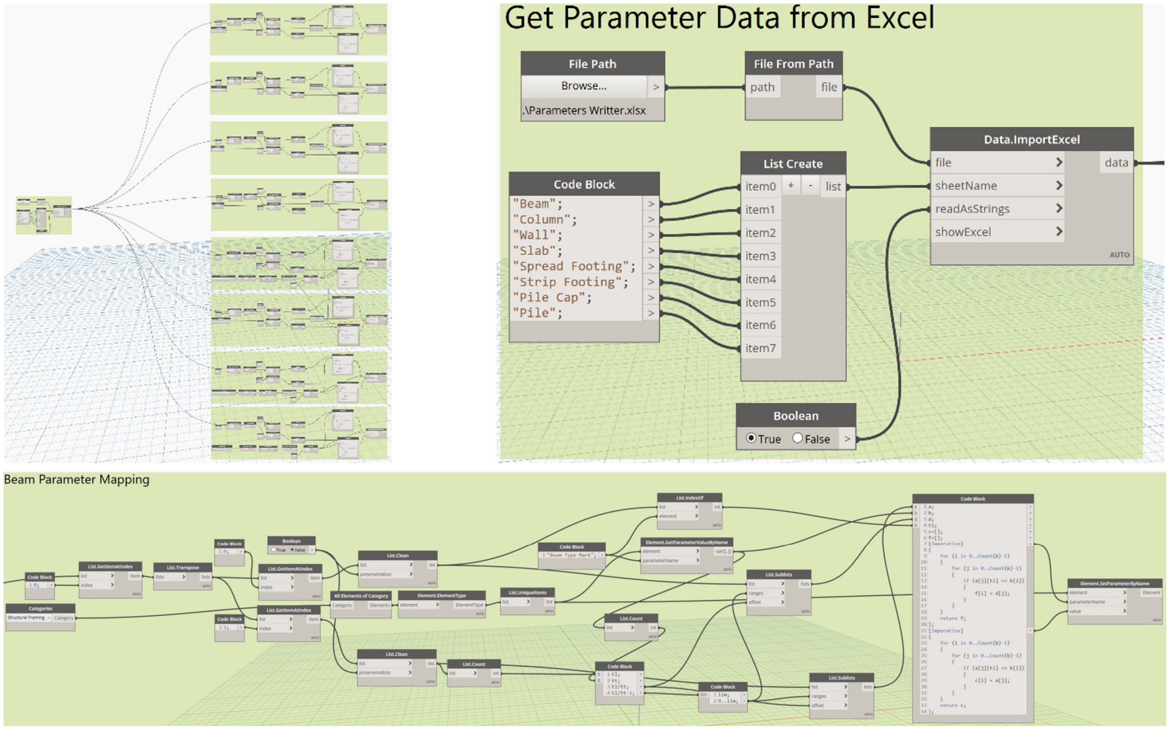


Figure 43. Matching and data filling code for properties

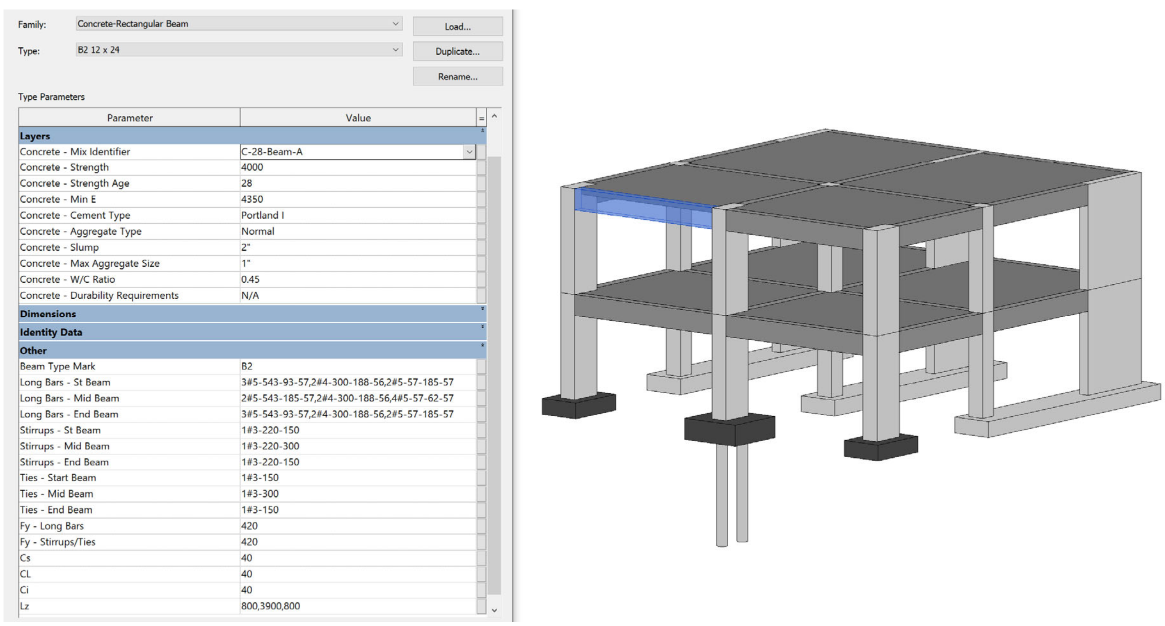


Figure 44. Beam object after mapping and populating algorithm

The next step was to define the property sets (step 6) and set up the export in the tool (step 7). **Figure 45** shows the set up of the property sets for the slab export of the design intent and the concrete mix.

```
#
PropertySet:	Pset_Pile_DI	T	IfcSlabType
	Long Bars - Top Pile - Pi	Text
	Long Bars - Mid Pile - Pi	Text
	Long Bars - Bottom Pile - Pi	Text
	Stirrups - Top Pile - Pi	Text
	Stirrups - Mid Pile - Pi	Text
	Stirrups - Bot Pile - Pi	Text
	Fy - Long Bars - Pi	Text
	Fy - Stirrups - Pi	Text
	Cs - Pi Text
	Lz - Pi Text
	Pile Type Mark	Text

#
#
PropertySet:	Pset_ConcreteMix_DI	T	IfcBeamType,IfcColumnType,IfcWallType,IfcFootingType,IfcSlabType
	Concrete - Mix Identifier	Text
	Concrete - Strength	Text
	Concrete - Strength Age Text
	Concrete - Min E	Text
	Concrete - Cement Type	Text
	Concrete - Aggregate Type	Text
	Concrete - Slump	Text
	Concrete - Max Aggregate Size	Text
	Concrete - W/C Ratio	Text
	Concrete - Durability Requirements	Text

#
```

Figure 45. Property sets set up for slab rebar design intent and concrete mix

To test if the properties were being exported properly and could be imported by a receiving application, the model was imported into an IFC visualization tool where the mapping between property sets and object properties was implemented (steps 8 to 10). **Figure 46** shows the beam properties after the model has been imported into a receiving application. The mapping and matching process was done using a similar set up as the one shown in **Figure 45**.

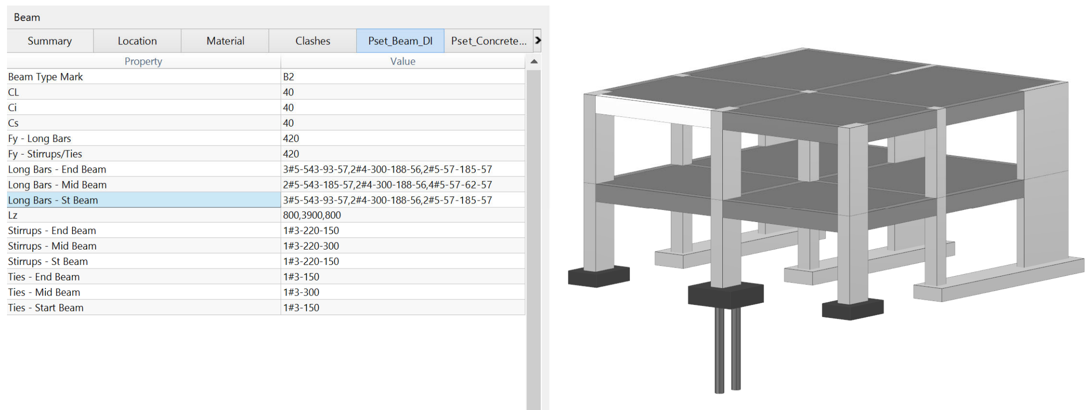


Figure 46. Visualization of properties after import in receiving tool

5.2.3 Construction Coordination Exchange

This section presents the implementation methods, testing and examples for the construction coordination exchange.

5.2.3.1 <u>Implementation Methods</u>

The implementation method to communicate and use the construction coordination information is shown in **Figure 47**. The method considers a preparation phase, tasks on the exporting side, tasks on the importing side, and a testing phase. Most of the tasks may be performed either through advanced plug-ins and programs for interested parties with advanced IT capabilities, or through simplified methods. To implement this method an important decision needs to be made regarding where the construction coordination information will be stored in the application. Some tools will not allow properties to be added to groups, and some tools will not allow grouping elements or parts of elements. Therefore some time it will be possible to map the properties directly to the group, while sometimes it will be required to map the properties to the elements or parts that belong to the activity, and implement an association/visualization algorithm.

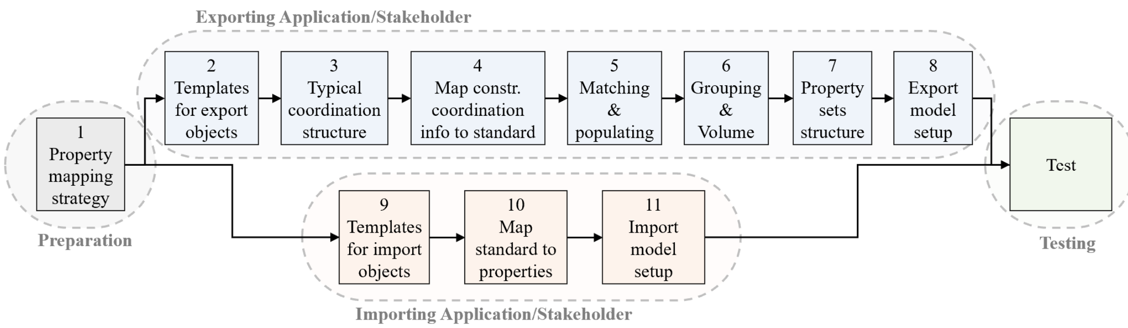


Figure 47. Implementation method for coordination planning exchange

1. Based on the exporting tool capabilities, select whether the properties will be mapped directly to the group, or to the elements or parts that belong to the group while implementing an association/visualization algorithm.
2. If the properties will be mapped to the elements that belong to the work package, in the modeling BIM tool create model templates that include the new standard properties in each of the CIP RC elements. If the properties will be mapped directly to the groups, in the modeling BIM tool create a model template for the pour groups that include the new standard properties. When modeling a new structure, these templates will be used when creating a corresponding CIP RC elements or groups.
3. Gather typical logistics, coordination and material information for CIP RC, and identify the typical structure of the information as it comes from the coordination phase.
4. Create a template/code/spreadsheet to map the typical information structure for the work packages as it comes from the coordination phase to the standard properties for the group.
5. Implement a matching and populating algorithm to populate the parametrized construction coordination information in the corresponding model objects or groups, depending on the approach taken. The matching can be done using a specific property

of the model object or group, or through the "Concrete Pour ID" property proposed. The process may be achieved using a guide for manual input, through a plug-in, or through intermediate platforms provided by the tool.

6. In case the tool does not allow proper grouping of concrete elements and parts of them, implement a visualization algorithm for particular groups based on a common characteristic or property (such as "Concrete Pour ID"), that includes calculation of the volume of the pour.
7. Define the property sets for IFC export. The following property sets are recommended:
   - PropSet_CM_PourIDInfo
   - PropSet_CM_ConcreteMaterial
   - PropSet_CM_ConcreteSequencing
   - PropSet_CM_ConcreteTemporary
8. Set up the IFC file export by assigning the properties to the corresponding property set to be exported.
9. In the importing BIM tool create model templates for each of the CIP RC elements or the groups depending on the approach, which include the new standard properties.
10. Map the standard properties to native tool properties as required depending on the application of the importing tool. This parsing may be done directly inside of the tool, through a plug-in, or through a mapping template applied after import.
11. Set up the IFC file import and population of the properties for each CIP RC element or groups accordingly.

Finally, this process should be tested using existing projects where the imported and exported results are known and can be used for comparison.

5.2.3.2 Testing - Example

All the level 1 to level 4 models were tested following the implementation and usage procedures. Since the level 3 model includes all the CIP RC elements under the scope of the dissertation, this section illustrates the entire process for this model to be used as an example for future implementations. **Figure 48** shows the concrete pour plan for construction.

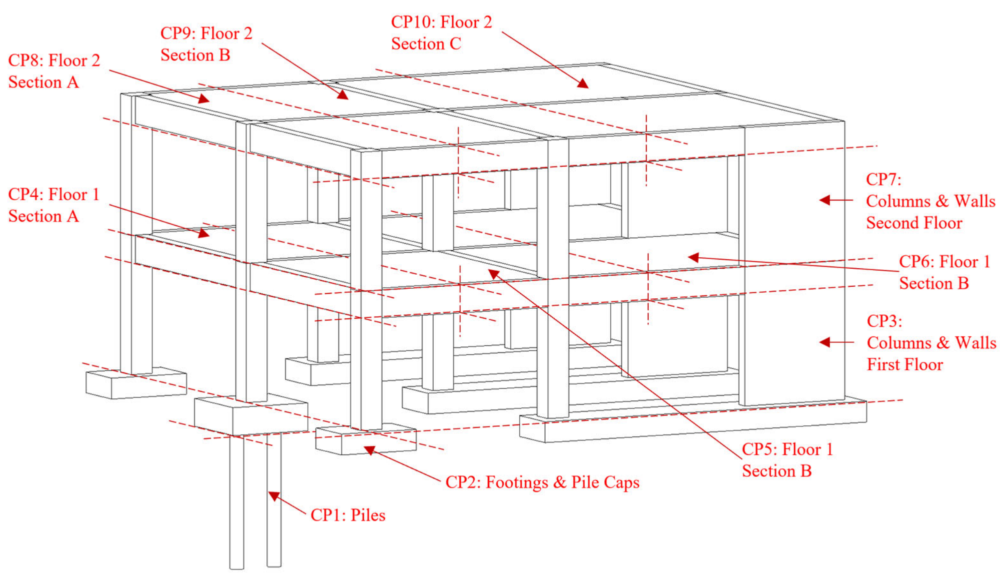


Figure 48. Pour planning for level 4 building

Each of the tasks performed in this test indicates the step number on the proposed implementation method. Since for the purpose of this exchange it is more complex to use a tool that does not allow grouping, the implementation selected is for such a case (step 1). Since in this scenario all the objects will have new properties, corresponding to the construction planning information, the same new properties were added to all CIP RC elements and this was implemented as a project template (step 2). **Figure 49** shows the properties assigned to all the model objects. The model has already broken into parts the elements to comply with the pour planning. Similarly, to the previous exchange, the selected modeling tool is Autodesk Revit.

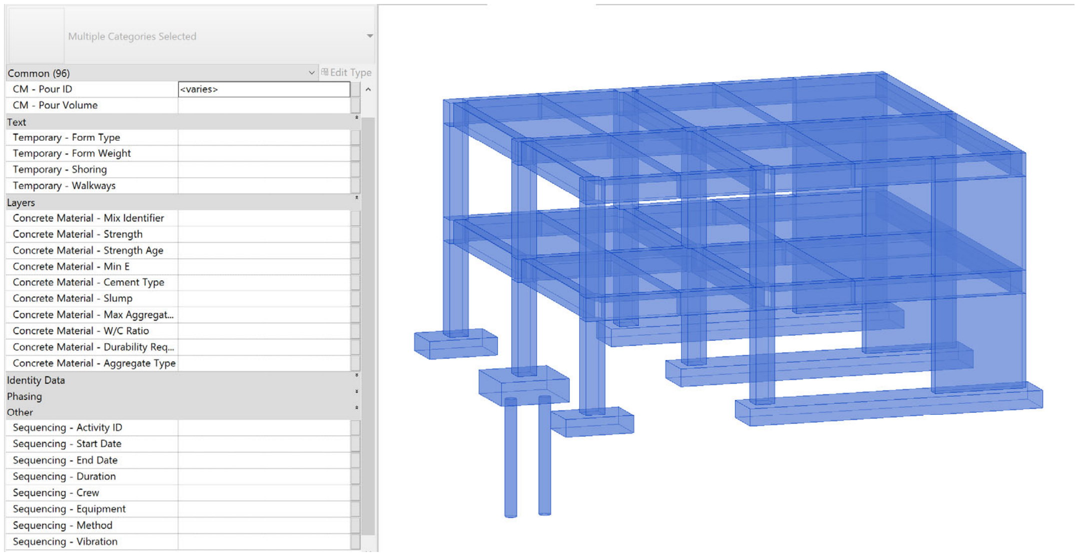


Figure 49. Template for beam including standard properties

A spreadsheet was developed to input the construction planning information (step 3) and to automatically convert it into the defined standard structure for the pour / work package parameter (step 4). **Figure 50** shows the template for the CP06 pour group, with all the properties, classified in the corresponding category. The concrete mix is selected from a list generated from a database that includes all the concrete mixes specified for the project. Each of the pours is stored to be loaded later into de model. The mapping between the properties and the model elements is done through the “Concrete Pour ID” parameter, so this is the only value that will need to be populated in the model by the coordinator to be able to perform the property mapping.

Concrete Pour ID:	CP06	Concrete Mix:	Mix B		
Concrete Pour Material Information		Concrete Pour Construction Logistics		Concrete Pour Temporary Structures	
Mix Identifier	Mix B	Activity ID	CT006 - Slab F1/C	Form Type	Timber- Standard
Strength	4000	Start Date	9/16/2022	Form Weight	10 lb/SF
Strength Age	28	End Date	9/18/2022	Shoring	Timber - 2"x4"@ 2'
Min E	4400	Duration	2 days	Walkways	N/A
Cement Type	Portland I	Crew	B-40		
Aggregate Type	Normal	Equipment	E-02		
Slump	2"	Method	Pump		
Max Aggregate Size	1"	Vibration	Standard External		
W/C Ratio	0.45				
Durability Requirements	N/A				

Figure 50. Template to convert coordination information into standard parameters

To automatically map the properties to the corresponding elements inside of Revit, a Dynamo code was created (step 5) and is shown in **Figure 51**. The matching criteria is the "Concrete Pour ID" parameter, previously populated inside each model element or part in Revit. In the model the planner assigns an object or a part to a pour by filling the "Concrete Pour ID" parameter with the proper pour code, then all the properties of the pour or work package will be populated in this item as part of that group. The next step is to implement the visualization algorithm to be able to visualize a specific group / work package if the tool is not capable of grouping objects or parts of them (step 6). This algorithm should also calculate the volume of the pour, and is shown in **Figure 52**. **Appendix F** presents the codes in a bigger size in case it wants to be implemented. **Figure 53** shows pour activity CP05 in the model after it has been isolated, the volume for the pour calculated, and the information has been populated using the developed algorithm.

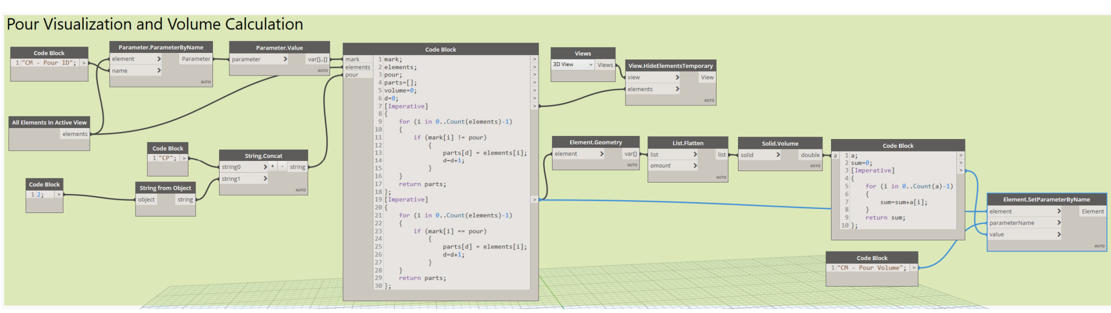


Figure 51. Matching and data filling code for properties

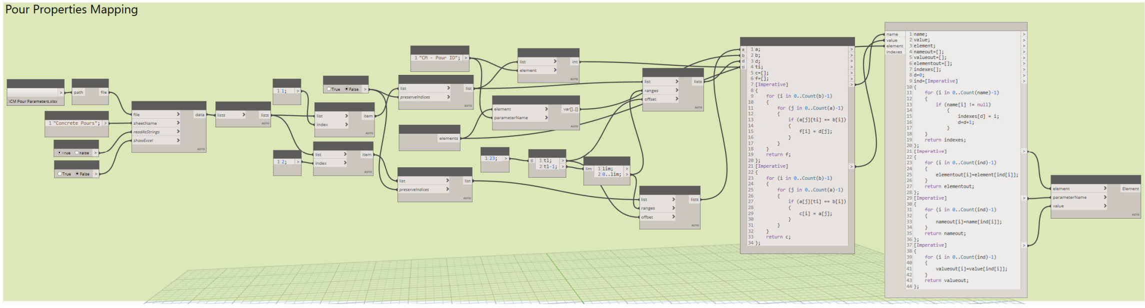


Figure 52. Group/pour visualization and volume calculation code

Common (15)	Edit Type
Set	
CM - Pour ID	CP05
CM - Pour Volume	496.80 CF
Text	
Temporary - Form Type	Timber- Standard
Temporary - Form Weight	10 lb/SF
Temporary - Shoring	Timber - 2"x4"@ 2'
Temporary - Walkways	N/A
Layers	
Concrete Material - Mix Identifier	Mix B
Concrete Material - Strength	4000
Concrete Material - Strength Age	28
Concrete Material - Min E	4400
Concrete Material - Cement Type	Portland I
Concrete Material - Slump	2"
Concrete Material - Max Aggregate ...	1"
Concrete Material - W/C Ratio	0.45
Concrete Material - Durability Requi...	N/A
Concrete Material - Aggregate Type	Normal
Identity Data	
Phasing	
Other	
Sequencing - Activity ID	CT005 - Slab F1/B
Sequencing - Start Date	9/13/2022
Sequencing - End Date	9/15/2022
Sequencing - Duration	2 days
Sequencing - Crew	B-40
Sequencing - Equipment	E-02
Sequencing - Method	Pump
Sequencing - Vibration	Standard External

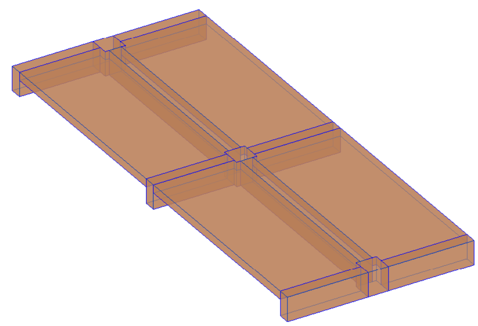


Figure 53. Beam object after mapping and populating algorithm

The next step was to define the property sets (step 7) and set up the export in the tool (step 8). **Figure 54** shows the setup of the property sets for the export of each of the properties.

```
#
PropertySet:    Pset_PourInfo_CM        I       IfcBeam,IfcColumn,IfcWall,IfcFooting,IfcSlab
        CM - Pour ID    Text
        CM - Pour Volume        Text
#
#
PropertySet:    Pset_ConcreteMaterial_CM        I       IfcBeam,IfcColumn,IfcWall,IfcFooting,IfcSlab
        Concrete Material - Mix Identifier      Text
        Concrete Material - Strength    Text
        Concrete Material - Strength Age        Text
        Concrete Material - Min E       Text
        Concrete Material - Cement Type Text
        Concrete Material - Aggregate Type      Text
        Concrete Material - Slump       Text
        Concrete Material - Max Aggregate Size  Text
        Concrete Material - W/C Ratio   Text
        Concrete Material - Durability Requirements     Text
#
#
PropertySet:    Pset_ConcreteSequencing_CM      I       IfcBeam,IfcColumn,IfcWall,IfcFooting,IfcSlab
        Sequencing - Activity ID        Text
        Sequencing - Start Date Text
        Sequencing - End Date   Text
        Sequencing - Duration   Text
        Sequencing - Crew       Text
        Sequencing - Equipment  Text
        Sequencing - Method     Text
        Sequencing - Vibration  Text
#
#
PropertySet:    Pset_ConcreteTemporary_CM       I       IfcBeam,IfcColumn,IfcWall,IfcFooting,IfcSlab
        Temporary - Form Type   Text
        Temporary - Form Weight Text
        Temporary - Shoring     Text
        Temporary - Walkways    Text
#
```

Figure 54. Property sets set up for slab rebar design intent and concrete mix

To test if the properties were being exported properly and could be imported by a receiving application, the model was imported into an IFC visualization tool where the mapping between property sets and object properties was implemented (steps 9 to 11). **Figure 55** shows the sequencing properties after the model has been imported into a receiving application. The mapping and matching process was done using a similar set up as the one shown in **Figure 54**.

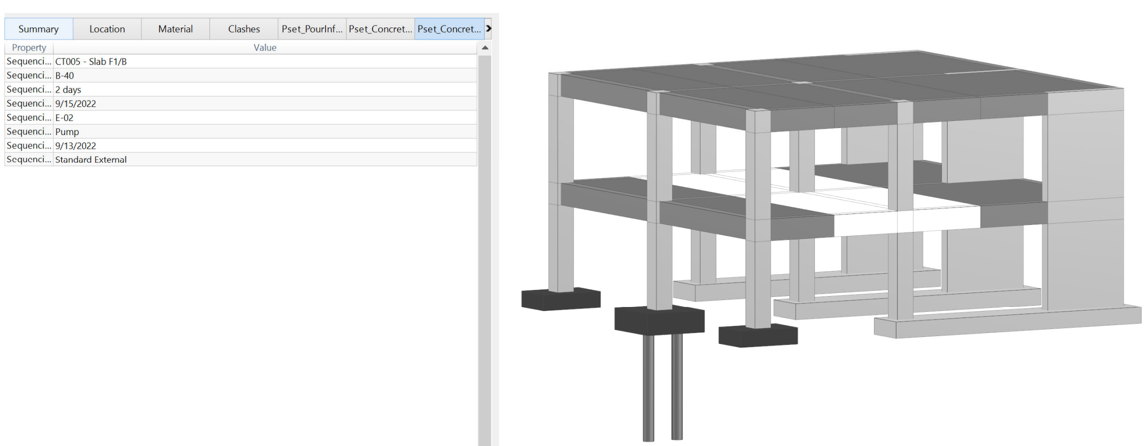


Figure 55. Visualization of properties after import in receiving tool

5.3 Adjusted Process with Exchange Standards

An important part of the ethnographic-action research methodology is for the researcher to have the opportunity to perform tasks proper of the processes observed. This approach is used here to compare traditional exchange processes that use BIM technologies but do not use exchange standards, with processes that use implemented exchange standards, in order to gain an insight into the value considerations. To do so, a model based on a section of one of the projects studied during the ethnographic observations is developed in Revit and shown in **Figure 56**. While not identical for confidentiality reasons, the model resembles a section of the building regarding its dimensions, element sections, and overall distribution. Furthermore, since the design process itself is not affected, the design results are based on common values for these types of objects. Since post-tensioned (PT) elements are outside of the scope of this research, the PT beams from the original project are assumed as normal CIP RC beams. For each exchange, the usage workflow of standard exchanges is presented, and is developed based on the implementation methods, the ethnographic study findings, and the workflows mapped from the studied company.

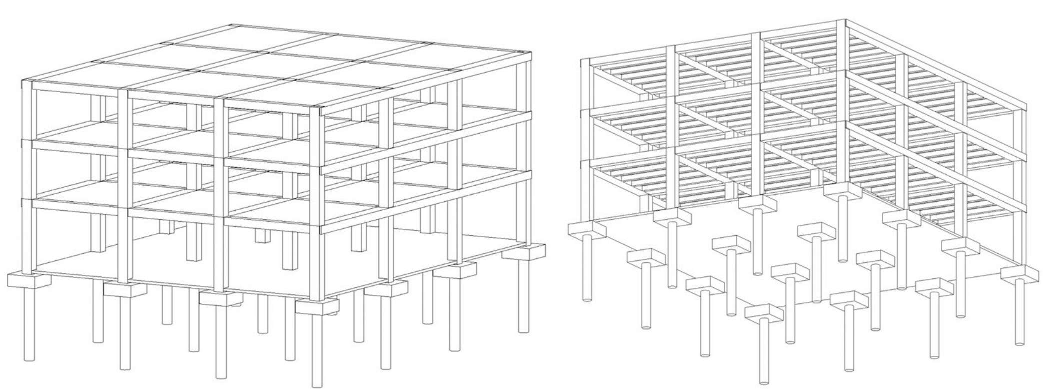


Figure 56. Adapted model section from project observed

5.3.1 *Structural Design Intent Exchange*

5.3.1.1 Usage Procedure

Once the standard has been implemented, **Figure 57** illustrates how the workflow may look like when exchanging the design intent to be used by another tool or stakeholder. This procedure would be applicable whether the exchange is implemented at a company level or at tool level once industry wide standards are published. On the exporting side, the main tasks include modeling the structure, designing the concrete elements, and producing the structural design intent, converting the results of the design into the standardized parameters, importing the values into the model, and exporting the model. On the receiving side the tasks involve importing and parsing the model, and subsequently using the information for the purpose of the import, such as detailing, QTO, or coordination.

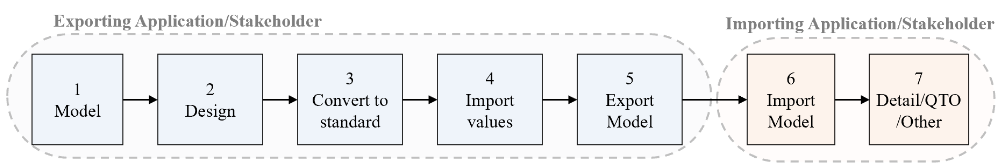


Figure 57. Usage procedure for design intent exchange

5.3.1.2 Adjusted Process in Project Model Section

The first process replicated is the exchange of data using conventional methods of communication, which are schedules. While schedules are likely to remain as part of the process, and be used in case clarifications are needed or specific situations arise, the differences come when the information is parsed, communicated in a standard manner, and used by a receiving application. **Figure 58** shows the structural floorplan with scheduled reinforcement for the members visible in the view, and **Figure 59** shows typical details to reference how the reinforcement is distributed in the cross section. The concrete volume of the model is 1,800 CY. The time required to embed the information and generate the schedules may vary widely based on the degree of automation available. While companies with advanced IT capabilities can do it in minutes with in-house applications, doing it without such advanced IT capabilities may take up to 60 minutes for this sample building.

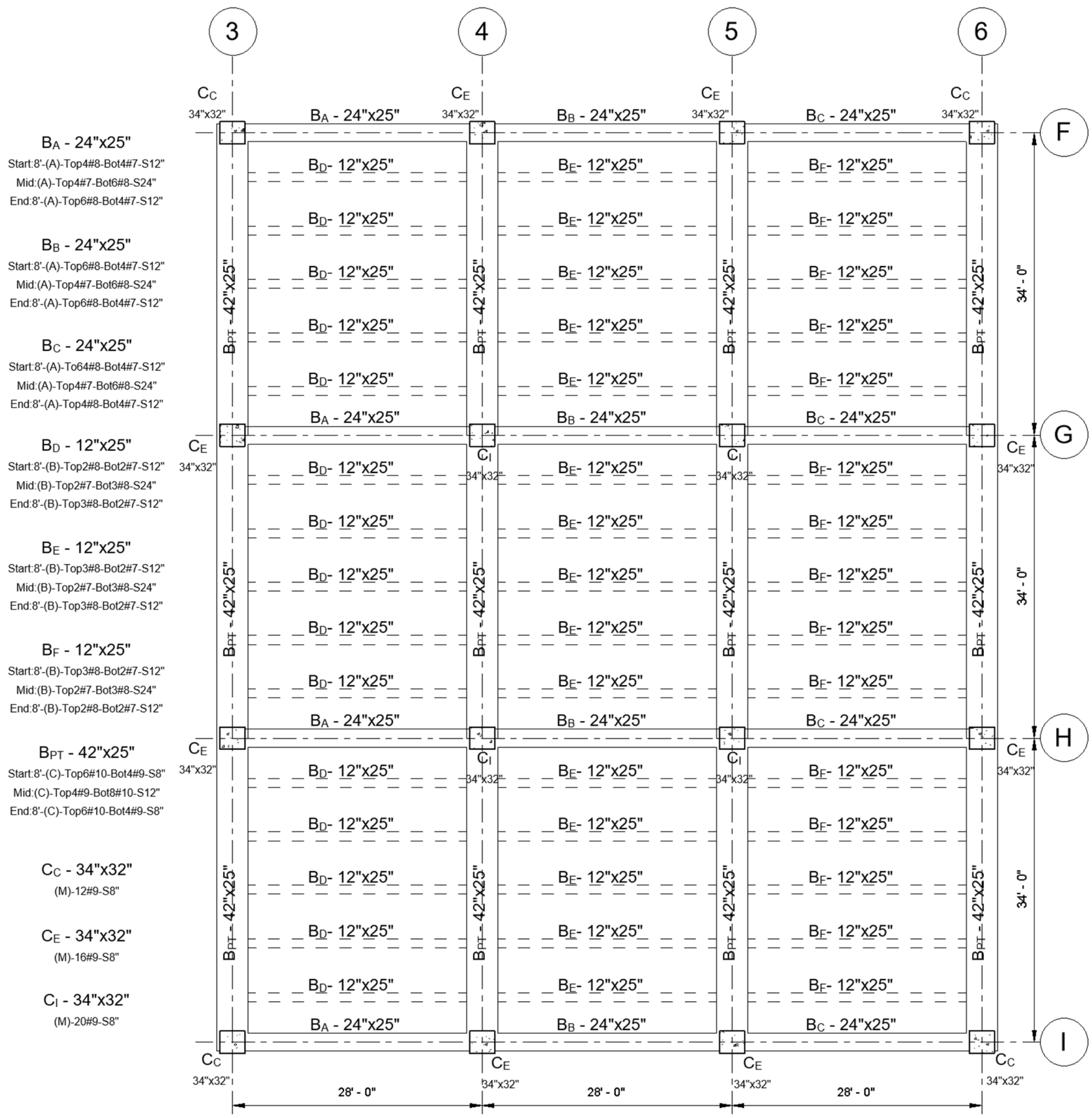


Figure 58. Structural floor plan of model section

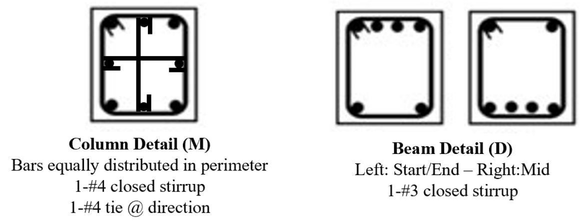


Figure 59. Typical details (M) and (D) in schedule

For the adjusted process, the tools and methods developed in the previous section were used to generate the parameters and populate the values inside the corresponding model elements. Although the translation and population of the parameters did not take more than a couple of minutes with the tools developed, the time it took to develop and implement the translation templates, the population codes, and the family templates should be taken into consideration as an initial implementation and familiarization time investment. **Figure 60** shows the populated parameters for one of the beams in the model.

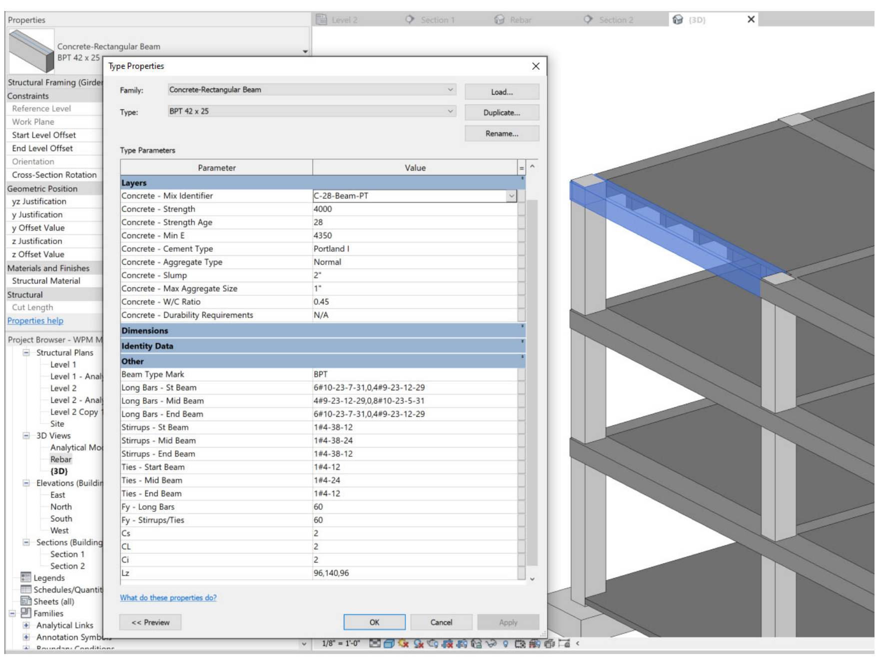


Figure 60. Populated standard parameters for beam element

To recognize the true advantage of using exchange standards, the receiving side of the information also needs to be reproduced. One of the biggest consumers of this model will be the rebar detailer, and on some occasions the general contractor for planning and estimating. Therefore, using a conventional process, the schedules were used to manually model the basic reinforcement of the elements, as shown in **Figure 61** for the third floor. This is not the detailed model, but the initial locations of bars based on which the detailing can take place as shown in the node in **Figure 62**. The time it takes to create this detailing varies considerably, and depends on the modeler's expertise, the degree of automation available in the company, and the tool used. In this case, it took about 80 minutes to create the basic reinforcement for the 1,800 CY of concrete elements. If an early QTO wants to be performed before modeling the rebar and based on the schedules, the rebar has to be read manually and calculated with a spreadsheet or similar tool. Doing this process manually for the 1,800 CY worth of concrete elements took around 30 minutes.

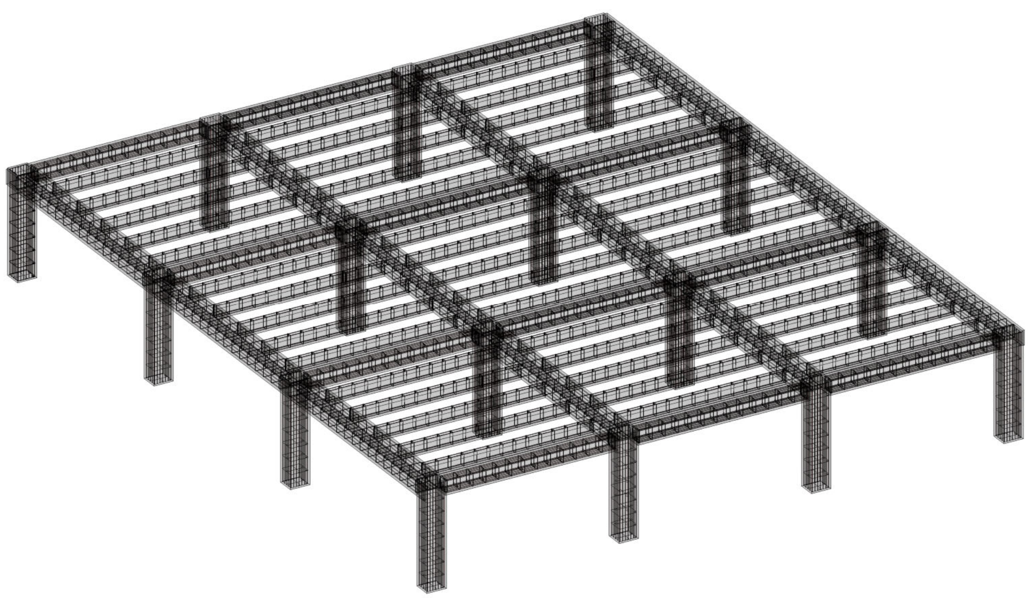


Figure 61. Basic reinforcement model created manually from schedules

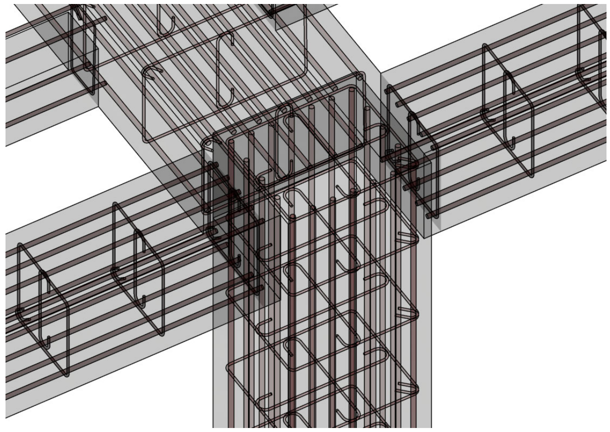


Figure 62. Detailed view of node showing only basic reinforcement

Finally, to understand the value of using exchange standards, the reinforcement model was created again but using the parameters populated inside of the model elements, which hold detailed information about the design intent. To process and leverage this data, a Dynamo code and the DynamoRebar add-on were used to automatically generate basic reinforcement in each element based on the standardized parameters the detailer would get as part of a standardized exchange. **Figure 63** shows the code created for this purpose, and although it took some time to develop and implement, once used in the project it only took a few minutes to create the reinforcement model. Furthermore, the QTO of the reinforcement was performed almost immediately based on the parameters available.

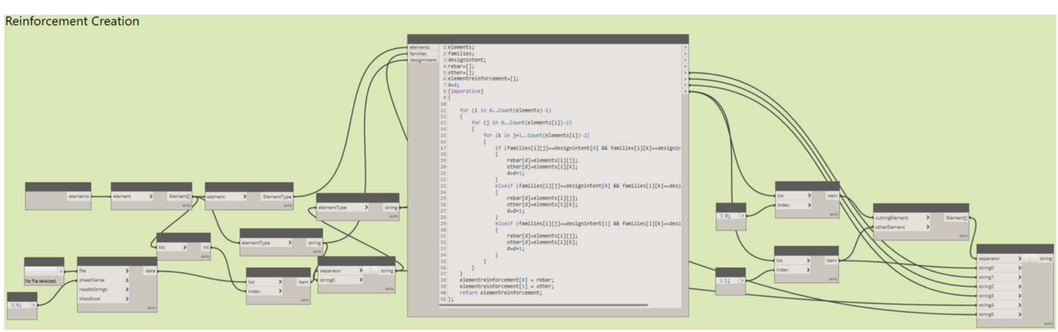


Figure 63. Dynamo code to model reinforcement using standard exchange

5.3.2 *Construction Coordination Exchange*

5.3.2.1 Usage Procedure

Once the standard has been implemented, **Figure 64** illustrates how the workflow may look like when exchanging construction coordination information to be used by another tool or stakeholder. This procedure would be applicable whether the exchange is implemented at a company level or at tool level once industry wide standards are published. On the exporting side, the main tasks include modeling the structure with the breaks or joints, performing the planning and coordination activities, converting the results of the planning into the standardized parameters, importing the values into the model and exporting the model. On the receiving side the tasks involve importing and parsing the model, and subsequently using the information for the purpose of the import, such as coordination, review from the engineer, or modeling and design of the temporary structures.

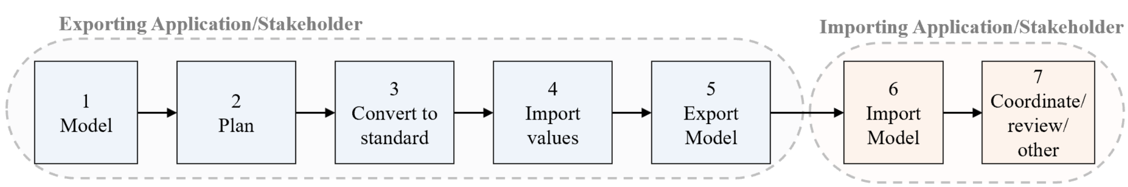
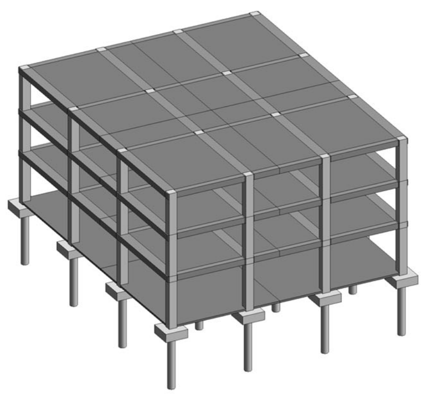


Figure 64. Usage procedure for construction coordination exchange

5.3.2.2 Adjusted Process in Project Model Section

In this case, the first process to replicate is the generation of concrete volumes or pours, in order to communicate information about the geometry, volume and develop coordination efforts. Using a conventional approach, the model is split into pours with the properties assigned, after which coordination information is exported as drawings and tables. **Figure 65** shows the model after being broken into pours, along with the drawings and a sample of the tables produced to communicate coordination information. Setting up this information for the entire building and representing it in this conventional manner took close to 30 minutes. The information shown in the table is only a sample, since the information included for coordination may include much more parameters as discussed in previous sections.



Pour	Elements	Vol (CY)	Mix	Start	End
1	Foundations	170	Fou-5k-N	08/01/22	08/03/22
2	SOG	56	Sog-3k-N	08/07/22	08/07/22
3	SOG	64	Sog-3k-N	08/08/22	08/08/22
4	SOG	47	Sog-3k-N	08/09/22	08/09/22
5	SOG	54	Sog-3k-N	08/10/22	08/10/22
6	Columns	72	Col-4k-N	08/14/22	08/16/22
7	Beams, Slab	88	Flo-4k-N	09/07/22	09/07/22
8	Beams, Slab	100	Flo-4k-N	09/08/22	09/08/22
9	Beams, Slab	74	Flo-4k-N	09/09/22	09/09/22
10	Beams, Slab	85	Flo-4k-N	09/10/22	09/10/22

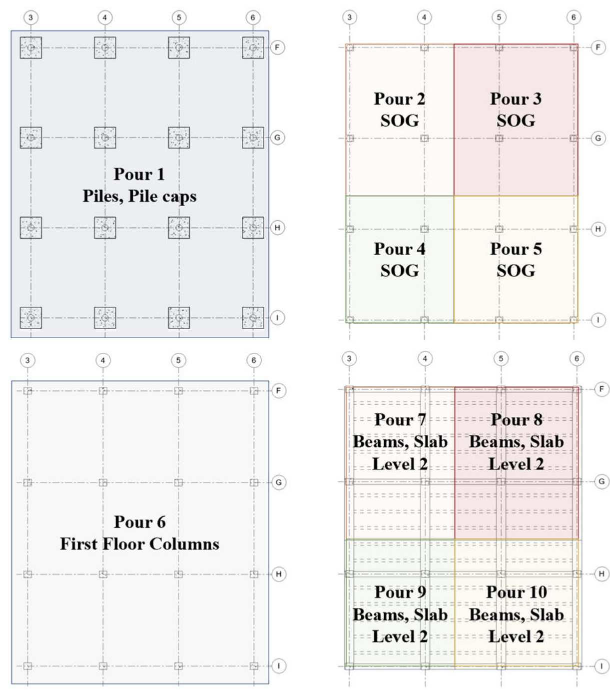


Figure 65. Coordination information for pours of model section

The most relevant applications of this information are construction processes simulation and trade coordination. Benchmarking the coordination processes is challenging under this approach, but based on the drawing and tables method used it is clear that every planning and modeling of trade scopes will require manual revision and re-modeling using the provided documentation as reference. Furthermore, 4D simulations for the concrete and trades may be set up, as shown in **Figure 66**, using the model as reference and then assigning additional scopes and schedules. The process of manually setting up the simulation and assigning additional properties for concrete mix and formwork coordination took around 40 minutes. This information, however, was automatically imported and the simulation was set up in just a few minutes by using the methods developed in the previous section.

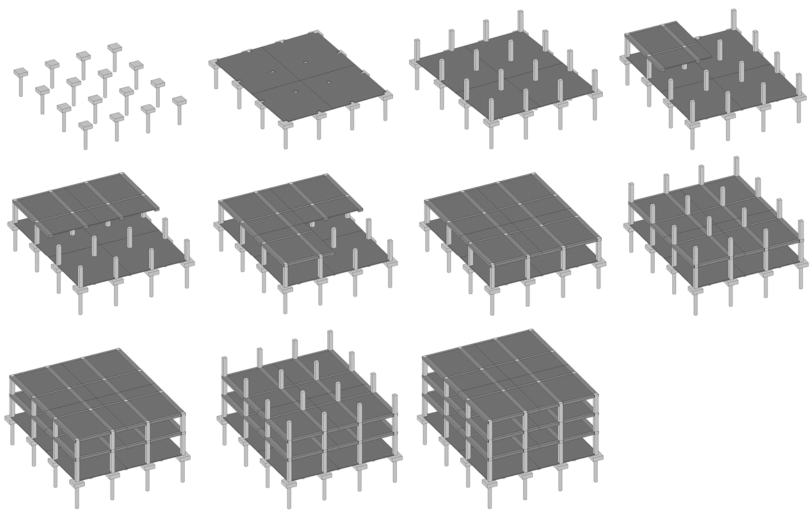


Figure 66. Construction process simulation for coordination

5.4 Value Considerations of Exchange Standards

5.4.1 Applicable Value Metrics and Dimensions

It was previously established that current state of practice is no longer concerned with whether BIM should be applied, but on how to enhance the application and make the process more efficient. The benefits of using BIM, as seen in the previous section, have been widely studied and reported. However, this dissertation focuses on the standardized exchanges of the information contained in BIM models for CIP RC structures, and the additional information that could be transmitted through them. Therefore, several of the metrics and value dimensions reviewed concerned with the benefits of the use of BIM do not translate to this specific application. After a review of the metrics and value dimensions related and applicable to the scope of this study, five metrics were defined and used to evaluate the value considerations of implementing BIM exchange standards for CIP RC buildings. **Table 12** shows the value dimensions selected along with a short description of each of them. Given that there is no significant cost associated with implementing and using standards (as there is with implementing BIM), the metrics mainly relate to savings in time and reduction in errors or omissions.

Table 12. Dimensions for Value of Implementing CIP RC Exchange Standards

Metric	Description
Implementation Time	Time required to implement new CIP RC exchange processes, including all the information attached to it.
Information Production Time	Time required to generate the design or coordination information in the format used to communicate it to other team members.
Reinforcement Detailing Time	Time required to detail the concrete reinforcement bars after the design intent has been produced.
Construction Coordination Time	Time required to coordinate the construction phase for CIP RC elements, including temporary structures, pour breaks, and constructability analyses.
Errors & Omissions	Errors or omissions identified during any of the information communication processes

5.4.2 Value Considerations for Exchange Standards

Finally, the findings from the ethnographic study, as well as the results from studying the adjusted process against the conventional process on a section of a real project model, allow the author to build an informed discussion regarding the value considerations of implementing exchange standards for CIP RC. **Table 13** presents the considerations for each of the metrics that were found relevant based on the scope of the dissertation. While some numbers are provided as reference based on the adjusted process evaluation, these numbers may vary widely based on the degree of automation available to the stakeholder prior to the implementation of the exchange standards. Furthermore, the potential productivity gains are reduced considerably as the building size increases, given that grouping and repetition simplifies certain tasks. However, regardless of the magnitude, the most relevant outcome is the clear advantages of the implementation in every dimension, which overall led to enhanced interoperability and better exchange performance.

Table 13. Value Considerations of Implementing CIP RC Exchange Standards

Metric	Value Considerations
Implementation Time	The time required to implement new standard processes varies based on the stakeholder's interests and IT capabilities. While the implementation may take weeks to be developed and tested, this is a one-time investment. The development and testing of the methods here presented took around 4 weeks, but all procedures are clearly laid out, with the hope that this will considerably reduce the implementation time for interested stakeholders.
Information Production Time	The time spent on information production varies depending on the degree of automation available. While in some cases a company may have the tools to perform this task in minutes, doing so without advanced automation may require a considerable amount of time. For the particular model section, the structural information production with conventional methods took 30 minutes per 1,000 CY of concrete. The construction information production with conventional representation methods took close to 15 minutes per 1,000 CY of concrete. In any case, in both scenarios a sizeable part of that time could be saved by communicating the information through the model using exchange standards.
Reinforcement Detailing Time	One of the biggest applications of the standard exchange of the design intent, is providing information that may be able to generate basic initial reinforcement set up, from which the detailer can start performing its tasks. For the particular model section, the manual set up of basic reinforcement took 45 minutes per 1,000 CY of concrete. A big part of this time could be saved by automatically creating baseline reinforcement using the design intent data. Furthermore, manual basic QTO of reinforcement for early estimating took 15 minutes per 1,000 CY; a task that can be performed automatically using the data in the standardized from for the design intent, thus saving this calculation time.

Table 13. Continued

Metric	Value Considerations
Construction Coordination Time	While contractors with BIM capabilities may model the pours in 3D to obtain volumes and assign properties to them, the information is conventionally still transmitted using drawings and tables or narratives. Converting the information to these means of representation took close to 15 minutes per 1,000 CY of concrete. If the information is transmitted using exchange standards and receiving stakeholders are able to parse and use it, most of this time could be saved by the producing stakeholder. Furthermore, setting up the construction simulation and coordination from the drawings and tables took around 20 minutes per 1,000 CY of concrete, while several of the tasks could be automated by using the standardized information embedded in the model.
Errors & Omissions	During the manual set up of models and information in the receiving side, there were several errors and omissions caught, mainly due to human errors in reading and writing information. However, specific values for errors and omissions are not easy to estimate since they heavily depend on the modeler and its proficiency with the tools. Regardless of the absence of particular values, one of the clear greatest advantages of using exchange standards is that, since there is no need to transform the information into intermediate means of representation to then re-model it in another application, the room for errors and omissions is substantially reduced.

As mentioned previously, these values for potential productivity gains are provided as reference for the project used and may vary considerably based on specific stakeholders IT capabilities, as well as be reduced as the project size increases. However, they convey the idea of how implementing exchange standards contributes directly to the overall CIP RC coordination process. These benefits are realized on both sides of the exchange. The producing stakeholder saves resources and reduces potential errors typically associated with transforming information into conventional means of representation, since the information will now be embedded in the model. The receiving stakeholder saves resources and reduces potential omissions typically associated with manual or semi-automatic conversion of the information from the conventional means of representation.

5.5 Conclusion

This chapter presented the implementation methods developed to bring exchange standards for CIP RC buildings into practice. The methods were developed based on an analysis of current tools, the findings and workflows obtained from the ethnographic study, and the data exchange requirements. To develop and test the methods, four levels of modeling with increasing complexity were considered, varying from single elements, up to a 5-story building. It was shown how the implementation methods serve both as guidelines for stakeholders to use as part of their processes, as well as a reference on how these guidelines could be developed for further interoperability and standardization efforts. Furthermore, the chapter presented the usage procedures after the standards have been implemented and proceeded to use the adjusted process to identify the value considerations of implementing exchange standards for CIP RC structures. The chapter performed exchanges in a section of the model of the project studied during the ethnographic observations, with and without using the implemented exchange standards. Based on comparison of the processes, as well as on the literature review and the findings of the ethnographic study, value considerations of the implementation were obtained. Although the value considerations included an increase in implementation time, which may vary considerably based on the available IT capabilities and expertise, there were reductions in information production time, reinforcement detailing time, construction coordination time, as well as errors & omissions. These benefits were seen on both sides of the exchange processes, and although may vary based on project size and the implementing stakeholder's

IT capabilities, were still well worth the one-time invested implementation time. Therefore, although implementing the exchanges and setting up the information for every usage does require additional effort at the beginning, the use of the standards does benefit greatly downstream processes, thus showing the advantages of their development and implementation.

CHAPTER 6. APPLICATION TO DESIGN INDICATORS

6.1 Review and Selection of Design Indicators

In the summary of indicators presented by (Suratkon and Jusoh 2015), the category that relates the most to the structure of the building from a design and construction standpoint is “Build Quality”. However, these indicators were mostly developed to evaluate the performance of a design after it has been completed, and do not consider the valuable information available during design, particularly the one contained in intermediate model exchanges done during the design process. Regarding the category of build quality, research performed around the efforts of design professionals to purse enhanced effectiveness of their designs during construction, found that most design professionals consider that constructability is a key indicator of the quality of the finished product or building (Arditi, Elhassan and Toklu 2002).

The concept of “Constructability” or “Buildability” refers to the application of construction knowledge during the planning and design phases to make the construction process more efficient, practical, or sometimes even realistic (Construction Industry Institute 1986). This concept has been around for several years, and while the focus has changed through time, a review on the previous, current and future research done around it found that its application today is as important as ever for reasons including increased project complexities, great amount of ambiguous information, new relationships between stakeholders, and increased use of powerful methods and software tools (Kifokeris and Xenidis 2017). Constructability can be approached from several angles, and pursue different benefits, including costs, time, labor, efficiency, and others. (Jergeas and Put

2001) grouped in seven themes the Construction Industry Institute constructability principles, and conducted a survey to estimate the potential and realized value of each of these groups. The group considering principles about designs that facilitate construction efficiency was ranked amongst the three with the highest potential value, which shows how much industry professionals value the positive impact that informed design decisions may have on the efficiency of the construction process.

Constructability is particularly important for CIP RC buildings, because as a process that is very labor-intensive, it can benefit greatly from considerations taken during design that lead to a more efficient construction process (Fischer and Tatum 1997). (Fischer 1993) developed a constructability adviser system based on an object-oriented enriched CAD tool (a predecessor of BIM tools), to provide constructability feedback for CIP RC structures using criteria such as layout, dimensioning and construction methods. The paper identified two levels of reasoning when performing constructability analyses: reasoning about attributes of objects, and reasoning about relationships between attributes of objects. Although the research focused mostly on elements' dimensioning and forming methods due to their high impact on the costs, it identifies the most important preliminary design variables that may be constrained or considered for constructability analyses: dimensions of elements, distance between elements, changes in dimensions and distances, concrete strength, quantity and type of reinforcement, and modularity. Out of these, the dimensions of elements and the quantity and type of reinforcement are applicable and relevant if the design intent and construction planning standards want to be used for analysis.

(Hartmann and Fischer 2007) in their ethnographic-action study analyzed how 3D and 4D models support the constructability analysis and propose an integrated process to communicate the constructability knowledge during construction review. The process proposed to transfer not only the information but also the knowledge necessary to perform constructability analyses, but relies mostly on fully detailed 3D models where all elements and parts were included in the model. (Zhong and Wu 2015) studied a series of indicators related to economic and environmental sustainability and constructability in order to compare and inform the selection process of CIP RC vs Steel Framed structures. The indicators towards constructability proposed in the research are labor savings, construction duration, construction safety and construction quality. Once again, constructability from the viewpoint of efficiency and quality of construction is found as a potential indicator that greatly benefits from the information available during the design process. (Kaveh, Kalateh-Ahani and Fahimi-Farzam 2013) worked on an optimization approach to optimize the design of RC cantilever retaining walls in terms of constructability. To measure the constructability of the wall, they selected two variables for the optimization process: cost and congestion. The congestion was estimated as the total number of reinforcing elements, affected directly by a balance of the diameter of the bars and the spacing between them. They defined 35 parameters to include in the optimization algorithm, out of which 7 described the geometry and 26 the reinforcement sizes and spacing.

The review shows that constructability of the design can be seen as a good quality indicator for CIP RC design and planning, particularly because it can use the information available during design intent and construction planning model exchanges, to contribute to efficiently achieve the intent during construction. Since the information about connectivity, dimensions and reinforcement design intent is something that is now available as part of the exchange model in a standard way, the congestion of the reinforcement, particularly in the areas between interacting elements, appears as an excellent alternative to measure the constructability of the design and planning, and to use as an indicator to develop predictions on potential future issues the design may encounter once it reaches more detailed stages. Current design tools allow the engineer to use the design intent to perform reasoning about attributes of objects as shown in blue in **Figure 67**, but do not typically perform reasoning about relationships between attributes of objects such as the ones shown in yellow and red. These are types of analyses that could be performed now that the design intent is available as part of a BIM model that holds the information about objects' connectivity and interacting volumes.

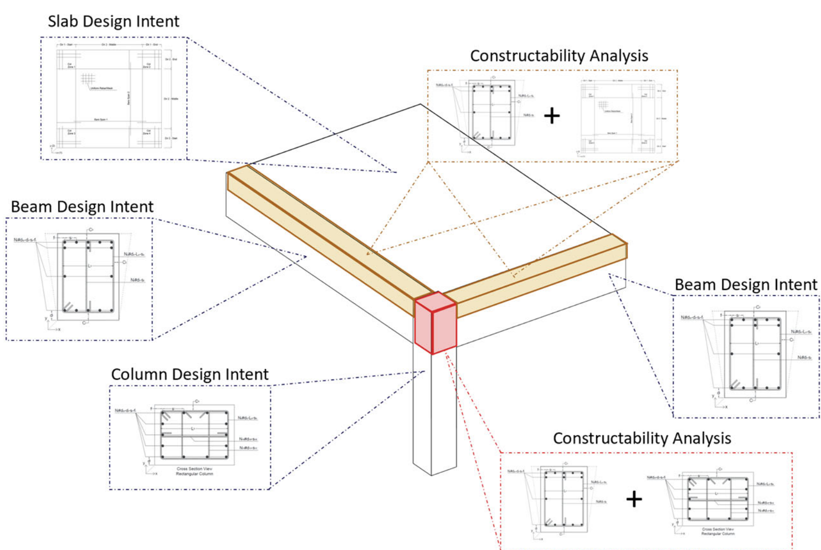


Figure 67. Types of design intent constructability analysis (Garcia and Castro-Lacouture . Under Review)

Since the steel ratio is typically a design decision based on requirements and demands, it is not a variable that can be modified for enhanced constructability. However, the way the steel ratio is achieved in terms of diameter of rebars, number of rebars and separation is an aspect that has a direct impact on constructability. Therefore, the design indicator selected, “Constructability”, for the application of design intent and construction coordination of CIP RC elements, will be estimated in terms of congestion as done by (Kaveh, Kalateh-Ahani and Fahimi-Farzam 2013). To create an estimating method applicable to several types of situations with different dimensions and steel distribution, the number of bars alone is not enough. Consequently, a similar concept to the steel volumetric ratio is proposed as the independent variable, which considers the number of bars per volume of concrete rather than the steel ratio, thus accounting for most of the parameters aforementioned. The proposed variable to measure the congestion at the intersections is shown in **Equation 1**.

$$\boldsymbol{Congestion} = \frac{\boldsymbol{\#\ of\ bars\ in\ the\ intersection}}{\boldsymbol{Volume\ of\ the\ intersection}} \quad \textbf{(1)}$$

6.2 Relationship Parameters – Indicators

The study considers the intersections of pairs of elements for framed structures, including beams, columns, and slabs. The specific interactions considered are beam-column, beam-slab, beam-beam, and column-slab, and are shown in **Figure 69**. The same method considered for slabs could be easily extrapolated to footings and pile caps, since the reinforcement distribution is not that different between these elements. The properties required to estimate the congestion of the intersection are the number of bars each element contributes, and the volume of the intersection itself. As shown in the simplified data structure on **Figure 68**, the number of bars is derived from the design intent property set containing the design intent reinforcement information, and the volume intersection is derived from the geometric representation of the elements. These properties could be easily extracted from an IFC file because of the way they have been standardized as proposed in this dissertation and aligned with the ACI efforts. Different types of elements will have some of the properties listed that contribute to the number of bars (for example, slabs will have top and bottom bars and rebar mesh, while beams will have longitudinal bars, stirrups and ties). The following sections provide the detail of what reinforcement and parameters are considered for each type of intersection to estimate the indicator.

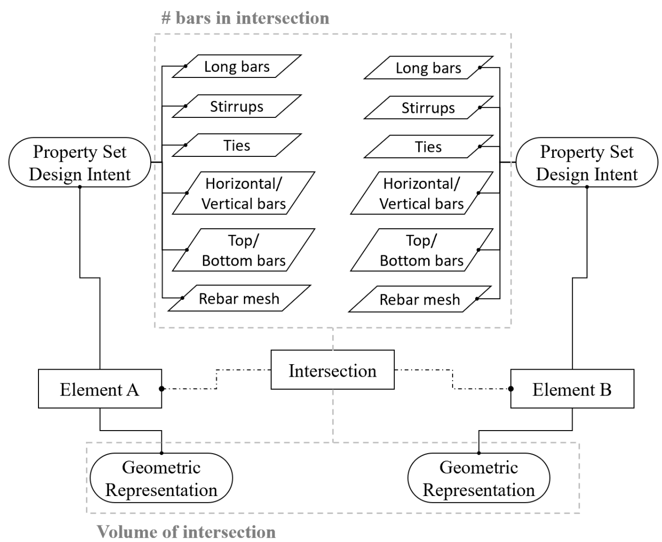


Figure 68. Data structure of parameters required for indicator estimation

As seen in **Figure 69**, the beam-slab interaction considers all the beam longitudinal and transversal reinforcement, up to the thickness of the slab, plus the slab reinforcement that enters and anchors in the beam. The beam-beam interaction considers all the mean beam longitudinal and transversal reinforcement, up to the height of the secondary beam, plus the secondary beam longitudinal reinforcement that enters and anchors in the main beam. The column-beam interaction considers all the column reinforcement, plus the beam longitudinal reinforcement that continues through the column. The column-slab interaction considers all the reinforcement of both elements.

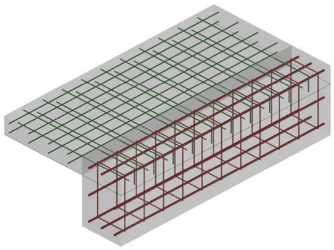
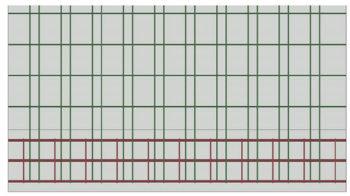
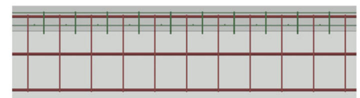
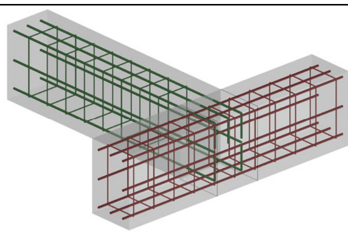
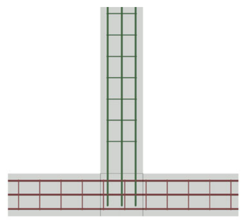
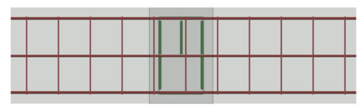
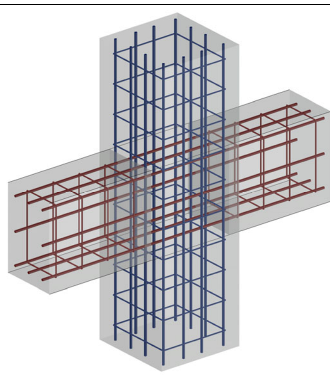
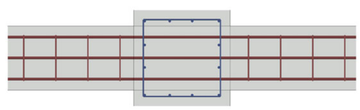
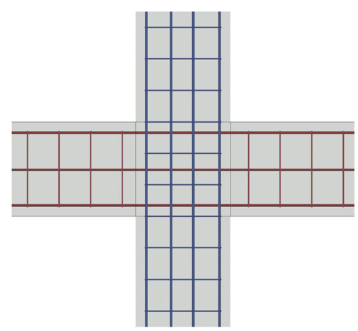
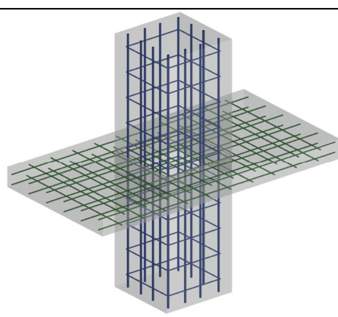
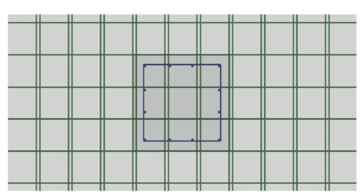
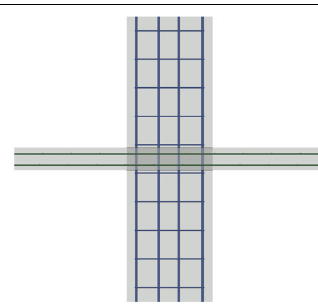
3D view	Top View	Side View
Beam – Slab Intersection		
		
Beam – Beam Intersection		
		
Column - Beam Intersection		
		
Column - Slab Intersection		
		

Figure 69. Visualization of intersection cases

6.3 Training Database

The first step to generate the database was to define a representative number of reinforcement distributions for each element. **Table 14** shows the three beam sections considered: small, medium, and large. For each of these sections, several options were generated varying the top and bottom reinforcement ratio (in one and two lines), the stirrup spacing, and the number of vertical legs. Combinations of these parameters were based on typical occurrences in practice, for example: stirrup spacings will typically be smaller where top reinforcement ratios are higher, which is near the supports. For each ratio, two alternatives were proposed: more smaller bars, or fewer bigger bars. This is a concept directly related to constructability: several times it will be more constructible to use fewer bigger bars that allow more spacing and lead to less congestion. This led to a total of 64 beams, all shown in **Appendix G**.

Table 14. Representative Beam Sections and Parameters for Database

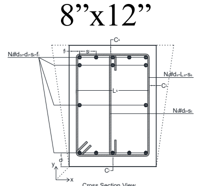
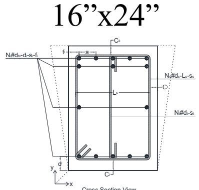
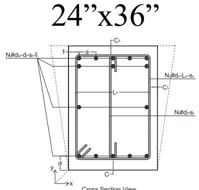
Section	Top Ratios	Bottom Ratios	Stirrup Spacing	Vertical legs	# of beams
8”x12” 	0.5% 1.0% 2.0%	0.5% 1.0% 2.0%	3” 6” 12”	2	16
16”x24” 	0.5% 1.0% 2.0%	0.5% 1.0% 2.0%	3” 6” 12” 24”	3 4	24
24”x36” 	0.5% 1.0% 2.0%	0.5% 1.0% 2.0%	3” 6” 12” 24”	4 5	24

Table 15 shows the three column sections considered: small, medium, and large. For each of these sections, several options were generated varying the reinforcement ratio, the ties spacing, and the number of legs. Combinations of these parameters were based on typical occurrences in practice, for example: the number of reinforcement legs will be higher for higher reinforcement ratios, where more bars are present and required to be tied. For each ratio, two alternatives were proposed: more smaller bars, or fewer bigger bars. This led to a total of 54 columns, all shown in **Appendix G**.

Table 15. Representative Column Sections and Parameters for Database

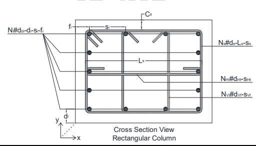
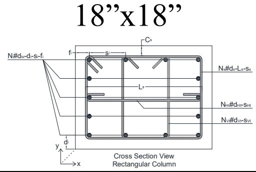
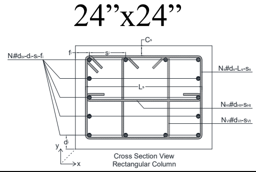
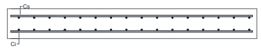
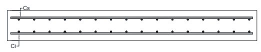
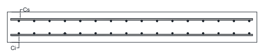
Section	Ratios	Tie Spacing	Tie legs	# of columns
12”x12” 	1.5% 5.0% 8.0%	2” 4” 6”	2	18
18”x18” 	1.5% 5.0% 8.0%	2” 4” 6”	2 3 4	18
24”x24” 	1.5% 5.0% 8.0%	3” 6” 12”	3 4 5	18

Table 16 shows the three slab thicknesses considered: small, medium, and large. For each of these sections, several options were generated varying the top and bottom reinforcement ratios (assumed equal in both directions). Combinations of these parameters were based on typical occurrences in practice. For each ratio, two alternatives were proposed: more smaller bars, or fewer bigger bars. This led to a total of 27 slabs, all shown in **Appendix G**.

Table 16. Representative Slab Sections and Parameters for Database

Thickness	Ratios	# of slabs
4” 	0.5% 1.0% 1.5%	9
6” 	0.5% 1.0% 1.5%	9
8” 	0.5% 1.0% 1.5%	9

Afterwards, logical occurrences of intersections of these elements were created. If, for example, the 8”x12” beam section was combined with the 12”x12” column section, this generated 16 x 18 = 288 possible interactions. Some combinations were not considered because they would not normally occur in practice, such as a 24”x24” columns with a 4” slab. **Table 17** shows all the combinations generated for each of the intersection types.

Table 17. Combinations to Generate Intersections

Beam-Column Interactions: 2736
Column-Slab Interactions: 1134
Beam-Slab Interactions: 1440
Beam-Beam Interactions: 2752

Beams	Columns	Slabs	Beams	Beams (Secondary)
8”x12”	12”x12”	4”	8”x12”	8”x12”
16”x24”	18”x18”	6”	16”x24”	16”x24”
24”x36”	24”x24”	8”	24”x36”	24”x36”

Once the database was built, the value of congestion as defined by equation (1) was calculated for each of the interactions, using the parameters and relationship illustrated in **Figure 68**. Since these points will constitute the base to build the model, it is necessary to identify whether or not each of them is considered to have or not constructability issues. The value of 1 is assigned to those occurrences with constructability issues, while the value of 0 is assigned to those without constructability issues. Three criteria were used to determine whether each of these interactions was constructible or not:

1. Minimum Separation (S_{min}): This criterion evaluated for each of the interactions that the reinforcement could physically and logically fit within the node, by ensuring minimum spacing was provided in critical cases. For the beam-column interaction, it was evaluated whether the longitudinal beam reinforcement could fit through the column reinforcement, with a 1/8" tolerance. For the column-slab interaction, it was evaluated whether the slab reinforcement could fit through the column reinforcement, with a 1/8" tolerance. For the beam-slab interaction it was evaluated whether the spacing between beam stirrups and anchoring slab reinforcement was at least 1", to allow the concrete to be placed and the biggest size of aggregate to pass. For the beam-beam interaction, it was evaluated if the secondary beam anchoring reinforcement would fit through the main beam reinforcement, with a 1/8" tolerance. Any interaction that did not satisfy these conditions, was assigned a value of 1, thus classifying it as an interaction with constructability issues.
2. Maximum volumetric ratio (ρ_{min}): This criterion was based on the ACI maximum ratio for column reinforcement. The ACI sets a maximum 8% steel ratio reinforcement in columns for longitudinal rebars mainly because above this numbers they consider the element to be hardly constructible (ACI 2014). If this limit is added to the maximum shear reinforcement caused by the minimum allowed separation, a value of 16% to 20% is obtained. Therefore,

any intersection with a volumetric steel ratio greater than 16%, was assigned a value of 1, thus dimming it as an intersection with constructability issues.

3. Finally, the remaining intersections were visually inspected to determine whether the node or edge would present constructability issues based on the number of bars. It was found that intersections tend to present constructability issues at numbers greater than 60 bars per cubic feet. These intersections found to have constructability issues were assigned a value of 1.

Table 18 shows the number of intersections that were determined to have constructability issues based on each of the criterion established. The total number of interactions with issues may be smaller than the sum of the number of interactions with issues based on each criterion, because some interactions were determined to have issues based on more than one of the criterion. To ensure the consistency of the data, it was revised that values of 1 did not concentrate on a specific section, but rather occurred in different sections as the number of bars increased. **Figure 70** shows the graphical result for the classification of each of the interaction types. As expected, intersections with fewer bars generally tend to be less prompt to cause constructability issues, while intersections with more bars are more likely to cause a constructability issue.

Table 18. Database Interactions Classification per Criteria

Interaction	Total Interactions	Interactions With Constructability Issues				Interactions Without Issues
		S_{min} Criteria	ρ_{min} Criteria	Visual Criteria	Total	
Beam-Col	2,736	144	120	208	336	2,400
Col-Slab	1,134	150	0	333	414	720
Beam-Slab	1,440	164	54	75	245	895
Beam-Beam	2,752	128	0	224	322	2,430

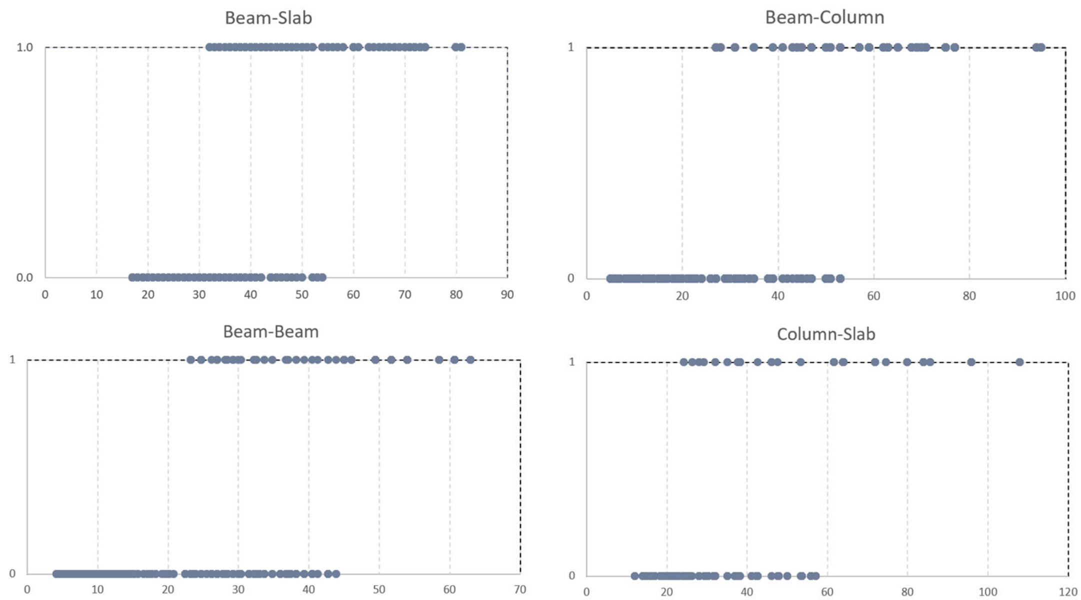


Figure 70. Database points for each of the interaction types

6.4 Design Indicator Estimating Model

The model selected was logistic regression, because it fits the goal of the study: to estimate whether there will be an issue or not with an indicator based on parameters obtained from the standardized exchange models. Particularly, estimate the probability that for a certain type of intersection, there will be a constructability issue based on the design intent. The procedure finds the best fitting curve by transforming the y-axis, odds of congestion, to a transformed logarithm log(odds of congestion / (1 – odds of congestion)). This new axis now goes from -infinity to +infinity, with all the data, previously lying at 1 or 0, now lying at +infinity and -infinity. Then a line is fit to this data, and its coefficients are determined based on a linear model using the transformed y-axis. To transform the line from the transformed y-axis to the initial y-axis, the transformation y= e^log(odds)/ 1+e^log(odds) is used. After this transformation, the line becomes an s-shaped curve. To find the best fitting line, the method uses the concept of maximum likelihood. The procedure projects the original data points (located at – and + infinity) onto the candidate line, and is then transformed to the original axis. The likelihood of the line is the sum of the probabilities of the points after being projected onto the curve and transformed to the original axis. This line is rotated multiple times recording its likelihood, after which the best fitting line is obtained by selecting the model with the highest likelihood. Finally, since this is a classification problem (1 or 0), a threshold value, typically 0.5, is used to classify a point as 1, congested, or 0, not congested. Based on this threshold value a weighted accuracy is calculated, which indicates the accuracy of the model to predict the points in the database as they were defined. The following sections illustrate the results of applying the algorithm to each of the datasets presented in **Figure 70**.

6.4.1 Beam-Slab Model

Figure 71 shows the logistic regression model for the beam-slab intersection using the datapoints obtained in the previous section.

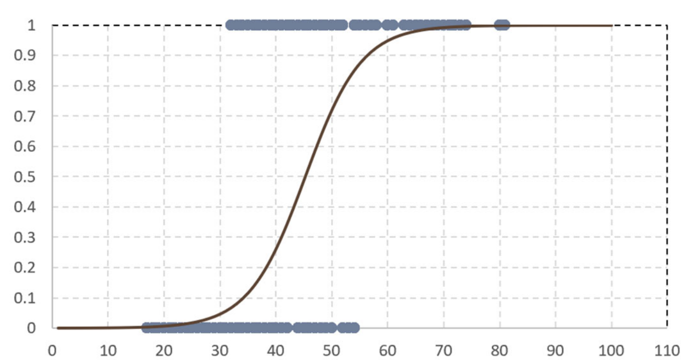


Figure 71. Logistic regression model for beam-slab intersection.

The coefficients of the regression are shown in **Table 19**, along with the standard error, the Wald number (a measurement of the precision of the estimate), and the p-value.

The values for the standard error, the Wald number, and the p-value (less than 0.05), show that the variable chosen (number of bars per CF of concrete at the intersection) is statistically significant for this model. **Equation 2** describes the model (best fitted curve), and can be used to calculate the probability of congestion, PC, based on the number of bars per cubic feet at the intersection, n. In other words, this model allows to estimate the probability that the intersection will present a constructability issue, which is the selected indicator.

Table 19. Regression Coefficients for Beam-Slab Intersection Model

		# Iter	20		Alpha	0.05	
	coeff	*s.e.*	*Wald*	*p-value*	*exp(b)*	*lower*	*upper*
intercept	-9.001	0.486	342.367	0.000	0.000		
var 1	0.199	0.012	283.554	0.000	1.220	1.192	1.249

$$\boldsymbol{PC(n)} = \frac{e^{(-9.001\,+\,0.199n)}}{1+e^{(-9.001\,+\,0.199n)}} \qquad \textbf{(2)}$$

Finally, **Table 20** shows the classification table for the model, based on a cutoff value of 0.5. The cutoff value is the threshold value, above which points are classified a success, or with constructability issues, and below which points are classified a failure, or without constructability issues. The values shown correspond to a typical cutoff value of 0.5 or 50%. The weighted accuracy of the model at predicting success and failure is 88%, which is a good indicator of how well the model fits the behavior of the data.

Table 20. Classification Table for Beam-Slab Intersection Model

	Obs Suc	Obs Fail	Total
Pred Suc	180	72	252
Pred Fail	108	1080	1188
Total	288	1152	1440
Accuracy	63%	94%	88%
Cutoff	0.5		
AUC	0.944		

6.4.2 Beam-Column Model

Figure 72 shows the logistic regression model for the beam-column intersection using the datapoints obtained in the previous section.

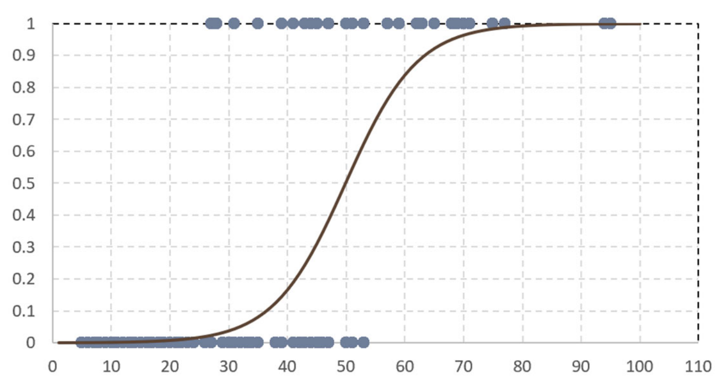


Figure 72. Logistic regression model for beam-column intersection.

The coefficients of the regression are shown in **Table 21**, along with the standard error, the Wald number, and the p-value. The values for the standard error, the Wald number, and the p-value (less than 0.05), show that the variable chosen is again statistically significant for this model. **Equation 3** describes the model for this intersection type and can be used to calculate the probability that the intersection will present a constructability issue.

Table 21. Regression Coefficients for Beam-Column Intersection Model

	# Iter		50		Alpha	0.05	
	coeff	*s.e.*	*Wald*	*p-value*	*exp(b)*	*lower*	*upper*
intercept	-8.163	0.391	435.032	0.000	0.000		
var 1	0.164	0.008	381.940	0.000	1.178	1.159	1.197

$$\boldsymbol{PC(n)} = \frac{e^{-8.163\,+\,0.164n}}{1+e^{-8.163\,+\,0.164n}} \qquad \textbf{(3)}$$

Finally, **Table 22** shows the classification table for the model, based on a cutoff value of 0.5. The weighted accuracy of the model at predicting success and failure is 94%, which is a good indicator of how well the model fits the behavior of the data.

Table 22. Classification Table for Beam-Column Intersection Model

	Obs Suc	Obs Fail	Total
Pred Suc	252	84	336
Pred Fail	84	2316	2400
Total	336	2400	2736
Accuracy	75%	97%	94%

Cutoff	0.5
AUC	0.977

6.4.3 Column-Slab Model

Figure 73 shows the logistic regression model for the column-slab intersection using the datapoints obtained in the previous section.

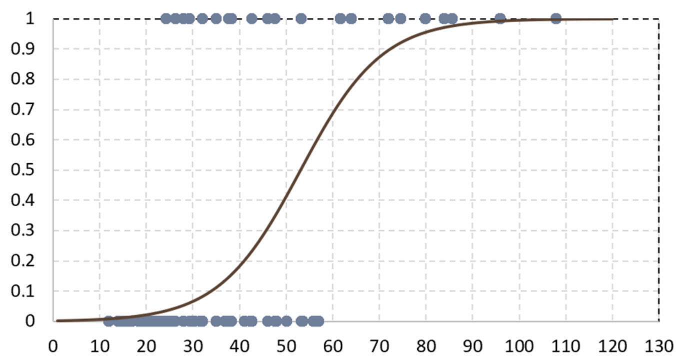


Figure 73. Logistic regression model for column-slab intersection.

The coefficients of the regression are shown in **Table 23**, along with the standard error, the Wald number, and the p-value. The values for the standard error, the Wald number, and the p-value (less than 0.05), show that the variable chosen is again statistically significant for this model. **Equation 4** describes the model for this intersection type and can be used to calculate the probability that the intersection will present a constructability issue.

Table 23. Regression Coefficients for Column-Slab Intersection Model

		# Iter	20		Alpha	0.05	
	coeff	*s.e.*	*Wald*	*p-value*	*exp(b)*	*lower*	*upper*
intercept	-6.094	0.329	342.209	0.000	0.002		
var 1	0.115	0.006	318.458	0.000	1.122	1.107	1.136

$$\boldsymbol{PC(n)} = \frac{e^{-6.094\,+\,0.115n}}{1+e^{-6.094\,+\,0.115n}} \qquad \textbf{(4)}$$

Finally, **Table 24** shows the classification table for the model, based on a cutoff value of 0.5. The weighted accuracy of the model at predicting success and failure is 94%, which is a good indicator of how well the model fits the behavior of the data.

Table 24. Classification Table for Column-Slab Intersection Model

	Obs Suc	Obs Fail	Total
Pred Suc	340	83	423
Pred Fail	74	637	711
Total	414	720	1134
Accuracy	82%	88%	86%
Cutoff	0.5		
AUC	0.938		

6.4.4 Beam-Beam Model

Figure 74 shows the logistic regression model for the beam-beam intersection using the datapoints obtained in the previous section.

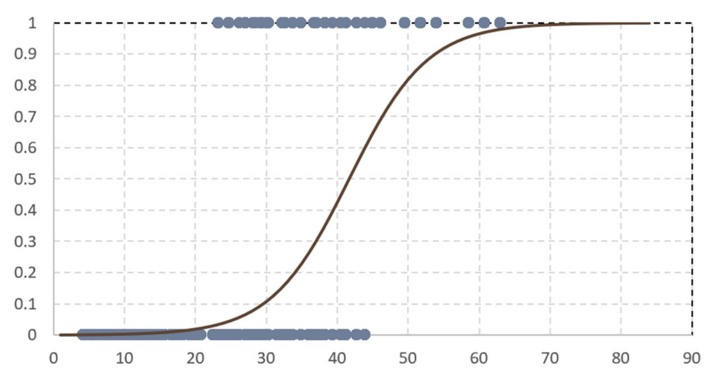


Figure 74. Logistic regression model for beam-beam intersection.

The coefficients of the regression are shown in **Table 25**, along with the standard error, the Wald number, and the p-value. The values for the standard error, the Wald number, and the p-value (less than 0.05), show that the variable chosen is again statistically significant for this model. **Equation 5** describes the model for this intersection type and can be used to calculate the probability that the intersection will present a constructability issue.

Table 25. Regression Coefficients for Beam-Beam Intersection Model

		# Iter	20		Alpha	0.05	
	coeff	*s.e.*	*Wald*	*p-value*	*exp(b)*	*lower*	*upper*
intercept	-7.587	0.339	501.575	0.000	0.001		
var 1	0.182	0.009	417.556	0.000	1.200	1.179	1.221

$$PC(n) = \frac{e^{-7.587\,+\,0.182n}}{1+e^{-7.587\,+\,0.182n}} \qquad \textbf{(5)}$$

Finally, **Table 26** shows the classification table for the model, based on a cutoff value of 0.5. The weighted accuracy of the model at predicting success and failure is 95%, which is a good indicator of how well the model fits the behavior of the data.

Table 26. Classification Table for Beam-Beam Intersection Model

	Obs Suc	Obs Fail	Total
Pred Suc	230	42	272
Pred Fail	92	2388	2480
Total	322	2430	2752
Accuracy	71%	98%	95%
Cutoff	0.5		
AUC	0.960		

6.5 Conclusion

This chapter presented the application of the information contained in the exchange standards to predict indicators of design quality for CIP RC structures early in the design process. The chapter started with a review of applicable design indicators for CIP RC related to the design intent and construction planning communication. Based on the review, constructability was found to be a good indicator of design quality, given that it relates the design result to how efficient is it to achieve it during construction and ensure the good performance of the structure as specified by the design. To measure the constructability the parameter of congestion was proposed, given that more congested nodes tend to be harder to fabricate and place. Congestion is defined as the number of bars in the node per unit of volume of the node. This parameter can be calculated based on the parameters and properties shared during the design intent and construction planning exchanges. Afterwards, a database of representative beams, columns and slabs was generated to train the predictive algorithm. For each node in the database, geometric, volumetric, and engineering criteria were used to define whether the node was likely to have issues with construction, which constitutes a binary classification model. Finally, a logistic regression model was applied to each node type of a frame structure: beam-column, slab-column, beam-slab, and beam-beam. All model results presented the significance of the variable chosen, as well as the classification table with very high values of prediction accuracy. The results obtained show how well the obtained models fit the data, and therefore may be used to estimate potential construction issues early in the process, based on the parameters of the design intent standard exchanges.

CHAPTER 7. CONCLUSIONS AND FUTURE WORK

Even though the AEC/FM industry has taken advantage of the benefits of using BIM for decades, to achieve the full potential of these advantages seamless interoperability between all the available applications is necessary. The CIP RC industry has focused on developing exchange standards to communicate the information for this type of structures, but factors such as the nature of the material and the complexity of the process have imposed multiple challenges to their development. This document is presented in the context of the development of such standards, and its goal was to provide further recommendations for standardization of CIP RC buildings based on current practices, to develop the implementation methods necessary to bring the standards into practice, to identify the value considerations of implementing these standards into the CIP RC industry, and to develop a model to use the information in the standards to estimate design indicators early in the process. The goal was achieved through an ethnographic-action study, the creation and testing of methods using test buildings, and a logistic regression model to predict the design indicators.

This dissertation performed a comprehensive review of the available data exchange representations, to relate other industry segments' developments to the research and developments focused on CIP RC concrete. The review illustrated particular challenges of CIP RC for standardization such as the boundary definition between elements as a function of the scope of the stakeholder interested, representation of partial elements for construction processes, and inclusion of a complex supply chain involving multiple stakeholders. It also explained the documents that have been published by the ACI

Committee 131, and that have started the process of standardization. A comprehensive review of how the value of using BIM has been studied and discussed in several publications and reports was also presented, evidencing the gap to identify the value considerations brought by using exchange standards.

Ethnographic-action research was selected as the guiding methodology for the first part of the dissertation, because it proposes the integration of practice and research, particularly through cycles of observations of practice for problem identification, which are carried out using ethnographic tools and methods. The study was performed at an engineering company with strong BIM practices for CIP RC structures. The design and coordination processes of two buildings were observed for a one-year period. Over the course of this year, field observations, process observations and interviews were gathered. To establish findings and conclusions, a coding system was proposed to organize and analyze the data obtained. To complement and validate the findings, they were compared with previously researched challenges for CIP RC modeling and interoperability, as well as consulted with four different professionals from different companies. The ethnographic approach was extremely useful to provide multiple sources of information, and the findings proved to be consistent and relevant enough to identify typical practices for CIP RC modeling, design, planning and coordination, as well as affordances and limitations.

Key findings include: a) automation and standardization require an increase in upfront work, with several benefits realized downstream; b) the required intensity to perform design and planning tasks, as well as the room for error, vary depending on the level of automation in the processes; c) connectivity and boundary definition of overlapping objects remain a great challenge for CIP RC models, leading engineers to develop their own in-house tools or start the modeling in an analysis tool from scratch instead of importing it from a BIM tool; d) interoperability based on tool plug-ins is tied to software developers and versions, which has led to companies with high IT capabilities to develop in-house tools; e) CIP RC has the additional challenge of communicating different views that change the boundary definition between objects based on the scope of the stakeholder modeling; f) current BIM efforts for CIP RC focus on translating the information to be represented using conventional methods (drawings), which stakeholders believe will need to change within the next few years; g) CIP RC has the particularity of requiring material assignment (concrete mixes) based on the usage; h) standardizing typical details for CIP RC reinforcement would have great value in simplifying communication and reducing the number of errors and room for interpretation; and i) there is a lack of confidence in the exchange of model data due to the lack of commitment or interest in proper modeling and data assignment. The results were used to map workflows of design and planning practices to be used as reference in the development of implementation methods for exchange standards, as well as to provide recommendations for future standardization. These recommendations centered in the standardization of connectivity between physical and analysis models, standardization of concrete elements' volume interaction, full standard parametrization of representative information, alignment with standardization of reinforcement detail, and development of guidelines to use data-analytics techniques for processing of non-standardized scenarios.

Based on the findings and workflows mapped, the study developed implementation methods to bring exchange standards for CIP RC buildings into practice. The methods were developed based on an analysis of current tools, the findings and workflows obtained from the ethnographic study, and the data exchange requirements. To develop and test the methods, four levels of modeling with increasing complexity were considered, varying from single elements, up to a 5-story building. It is shown how the implementation methods have the potential to serve both as guidelines for stakeholders to use as part of their processes, as well as a reference on how these guidelines could be developed for further interoperability and standardization efforts. Furthermore, the usage procedures after the standards have been implemented were presented, and the adjusted process was used to identify the value considerations of implementing exchange standards for CIP RC structure models and data. The exchanges were then performed in a section of the model of the project studied during the ethnographic observations, with and without using the implemented exchange standards. Subsequently, value considerations of the implementation were presented based on comparison from the two processes, as well as on the literature review and the findings of the ethnographic study. Although the value considerations include an increase in implementation time, which may vary considerably based on the available IT capabilities and expertise, there are reductions in information production time, reinforcement detailing time, construction coordination time, as well as errors & omissions. These benefits are seen on both sides of the exchange processes, and although may vary based on project size and the implementing stakeholder's IT capabilities, are still well worth the one-time invested implementation time. Therefore, although implementing the exchanges and setting up the information for every usage does require additional effort at the beginning, the use of the standards does benefit greatly downstream processes, thus showing the advantages of their development and implementation.

To further encourage the development of exchange standards, and to further apply the data contained within the exchanges evaluated, a model was produced to apply the information contained in the exchange standards to predict indicators of design quality for CIP RC structures. After a review of applicable design indicators for CIP RC related to the design intent and construction planning communication, constructability was found to be a good indicator of design quality, given that it relates the design result to how efficient it is to achieve it during construction, and ensure the good performance of the structure as specified by the design. To measure the constructability, the parameter of congestion was proposed, given that more congested nodes tend to be harder to fabricate and place. Congestion was defined as the number of bars in the node per unit of volume of the node. It was shown how this parameter may be calculated based on the parameters and properties shared during the design intent and construction planning exchanges. Afterwards, a database of representative beams, columns and slabs was generated to train the predictive algorithm. Using the database, a logistic regression model was applied to each node type of a frame structure: beam-column, slab-column, beam-slab, and beam-beam. The results obtained show how well the obtained models fit the data, and therefore may be used to estimate potential construction issues early in the process, based on the parameters of the design intent standard exchanges.

The contribution highlights of this dissertation consist of

- Evaluation of design and construction coordination practices for CIP RC buildings from the perspective of developing exchange standards;
- Recommendations for further standardization of CIP RC;
- Fully parametrized specification for the representation of design intent information;

- Implementation methods for relevant CIP RC exchange standards to be used for application and as reference for future implementation efforts;
- Value considerations of implementing CIP RC exchange standards in design and construction workflows;
- Criteria for classification of CIP RC element intersections based on their constructability using design intent parametrized information; and
- Logistic regression model to estimate the probability of having constructability issues on CIP RC intersections (e.g., beam-column, column-slab, beam-beam, beam-slab) based on early design intent parametrized information.

Future work involves the development and inclusion of further exchange models used in other parts of the CIP RC supply chain. The methodology of this dissertation may also be applied to other projects and CIP RC structures in order to extend the reach of the findings and develop more comprehensive implementation methods, and size-base estimations of the value of implementation. The methods are easily extensible to other tools and platforms, since they are developed with a generic approach and only the testing is done using specific tools. Furthermore, these methods may be adapted to other contexts, such as countries where BIM implementation has not been as advanced as it has in companies with heavy IT capabilities; or CIP RC bridges, where the development of standards poses other challenges and requirements. The model for prediction of constructability issues may be extended to include more CIP RC element interactions, and further refined as it is used in practice and more data becomes available. The method pursued to develop these models may also be used as a guideline for further data analytics applications to the modeling and exchange procedures related to CIP RC structures.

APPENDIX A. LITERATURE REVIEW OF METRICS

Reference	Description	Metrics		
		Category	Metric	Measurement
Barlish and Sullivan, 2012	Reviewed multiple resources and developed a methodology (metrics) to quantify the impact of implementing BIM. The methodology is applied on three case studies, each with BIM and Non-BIM scenarios, to asses the investment and return metrics. Projects focused on industrial structures.	Investment Metrics	Design Cost	BIM cost of services/cost of total design
			3D Background Modeling Cost	BIM cost of 3D background model creation/cost of total design
			Construction Cost	BIM contractor cost/cost of construction
		Return Metrics	RFIs	Quantity/assembly or tool quantity
			COs	Cost of changes/cost of project
			Time Improvements	Actual duration/standard duration
Cannistraro, 2010	Studied $558M worth of projects of a mechanical construction company, that either used 2-D representation, 3-D lonely BIM, or Collaborative BIM.	N/A	COs	Cost of changes/cost of project
Kuprenas and Mock, 2009	Documents the process and results of using BIM on a $320M public project, where the model was developed between GC and subcontractors, without participation of designer.	Intra Trade	Rework	Cost Saved
			Construction Duration	Cost Saved
			Preassembly and Prefabrication	Cost Saved
			Bundling	Cost Saved
		Inter Trade	Conflict Checking	Cost Saved
			Changes and Bulletins	Cost Saved
Khanzode, Fischer and Reed, 2008	Presents the process and results of using VDC for MEP on a $97M healthcare project, and reports the challenges faced, and the qualitatives and quantitatives advantages.	N/A	Labor	Cost Saved
			Rework	Cost of rework / cost of project
			Prefabrication	% prefabricated
			Safety	# of injuries
			Coordination	# of conflicts
			RFIs	# of RFIs
			Time	Days/Months saved
			Project Cost	Total cost saved
McGraw Hill Construction, 2014	Reports the result of a study to stablish the business value of BIM for Owners.	N/A	N/A	N/A
Walasek and Barszcz, 2016	Analyzed the barriers for BIM adoption and implementation and proposed methods to address them. Then it studied a company to calculate the ROI for adoption in design following a project in Poland.	N/A	Investment Cost	# and $ of staff, cost of training, # and $ of hardware/software.
			Income	Revenue
			Return on Investment	Change in income - investment cost
Sacks and Barak, 2008	Measured the advantages and productivity increase of using 3D parametric modeling in the structural engineering practice	Productivity	Documentation productivity	Modeling time (parametric)/drafting time (non-parametric)
			Benchmark productivity	Hours/area or hours/concrete volume
		Economic	Cashflow Change Over Adoption Period	Income(w/ increase) - Operating Costs(+modeling -drafting)
Eastman et al, 2011	In one of the chapters of the handbook, they present an analysis of 10 case studies, each of which consisted of a project that implemented BIM in different levels and during different project	N/A	N/A	N/A
Bryde et al, 2013	Studied the project benefits of BIM and used multiple criteria to evaluate the success of BIM use.	N/A	N/A	N/A
CRC Construction Innovation Group	Results of a research project that studied the business drivers to adopt BIM through a set of case studies.	N/A	N/A	N/A
Ghaffarianhoseini et al, 2017	An updated analysis of the benefits, level of adoption, risks and recommendations of BIM implementation	N/A	N/A	N/A
Giel and Issa, 2013	Calculated the ROI on three cases studies, each of which had a BIM and a similar non-BIM project. The return is expressed in terms of reduced schedule overruns, RFIs and Cos.	N/A	Return on Investment	Increase in Income / Cost of Investment
			COs	Cost of # of COs that could've been saved by BIM
			Schedule Behavior	Cost of # of days that could've been saved by BIM
			RFIs	Cost of # of RFIs that could've been solved by BIM
			Cost of Investment	(Training + VDC Staff + Software&Hardware) or Billed Cost
Abdirad, 2016	Sumarizes the multiple developments on assessing BIM implementation using metrics, and identifies the related gaps and limitations.	N/A	Costs	Costs of tools and training, costs savings, design costs
			Time	Time savings, design and modeling times, document production time, time of data exchanges
			Rework	Cost, time or # of reworks
			RFIs	# of RFIs
			COs	# of COs
			Errors & Omissions	# of Errors and Omissions
			Completeness of Information	N/A
McGraw Hill Construction, 2009	Presents an overview of the value of BIM for the different stakeholder in the AEC industry. The value mostly comes from interviews and perceived benefits from several professionals.	N/A	N/A	N/A
Won et al, 2013	Performs a statistical analysis of the critical and relevant factor for BIM implementation based on surveys to experts.	N/A	N/A	N/A
Liu et al, 2010	Paper presented the results of a survey distributed to professionals regarding the factors influencing BIM adoption.	N/A	N/A	N/A
Azhar, 2011	Measured the financial benefits of BIM through the analysis of case studies, considering the costs of implementing the technologies, therefore aiming to estimate the Return on Investment (ROI) BIM had on each case.	N/A	BIM Cost to Project	$ directly associated with project
			Cost Benefit	$ of savings from clashes, time and alternatives' evaluation
			Time Savings	# of hours saved
			ROI	(Benefits-Cost)/Cost
Lu et al, 2013	Developed a measurement model considering the learning curve of the benefits of using BIM as a learning tool within construction	N/A	Productivity	Staff-hours/cycle or Staff-hours/area
			Cost	Cost/cycle
			Time	Time/cycle
Lu et al, 2014 / 2015	Proposed an approach to develop actual time-effort distribution curves of projects that allow identifying the true benefits of BIM, and used two projects to test the method and show the curves and benefits.	N/A	Cost	Design Cost/area or Construction Cost/Area or Total Cost/Area
Kaner at al, 2008	Reported the improvements derived from BIM implementation in the pre-cast concrete structural engineering practice	N/A	Time	Modeling/CAD working hours
			Productivity	Hours/concrete volume or hours/drawing
Sacks et al, 2004	Assessed the short-term economic benefits and costs of adopting 3D modeling in precast concrete engineering.	Quantifiable	Reduced costs of engineering	Cost saving/Total project cost
			Productivity gains in design & drafting	Hours per activity (new)/Hours per activity (old)
			Reduction of design & drafting errors	Cost saving/Total project cost
			Direct costs of 3D BIM stations	Cost of stations
			Replacement cost of existing systems	Cost of system per station
			Indirect costs in adoption phase	N/A
		Qualitative	Improved project definition	N/A
			Enhanced cost estimating accuracy	N/A
			Streamlined logistics	N/A
			Production automation	N/A

Sacks et al, 2005	Assessed the short-term economic benefits and costs of adopting 3D modeling in precast concrete engineering, with an emphasis on productivity and a classification of the activity types and how automatable they are.	N/A	Modeling Productivity	Engineering(drafting) hours/1000 sqft
CIFE (Gilligan and Kunz), 2007	Assessed the main value propositions of VDC for different stakeholders through interviews. Reviewed 7 case studies and identified the quantifiable advantages that could be seen in them.	N/A	Cost to project	Cost of implementation or Cost of Implementation / Project budget
			Cost benefit	Cost savings attributed to benefits
			Schedule benefit	Days savings attributed to benefits
Kim et al, 2017	Measure the value of implementing BIM in a large-scale project. The case identifies value-assignable BIM issues. Then calculates the contractual value of the resolved issues. It also defined the perceived value of BIM implementation on the trade contractors.		BIM Utilization Value (BUV)	Sum of: Contract Budget per Item * (Size of issue/total size of item)
			BIM Contribution Value (BCV)	BUV * Contribution Rate or BUV * Ident. Index * Cost Impact Index
			BIM Sensible Value (BSV)	N/A
Jin et al, 2017	Conducted surveys to determine BIM investment areas to focus on, expected returns from BIM investments, methods to enhance those returns, and risks associated with implementation.	N/A	N/A	N/A
Love at al, 2014	Proposed framwork for performing a benefit realization analysis of the effects of BIM to determine the necessity and validity of BIM investment from the viewpoint of an owner or a business.	N/A	N/A	N/A
Jones et al, 2015	Shows some global cases of BIM adoption, its effects, and the opinions of the AEC participants who have experienced BIM.	N/A	Reduction in Final Construction Cost	(Estimate - Cost)/Estimate
			Accelerated Project Completion	(Schedule - Duration)/Duration
			RFI Reduction	(Typical RFIs - RFIs)/Typical RFIs
			Reduction in Safety Indicents	(Typical Incidents - Incidents)/Typical Incidents
			Improved labor productivity	(Typical Productivity - Productivity)/Typical Productivity
Lee at al, 2011	Analyzed the 700+ design errors, focusing on a specific case of BIM adoption in a big project (6 buildings), and compared the prevented rework cost and the BIM-related cost of labor, software, hardware, and training. This data was used to report an ROI.	N/A	Errors - Illogical design	# of clashes, drafting errors, other
			Errors- Dicrepancies	# of discrepancies per trade and between trades
			Errors - Missing Items	# of missing identifiers, symbols, schedules, dimensions, details, finish materials, others per trade
			ROI	(Cost of Errors Saved - Cost of Implementation)/Cost of Implementation
Francom and El Asmar, 2015	Performs univariate and multivariate analysis on the performance of 35 projects using BIM, especially change and quality performance. Measured 36 variables and alayzed against project performance based un survey replies from projects' personnel.	N/A	CO Processing Time	Time of Approval - Time of Initiation
			Cost of Warranty and Latent Defects	Cost of repairs
PWC, 2018	Proposed a sophisticated methodoloty to estimate the financial benefits of using BIM in the UK.	Time	Time savings in design	Automated rule checking, quick implementation of design changes, standard solutions, faster coordination, easier change control, faster qto and cost estimation, easier design-construction coordination, reduction in error, fewer RFIs
			Value of time savings	#days saved project * project prelim costs per day + # days (sum of all trades) * average daily rate + benefits from acceleration of asset delivery
		Material	Material savings in design	Reduced human error, design optimization, improved constructability and prefab, reduced rework and waste, reduced changes
			Value of material saved	Sum: reduction in material * unit cost of material + reduction in material*unit CO2 eq*cost of CO2
		Cost	Cost savings in design	Reduced rework due to clash detection, reduced changes,
			Value of cost savings	Reduction in # of instances of event * change in avg cost of instance (time + material) OR Cost of all events w/o BIM - Cost of all events w/ BIM
		Risk	Risk savings in design	Increased accuracy of estimates (reduced risk of human error), better visibility of project costs
			Value of risk savings	Reduction in contingency held (per annum) * Opportunity cost per annum

APPENDIX B. EXAMPLES OF ETHNOGRAPHIC STUDY FILLED FORMS

B.1 Field Observation Form – Healthcare Building Project

Document No.	FO – 001 – SE/M
Document Type	Observation
Company/ Discipline	Structural Engineering + Construction Coordination
Subject/Actor	Structural Engineer
Recording Method	Videocall
Date	4/15/2021
Duration	1.5 hours
Project	Healthcare Facility
Participants	Principal, Project Manager, Design Manager (responsible for project technical oversight), Lead Engineer, Lead Modeler, Technical Designer 1, Technical Designer 2, Director of Digital Practice.
Observations	The goal of the work session is to discuss the concrete matrix and using it as a live schedule to track the material information on the concrete elements, and go beyond the conventional “dumb” text methods. The goal is to have live tracking of concrete properties and quantities. The building is a new patient tower and emergency podium made of Cast-in-Place Reinforced Concrete Building that will serve as an expansion to an existing healthcare facility. There is a small metal building and a pre-cast concrete parking deck outside of the scope of the meeting. The project is on the early design development (DD) phase, still dealing with schematic design (SD) decisions. The building is a Cast-in-Place reinforce concrete intermediate moment frame (IMF) building, with no shear walls. Foundations consist of piles and pile-caps. This is standard for many framed projects made of CIP RC. The process wants to go beyond referencing the strength of the concrete, and wants to be able to track the details of the mix used, and its association with the corresponding elements made of that mix. The concrete matrix wants to be able to associate to each element the concrete material parameters, or types of concrete mix. (This is closely related to the intent to transmit material information during the EM.6 and EM.20 exchanges). To create the model of the building, the modeler firs created an ETABS model that was used to instantiate the Revit model, through the company’s tools created for that purpose. Given the time constraints of the project, the team wanted to be able to quickly push stuff, so the model is not cleaned up (model needs “cleaning” on the new tool). Elevator shafts are still moving around, and edge of slab is still moving around. Model does not have the concrete matrix implemented, but team wants to understand how it fits within an actual project, what works, and what doesn’t. Team expects to have 56-day mixes on foundation, and standard 28-day standard mixes on the rest of

	the structure. The concrete matrix is implemented in Revit as a Revit Material, to which the parameters are assigned to. Most of the time the materiality definition in the model is done so that there is proper joining between intersecting concrete elements. Conventionally, the reference to materiality, is done through an element parameter that has a code to a scheduled mix. The new approach is to name the material based on the element type it will be used on, so that if the resistance is changed in the schedule, it is not inconsistent with the name of the material. Essentially based on material usage. The initial definition of materials in Revit comes from a selection of options of a database, which has over 60 alternatives for concrete mixes. The database considers requirements for material based on location, exposure, etc. This is the baseline, or out-of-the-box option, and then the material can be individually tailored within the model for the project. The old workflow consisted of pulling data from an available matrix on excel. The new workflow pulls the baselines available into Revit from a web-based relational database, and after selection and assignment, allows the user to have a live QTO instead of having to go back and perform calculations based on associations by parameters. Special care needs to be given when relying on information reported by the tools. Some tools do not report information about all the objects or considerations included. For example, Revit does not schedule slab edge quantities (slab turn down), so the team had to implement a plug-in for that. An extremely important consideration is that many behaviors and quantities depend heavily on how elements are modeled. Consistency between how things are modeled, and the processes used to get information out of the model is vital. Some perspectives on what wants to be seen in a model change over time. Before, engineers did not want to see joints in the concrete, to have a cleaner model. However, now that the LOD in modeling is getting closer to 350, they do want to see the joints when the material changes to have control over where they expect a change in concrete mix. Team acknowledges that this process may involve more upfront work, but they also acknowledge the great benefits, which are realized downstream when the time comes to perform a QTO. They also like working with the development team, to understand what is working, what is not, see the way it works, and get feedback from it. Steel is treated as catalog material. Reinforcement bars are easier to deal with because the material is standard (a "catalog" material). However, to be consistent between concrete and steel models, steel materials are usage-based as well. he concrete cover (exposure class) has been typically included in the matrix, but it is not related to concrete itself, it is more related to the specific usage and element. Two elements may have the same concrete and mix, but different exposures (exterior vs interior). Therefore, exposure/cover should not be included in the matrix as it is not a material parameter but an element parameter. An argument was made regarding that the matrix is for the purpose of 2D drawings and estimators, but 10 years from now this could all be instance parameters and schedules embedded into the model elements themselves or through associations. This would require standard exchanges to be implemented. Further applications could involve grouping elements with same/similar mixes for pour planning.

B.2 Field Observation Form – Commercial Building Project

Document No.	FO – 005 – SE/M
Document Type	Observation
Company/ Discipline	Structural Engineering
Subject/Actor	Structural Engineer/Modeler
Recording Method	Videocall
Date	12/09/2021
Duration	1.5 hours
Project	Commercial Building
Participants	Principal, Structural Engineer/Modeler 1, Structural Engineer 2.
Observations	The purpose of this meeting is to coordinate modeling and design efforts of the building, including vertical and lateral resistance systems. The meeting is an active discussion between the principal and engineers regarding results and challenges of the process. The design progress has been a little delayed because of the heavy workload and deadline accommodations. Most designs have not been performed yet because there are a lot of things still changing in terms of geometry and location, so there really is no point on designing until the geometry is more set. The structural engineer 2 has over 30 years of experience with design of concrete structures, and has been with this company for over 10 years. The structural engineer 1/modeler has been with the company for several years, involver both in the design and the modeling of CIP RC buildings. Structural engineer 1 is in charge of the design of the lateral resistance system, while structural engineer 2 is in charge of the design of the vertical resistance system. Since this process also uses the BIM/Kodiak design workflow, the team acknowledges the heavy dependency on the BIM model and the inability to start any design tasks until that has been completed and the model can be imported into Kodiak. The project also involves several PT girders that are designed in ADAPT-PT/RC, which currently has no interoperability with the rest of the tools. The process starts in Revit, which is the driver model for the geometry and connectivity. Sometimes the process is started in ETABS for better connectivity, and then the structure geometric model is generated from the analysis model. For when the model is started in Revit, there are tools that within a certain tolerance merge nodes or flatten elements to specific planes. When the model starts in ETABS is better for connectivity, but they are harder for coordination and interoperability. It heavily depends on the project, the staff available at the time the project starts, and the challenges expected on each. There are also comparison routines in place for when an element has to be moved in one of the models, a consistent indexing strategy allows the other model to be properly updated. Consistent indexing is key for interoperability. Challenges on connectivity and offsets are not only horizontal but also vertical. For example, sudden section changes of beams pose a challenge on where the analytical line will be placed. Furthermore, the location of the end point for the analytical beam element, typically taken at the column node, may not always coincide with the geometric model when sudden section changes are present, because the bigger element may go all the way until the opposite face of the column.

	The company has a huge database of typical details from which an engineer may choose from to represent or provide visual representation of the design intent. This is particularly important in situations where detail is required, such as stepped elements or sudden section changes. Even for standard details, the design tool references bar types that correspond to standard details. A new addition to the process is differentiating left, center, and right reinforcement for bottom bars, which allows the automation of the hook generation and location without necessarily looking at the structural floor plan (from which the location of the hook can be derived by simple inspection. The bar types can be understood by a third party or external stakeholder such as a detailer or contractor, by looking at a graphical key provided by the engineer. The key contains a graphical representation of what is meant by each of the letters or bar types referenced in the structural floorplans.

B.3 Process Observation Form

Document No.	PO - 002 – SE/M
Process	Framing Structural Design
Company/Discipline	Structural Engineering
Subject/Actor	Structural Engineer + Modeler
Recording Method	Videocall
Date	8/26/2021
Duration	1.5 hours
Tools Used	ETABS, Autodesk Revit, Kodiak
General Considerations	The process intents to model and design CIP RC framing elements, particularly beams for vertical loads and deflections.
Steps and Processes	- Generate an analytical model in a structural analysis tool, to revise and correct the connectivity between the elements. Sometimes modeling starts in BIM tool, in which case the model is later pushed into the analytical model for connectivity revision and analysis. - Push model to BIM tool to add information and hold a structural BIM model for coordination. If modeling starts in BIM tool, model CIP RC elements in BIM tool (Revit), ensuring proper dimensions and 3D interactions. - Export the model with the proper connectivity to a central database or neutral file, that can be used to retrieve the geometry and connectivity. - Import the geometric model in the design tool and verify consistency in relationships and connectivity. - Assign loads and load patters to the different elements based on the use of the facility. - Run the analysis and design program. - Verify force diagrams for logic, consistency. and output of design results. Note potential necessary connectivity and geometry adjustments. - Verify deflections in all elements and compliance with limits. Ensure consistency between continuity and connectivity. Note potential necessary connectivity and geometry adjustments. - If adjustments are necessary, modify geometric model as required, re-export to central file or database, re-import on tool, and re-run analysis. Verify forces and deflections again. - Export design intent results associated with each of the elements. The association may be done through specific parameters or type marks. This export may be done to the database or through the generation of schedules. - If desired, import the design intent results into the BIM model as parameters that may be used for further coordination or visualization. - Generate typical and specific (if required) details as required of the distribution of the scheduled reinforcement.

B.4 Data Exchange Form

Exchange Requirement	Concrete Material		
File Type	PDF		
Producing Actor(s)	Structural Designer / Revit		
Consuming Actor(s)	General Contractor / PDF		
Description	The purpose of this exchange is to transfer concrete material information from the structural engineer to the contractor. Information is produced by a tool, but communicated through conventional 2D schedules. The concrete material is associated with the relevant concrete elements		
Information Units	Concrete Element	ID	Concrete Element ID
		Type	Concrete Element Type
		Dimensions	Concrete Element Dimensions
		Material	Concrete Mix Assignment
	Concrete Mix (Material)	ID	Unique identifier of the Mix
		Material Class	Class of material classification
		Name	Name of the mix
		Description	Description of the mix
		Strength	Design concrete strength
		Concrete Type	Normal or lightweight
		Exposure Class	Class exposure per ACI
		Max WC Ratio	Maximum water/cement ratio
		Target Air Content	Target air content of mix
		Cement Replace.	Required Cement Replacement
		Max. Agg. Size	Maximum Aggregate Size
		Additives	Notes on additives

B.5 Interview Form

Document No.	IN - 002 – SE/M
Document Type	Interview
Company/ Discipline	Structural Engineering
Subject/Actor	Structural Engineer 1
Recording Method	Videocall
Date	3/25/2022
Duration	1 hour
Description	This interview was intended to gather information from one of the key actors involved in the processes observed, and gain information on his perspective and approaches. This information is also used for triangulation with the information acquired during the observations.
Question	What are your typical responsibilities during the design and modeling of CIP RC buildings?
Answer	*I have done actually almost all the tasks within what you call structural engineering, not only design any part of the building… but actually for overseas projects I'm actually project manager. So, I've done both things: coordinating structural design but also working on the structural design itself… I've been lucky enough to be able to create drawings/models if that is needed… there some specifics that is better if done by an engineer because doing a mark up, and transferring it to someone else, then back again, that may take more time than you taking 20% extra time drafting it yourself.*
Question	What are your greatest challenges when modeling CIP RC buildings?
Answer	*In shear wall jobs, same as braced frames, they create issues. But, the other thing with shear wall jobs is that in brace frames you can maybe have a door fir inside braces depending on the size, but in the shear wall it's difficult because you have to redesign the shear wall if you have an opening in it… you have a new link beam, you have to schedule it, design it…* *The other issue is if you have posttensioning in your slabs. Tendons are alive, they have force in them, and we often want to know all the penetrations, specially big ones, because there is going to be tendons sweepings in all these kind of elements, so during the design part we need to know that. Then, on the construction side there is always that issue with "I hit a tendon, what do I do?".*
Question	What information do you require to model? What about design?
Answer	*Most of the projects start this way. We usually get a Revit model from the architect, most of the time they are ahead, which is good because then we have a base from which we can start our model, so we will give that to our modeler and they will start just placing columns all around the building, and define the edge of slab, and start creating an ETABS model later.* *Now there are some projects, in which the project actually starts in ETABS. You create the grids matching the architectural model, and maybe you don't even have a model, just PDFs, and then you create the Revit model from the ETABS model. The reason to do that is because if you do the Revit model first and then you export it into ETABS, you have to ensure perfect connectivity. If you do it all the way around, then you first ensure the connectivity, and then you push to Revit. Sometimes that makes the architect nervous because they don't see the structural model, and maybe just a few days before the SD set of drawings we say "Okay, we are going to push a button, and suddenly there is a Revit model created from an ETABS model".* *Most of the time we get a narrative: "This floor is office, that floor is whatever use", and then we'll fill in the blanks on the loading ourselves. Sometimes, if we are lucky, we are going to have architectural backgrounds. They are going to name the uses and be more specific. We also get early on he geotechnical report, and we are sometimes involved in that, because sometimes we request them to do downhole examinations so we can maybe get a better site coefficient. In this projects we were involved in that. We wanted to come down from a seismic category C to B, because you want to use OMF, which are cheaper, and without that you we wouldn't have been able to use OMF. It was originally going to be a seismic design category C, which would have been IMF.*

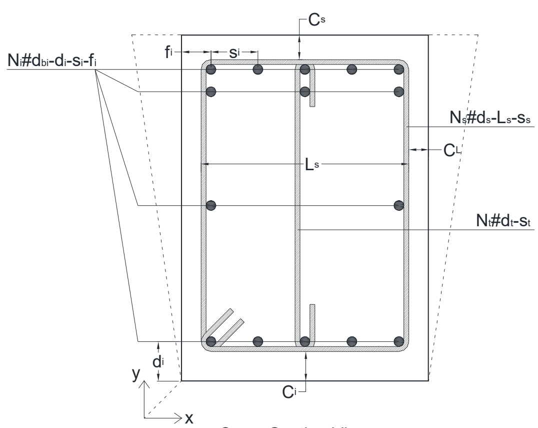
Question	How do you typically communicate design intent information to the detailer or contractor?
Answer	*Luckily we do have some tools internally. Let's talk about columns. We have a tool internally which lets us take the results from ETABS, and then process those results, because ETABS only yields area reinforcement, not number of bars, so we process that into number of bars and spacing. Then we push it to Revit which Is the important part, Once it is in Revit we can create a column schedule from that…. The out of the box family does not have a lot of things that we want to populate, we have created parameters in the family… and our tool can populate that.* *For beams we also have an internal tool, Kodiak, which basically does design, and pushed that design into Revit. The design is pushed and also the labels are pushed, I mean the beam types, so if you do a beam schedule, its already there.* *We also have tools to create foundations. We have a tool that does that and then pushes it to Revit. The one that is a little bit green is shear walls, and link beams, we don't have any sophisticated tool that helps us push from ETABS to Revit. Let's say it's yellow. The design of a two way slab has always been a challenge for any company, we do have an internal tools that has been developed. I think it's at 75%. It's pretty good but still needs some tweaks.* *Most of the times it's schedules.*
Question	What challenges or issues do you typically encounter when communicating this information?
Answer	*If all beams have the same top of concrete, you don't need other than details on how you are supposed to anchor the reinforcement and all that. But let's say you have a beam step, that the top of beam does not match the top of the adjacent beam. So we do have to sometimes cut specific sections just to show the intent of how the reinforcing should be lapping for example. Every time you try to do something that is outside of the tools that you already have. That will always be a specific detail that you have to think.*
Question	How is construction information relevant to the structure such as pour breaks or joints typically communicated?
Answer	*We try never to do a design in which we are forcing the hand of the contractor on how to do construction. They have to follow some specifications, but they are the ones who have to plan for it and we review it. Usually, we get a PDF with the colored pour breaks. In the projects I've worked on modeling of the pours is not that common.*
Question	What challenges or issues do you typically encounter when communicating this information?
Answer	*Most of the time when they send a PDF and it's colored and they have clouds its understandable. What gets hard is when the don't send any of that and it's just a narrative. Then it is impossible to understand… so we do ask them to give more context.*
Question	What were your greatest challenges in design and modeling for this project?
Answer	*Connectivity, and that's because we use a lot of tools in this project. If it wasn't because we were using Kodiak and all these other tools, then connectivity would have been less of an issue in the design part.* *Foundation was a delegated design. It's always a little bit of a challenge when something is a delegated design, because if you are doing things yourself you are in control of your own destiny, but when you have someone else then you have to communicate the design criteria to them, you have to communicate all the assumptions that you made, and you have to then check their assumptions, and check their reasoning.*
Question	How do these challenges compare to other projects you have done? What other typical challenges for CIP RC buildings come to mind?
Answer	*Constant changes. And changes beyond milestones. If you make a whole bunch of changes between the SD and DD designs none cares… but whenever there is a lot of changes between let's say a framing package, a foundation package, and then there is a construction package, and there's a lot of changes then there is a lot of uncertainty because the contractor will most of the time use the foundation or framing package to bid and procure materials, and if you did changes usually you do not cloud things until after you have submitted your CDs. In this project because of the very high nature of changing we had to cloud for the CD drawings, because otherwise this could have been missed.* *Changes happen in every project, but in this project changes happened when the ship had sailed. And this is something the manager will agree is one of the biggest deals. Changes are expected on different phases, but to do big changes when someone has issued a package for construction, then it's a big issue.*

Question	Approximately how many hours did the modeling of this building take? How many hours the design? How does it compare to other projects?
Answer	*The amount of changes will be such that you won't use a unit of work per task anymore.* *In this project, without changes, let's talk about foundations and lateral design, would probably take 5 days, with our tools… Let's say it's a static project. Just the model, the skeleton, is maybe 5 more days… For beams, based on what I saw on the project, I would say a week. Just working on design, not working on coordination… Any design is mostly coordination, making things work, changes, actual design was about 20% of the work.*
Question	Approximately how long did you spend putting together design intent information so it can be communicated? How does it compare to other projects?
Answer	*That will take a little bit longer. If the tool pushes it itself into a live schedule then it's there, but then you still have to show more things. For example, if you have a column transfer, or you have certain weird conditions, then you have to do details. Your strange conditions.* *If your design is a 1, then maybe the rest of it is a 2, on top of the design.*
Question	What errors did you identify in the modeling after it had been completed? How long did it take to correct them? How does this compare to other projects?
Answer	*Connectivity.* *When there is a lot of changes, the tags are sometimes floating, and they do not have an assignment.* *Whenever you do lots of changes, you may be aware of the changes at the elevated structure, but you may forget about what is happening at the foundation. One example of that is when you move an elevator, you may move the framing around the elevator, but you forget at the foundation level you have to drop some foundations.*
Question	What errors did you identify in the design intent documents/information after it had been completed? How long did it take to correct them? How does this compare to other projects?
Answer	*Our program that we told you about the columns, will essentially process reinforcement, but you have to tell it the bar size you want, and it will say how many bars you need. It will check that it fits and all that. However, if you mis-click a button it will instead of No. 8 lets say schedule No. 5, and it will fit, and it will be code compliant and all that. But, you don't want a job where you have No. 8 and No. 5 and all kinds of crazy combinations of bar sizes. Even the tie spacing, most of them had the ties at 12in, and a group of columns had ties at 13 in. So that happened in this project and that was my bad. A couple of columns were using No. 5, and it was working for strength and everything, but none wants a party of rebar. That was actually caught in out QC, and we issued that revised column section.* *The same could be said about beam design, and that is the kind of things programs won't check, because they will only check strength and all these kind of things. They don't check for uniformity, which is a separate issue.*

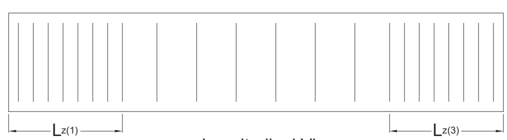
APPENDIX C. STANDARD PARAMETERS TO COMMUNICATE STRUCTURAL DESIGN INTENT

This appendix presents the proposed parameters to communicate the design intent of each of the CIP RC elements considered within the scope of the dissertation.

C.1 Beam



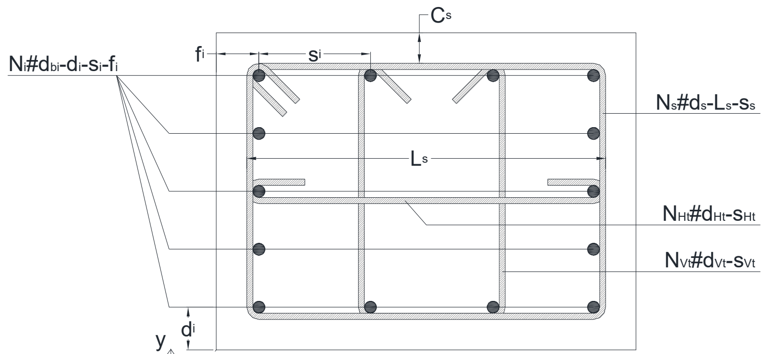
Cross Section View



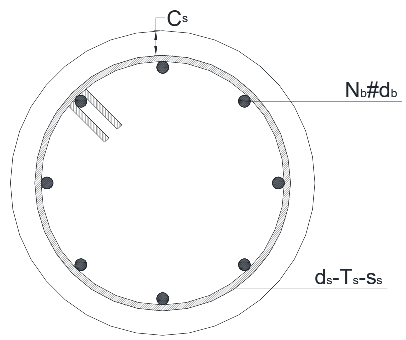
Longitudinal View

Element	Parameter	Description	Example
Beam	Longitudinal Bars - Start Beam	Comma separated values, with each value containing information of a reinforcement row. Each value contains 5 parameters of the row: Number of bars, diameter of the bars, distance of row from bottom (local y=0), bar spacing and first bar distance from left face (x=0). There can be 3 different lists: one for the start, one for the middle	5#6-630-95-55, 3#5-580-190-55, 2#5-350-380-55, 5#6-630-95-55
	Longitudinal Bars - Mid Beam		3#6-630-95-55, 2#5-350-380-55, 3#6-630-95-55
	Longitudinal Bars - End Beam		5#6-630-95-55, 3#5-580-190-55, 2#5-350-380-55, 5#6-630-95-55
	Stirrups - Start Beam	There are 4 parameters for the stirrups: Number of closed stirrups, diameter of closes stirrups, horizontal length of each closed stirrup, separation of closed stirrups. There can be 3 different values, one for the start, one for the middle and one for the end of the beam.	1#4-420-100
	Stirrups - Mid Beam		1#4-420-200
	Stirrups - End Beam		1#4-420-100
	Stirrups S - Start Beam	There are 3 parameters for the ties: Number of ties, diameter of ties, separation of ties. There can be 3 different values, one for the start, one for the middle and one for the end of the beam.	1#4-100
	Stirrups S - Mid Beam		1#4-200
	Stirrups S - End Beam		1#4-100
	Fy - Long. Bars	Steel Strength for Longitudinal Bars (Units by file)	420
	Fy - Stir & Ties	Steel Strength for Stirrups and Ties (Units by file)	420
	Cs	Top Cover	50
	CL	Lateral Cover	40
	Ci	Bottom Cover	60
	Lz	Length of zones. 3 values: start, middle, end length	1000,4000,1000

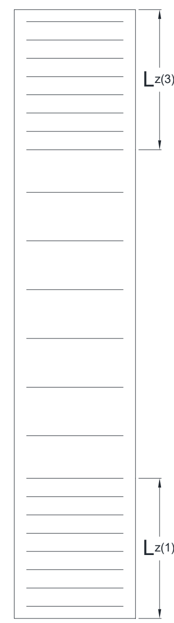
C.2 Column



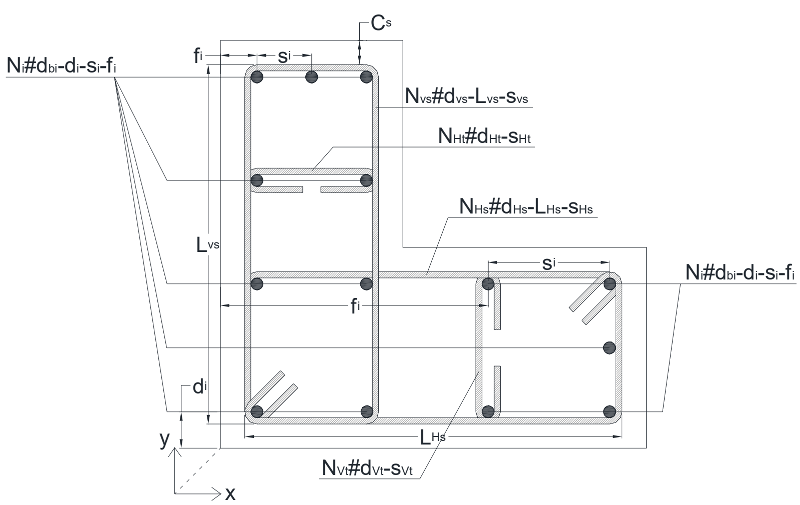
Cross Section View
Rectangular Column



Cross Section View
Circular Column



Longitudinal View



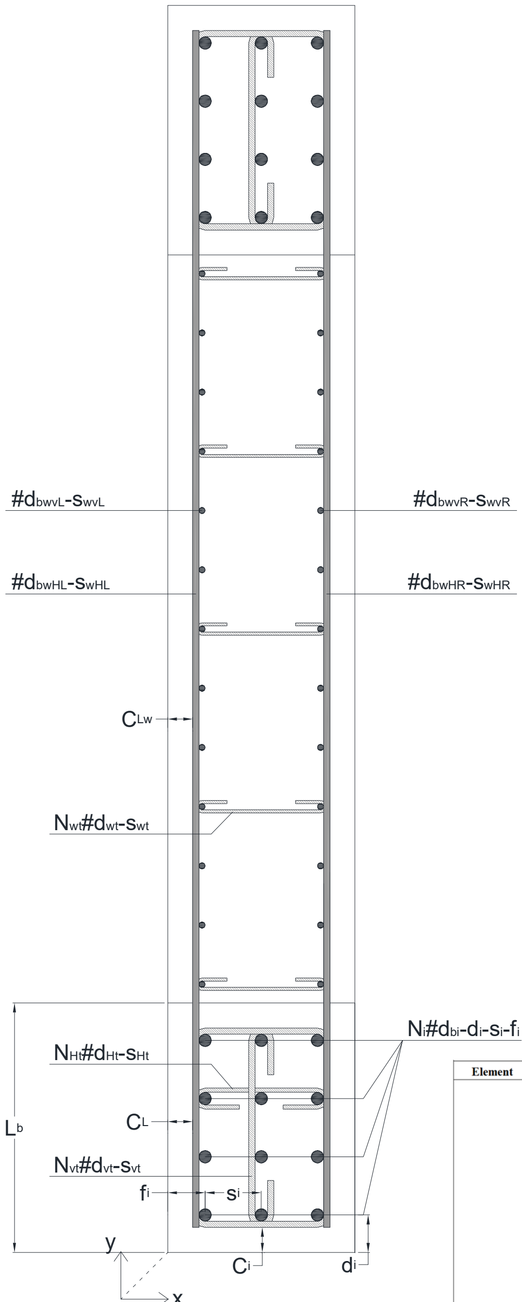
Cross Section View
Lshape Column

Element	Parameter	Description	Example
Column - Rectangular	Longitudinal Bars - Start Column	Comma separated values, with each value containing information of a reinforcement row. Each value contains 5 parameters of the row: Number of bars, diameter of the bars, distance of row from bottom (local y=0), bar spacing and first bar distance from left face (x=0). There can be 3 different lists: one for the start, one for the middle and one for the end of the	4#6-450-180-55, 2#6-250-560-55, 4#6-70-180-55
	Longitudinal Bars - Mid Column		4#6-450-180-55, 2#6-250-560-55, 4#6-70-180-55
	Longitudinal Bars - End Column		4#6-450-180-55, 2#6-250-560-55, 4#6-70-180-55
	Ties - Start Column	There are 4 parameters for the stirrups: Number of closed stirrups, diameter of closes stirrups, horizontal length of each closed stirrup, separation of closed stirrups. There can be 3 different values, one for the start, one for the middle and one for the end of the column.	1#4-590-100
	Ties - Mid Column		1#4-590-200
	Ties - End Column		1#4-590-100
	Vertical Ties - Start Column	There are 3 parameters for the ties: Number of ties, diameter of ties, separation of ties. There can be 3 different values, one for the start, one for the middle and one for the end of the column.	2#4-100
	Vertical Ties - Mid Column		2#4-200
	Vertical Stirrups - End Column		2#4-100
	Horizontal Ties - Start Column		2#4-100
	Horizontal Ties - Mid Column		2#4-200
	Horizontal Ties - End Column		2#4-100
	Fy - Long. Bars	Steel Strength for Longitudinal Bars (Units by file)	420
	Fy - Stir & Ties	Steel Strength for Stirrups and Ties (Units by file)	420
	Cs	Column Cover	50
	Lz	Length of zones. 3 values: start, middle, end length	1000,4000,1000

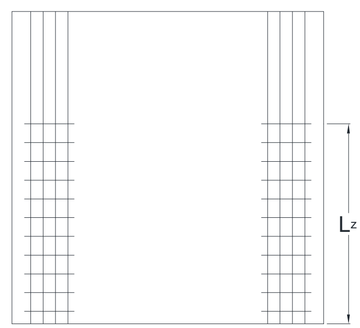
Element	Parameter	Description	Example
Column - L shape	Longitudinal Bars - Start Column	Comma separated values, with each value containing information of a reinforcement row. Each value contains 5 parameters of the row: Number of bars, diameter of the bars, distance of row from bottom (local y=0), bar spacing and first bar distance from left face (x=0). There can be 3 different lists: one for the start of the beam, one for the middle of the beam	4#6-450-180-55, 2#6-250-560-55, 4#6-70-180-55
	Longitudinal Bars - Mid Column		4#6-450-180-55, 2#6-250-560-55, 4#6-70-180-55
	Longitudinal Bars - End Column		4#6-450-180-55, 2#6-250-560-55, 4#6-70-180-55
	Vertical Ties - Start Column	There are 4 parameters for the stirrups in the y direction: Number of closed stirrups, diameter of closes stirrups, vertical length of each closed stirrup, separation of closed stirrups. There can be 3 different values, one for the start, one for the middle and one for the end of the column.	1#4-590-100
	Vertical Ties - Mid Column		1#4-590-200
	Vertical Ties - End Column		1#4-590-100
	Horiz Ties - Start Column	There are 4 parameters for the stirrups in the x direction: Number of closed stirrups, diameter of closes stirrups, horizontal length of each closed stirrup, separation of closed stirrups. There can be 3 different values, one for the start, one for the middle and one for the end of the column.	1#4-620-100
	Horiz Ties - Mid Column		1#4-620-200
	Horiz Ties - End Column		1#4-620-100
	Vertical Ties S - Start Column	There are 3 parameters for the ties: Number of ties, diameter of ties, separation of ties. There can be 3 different values, one for the start, one for the middle and one for the end of the column.	2#4-100
	Vertical Ties S - Mid Column		2#4-200
	Vertical Ties S - End Column		2#4-100
	Horizontal Ties S - Start Column		2#4-100
	Horizontal Ties S - Mid Column		2#4-200
	Horizontal Ties S - End Column		2#4-100
	Fy - Long. Bars	Steel Strength for Longitudinal Bars (Units by file)	420
	Fy - Stir & Ties	Steel Strength for Stirrups and Ties (Units by file)	420
	Cs	Column Cover	50
	Lz	Length of zones. 3 values: start, middle, end length	1000,4000,1000

Element	Parameter	Description	Example
Column - Circular	Longitudinal Bars - Start Column	There are 2 parameters for the longitudinal reinforcement of a circular column: number of bars and diameter of the bars	8#8
	Longitudinal Bars - Mid Column		8#8
	Longitudinal Bars - End Column		8#8
	Ties - Start Column	There are 3 parameters for the stirrups: diameter of stirrup, type (stirrup or spiral), spacing. There can be 3 different values, one for the start, one for the middle and one for the end of the column.	#4-stirrup-100
	Ties - Mid Column		#4-stirrup-200
	Ties - End Column		#4-stirrup-100
	Vertical Ties - Start Column	There are 3 parameters for the ties: Number of ties, diameter of ties, separation of ties. There can be 3 different values, one for the start, one for the middle and one for the end of the column.	1#4-100
	Vertical Ties - Mid Column		1#4-200
	Vertical Ties - End Column		1#4-100
	Horizontal Ties - Start Column		1#4-100
	Horizontal Ties - Mid Column		1#4-200
	Horizontal Ties - End Column		1#4-100
	Fy - Long. Bars	Steel Strength for Longitudinal Bars (Units by file)	420
	Fy - Stir & Ties	Steel Strength for Stirrups and Ties (Units by file)	420
	Cs	Column Cover	50
	Lz	Length of zones. 3 values: start, middle, end length	1000,4000,1000

C.3 Wall



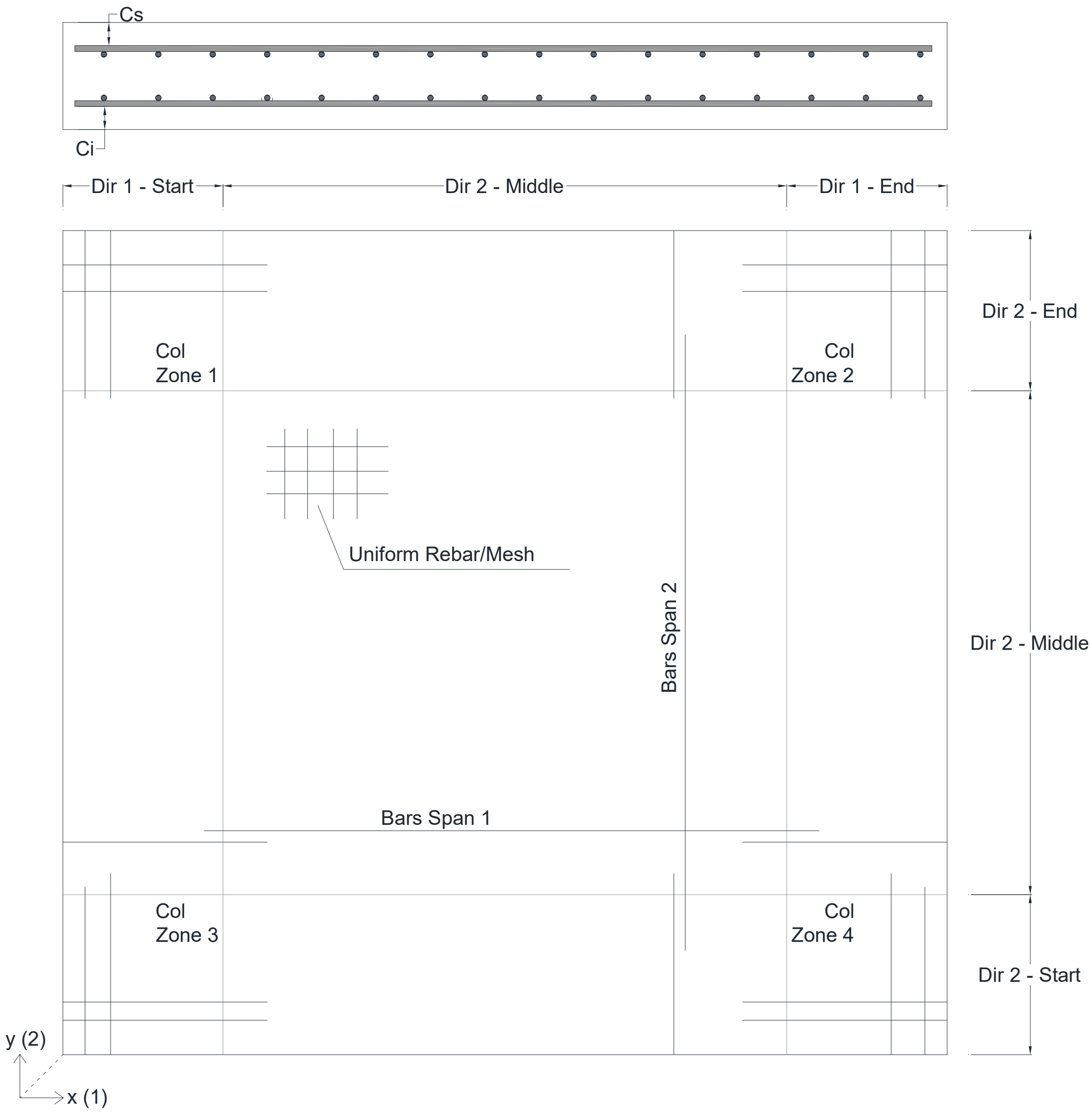
Cross Section View



Longitudinal View

Element	Parameter	Description	Example
Wall	Long. Bars - Border Element	Comma separated values, with each value containing information of a reinforcement row. Each value contains 5 parameters of the row: Number of bars, diameter of the bars, distance of row from bottom of section (local y=0), bar spacing and first bar distance from left face (x=0).	3#6-340-90-60, 3#6-250-90-60, 3#6-150-90-60, 3#6-70-90-60
	Ties - Border Element	There are 4 parameters for stirrups: Number of closed stirrups, diameter of closes stirrups, vertical length of each closed stirrup, separation of closed stirrups in z.	1#4-320-100
	Vertical Ties S - Border Element	There are 3 parameters for the ties: Number of ties, diameter of ties, separation of ties.	1#4-100
	Horizontal Ties - Border Element		1#4-100
	Vertical Wall Bars - Right Side	Vertical (z direction) bars on the rigth side, using y axis as reference. The two parameters are diameter and spacing	#3-200
	Horizontal Wall Bars - Right Side	Horizontal (y direction) bars on the rigth side, using y axis as reference. The two parameters are diameter and spacing	#3-150
	Vertical Wall Bars - Left Side	Vertical (z direction) bars on the left side, using y axis as reference. The two parameters are diameter and spacing	#3-200
	Horizontal Wall Bars - Left Side	Horizontal (y direction) bars on the rigth side, using y axis as reference. The two parameters are diameter and spacing	#3-150
	Wall Ties	There are 3 parameters for the ties: Number of ties, diameter of ties, separation of ties.	5#4-200
	Fy - Long. Bars	Steel Strength for Longitudinal Bars (Units by file)	420
	Fy - Stir & Ties	Steel Strength for Stirrups and Ties (Units by file)	420
	Fy - Wall Reinf	Steel Strength for Wall Reinf. Or Mesh (Units by file)	420
	CLw	X direction (lateral) Wall Cover	20
	Ci	Y direction Boundary Element Cover	30
	CL	X direction (lateral) Boundary Element Cover	20
	Lz	Length of boundary element	2,000

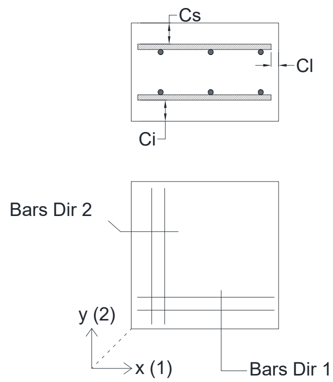
C.4 Slab


Cs
Ci
Dir 1 - Start
Dir 2 - Middle
Dir 1 - End
Dir 2 - End
Col
Zone 1
Col
Zone 2
Uniform Rebar/Mesh
Bars Span 2
Dir 2 - Middle
Bars Span 1
Col
Zone 3
Col
Zone 4
Dir 2 - Start
y (2)
x (1)

Element	Parameter	Description	Example
One-Way Slab	Span Orientation	The span orientation relative to the project north. On most cases this value will be 0 for vertical direction and 90 for horizontal direction. The span direction, to define "start" and "end" shall be defined by the angle of the direction.	90
	Top Uniform Rebar/Mesh	There are 4 parameters for the uniform rebar/mesh if it exists: diameter and separation in span orientation, and diameter and separation in temperature bars orientation.	4-150-4-150
	Bottom Uniform Rebar/Mesh		3-150-3-150
	TopBars - Span Orientation	There are 2 parameters for the top bars: Diameter and separation of bars. There can be up to 3 different values in each direction, one for the start, one for the middle and one for the end of the slab.	#4-150, 0, #4-150
	TopBars - Temperature		0, 0, 0
	TopBars - Col Zone	This parameter exists for slabs with four sides. There are four column zones names with respect to the direction of Span 1 when looking at a floorplan: 1 (top-left), 2 (top-right), 3 (bottom- left), 4 (bottom-right). Each zone, separated by a comma from the next will have 4 parameters: diameter and separation in span orientation, and diameter and separation in temperature bars orientation.	0, 0, 0, #4-150-#4-150
	BotBars - Span Orientation	There are 2 parameters for the bottom bars: Diameter and separation of bars. There can be up to 3 different values in each direction, one for the start, one for the middle and one for the end of the slab.	0, #4-150, 0
	BotBars - Temperature		0, 0, 0
	Cs	Top Cover	20
	Ci	Bot Cover. Empty if "BotBars" parameters are empty.	20
	Fy - Uniform	Steel Strength for Uniform Rebar/Mesh (Units by file).	540
	Fy - Additional	Steel Strength for Non-Uniform Rebar (Units by file).	420
	Lzd	Length of zones in span direction. 3 values: start, middle, end length.	1500, 2000, 1500
	Lzt	Length of zones in temp direction. 3 values: start, middle, end length.	1500, 2000, 1500

Element	Parameter	Description	Example
Two-Way Slab	Orientation - Span 1	The span orientation relative to the project north. On most cases this value will be 0 for vertical direction and 90 for horizontal direction. The span direction, to define "start" and "end" shall be defined by the angle of the direction.	90
	Top Uniform Rebar/Mesh	There are 4 parameters for the uniform rebar/mesh if it exists: diameter and separation in span orientation, and diameter and separation in temperature bars orientation.	4-150-4-150
	Bottom Uniform Rebar/Mesh		3-150-3-150
	TopBars - Span 1	There are 2 parameters for the top bars: Diameter and separation of bars. There can be up to 3 different values in each direction, one for the start, one for the middle and one for the end of the slab.	#4-150, #3-150, #4-150
	TopBars - Span 2		#3-200
	TopBars - Col Zone	This parameter exists for slabs with four sides. There are four column zones names with respect to the direction of Span 1 when looking at a floorplan: 1 (top-left), 2 (top-right), 3 (bottom- left), 4 (bottom-right). Each zone, separated by a comma from the next will have 4 parameters: diameter and separation in span 1 orientation, and diameter and separation in span 2 orientation.	0, 0, #3-150-#3-150, #4-150-#4-150
	BotBars - Span 1	There are 2 parameters for the bottom bars: Diameter and separation of bars. There can be up to 3 different values in each direction, one for the start, one for the middle and one for the end of the slab.	#3-150, #4-150, #3-150
	BotBars - Span 2		#3-200
	Cs	Top Cover	20
	Ci	Bot Cover. Empty if "BotBars" parameters are empty.	20
	Fy - Uniform	Steel Strength for Uniform Rebar/Mesh (Units by file).	540
	Fy - Additional	Steel Strength for Non-Uniform Rebar (Units by file).	420
	Lzd	Length of zones in span 1 direction. 3 values: start, middle, end length.	1500, 2000, 1500
	Lzt	Length of zones in span 2 direction. 3 values: start, middle, end length.	1500, 2000, 1500

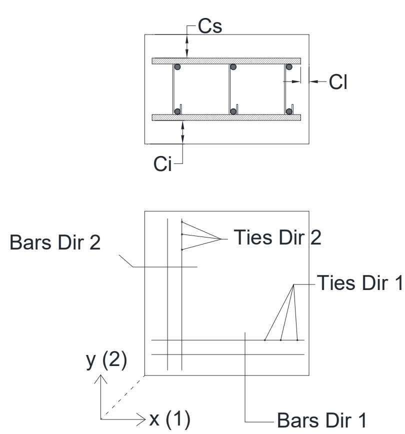
C.5 Footing



Element	Parameter	Description	Example
Strip Footing	TopBars - Strip Dir	There are 2 parameters for the top bars: Diameter and separation of bars.	#3-100
	TopBars - Short Dir		#3-250
	BotBars - Strip Dir	There are 2 parameters for the bottom bars: Diameter and separation of bars.	#4-100
	BotBars - Short Dir		#4-200
	Cs	Top Cover.	60
	Ci	Bot Cover	60
	Cl	Lateral Cover	60
	Fy	Steel Strength for Rebar (Units by file).	420

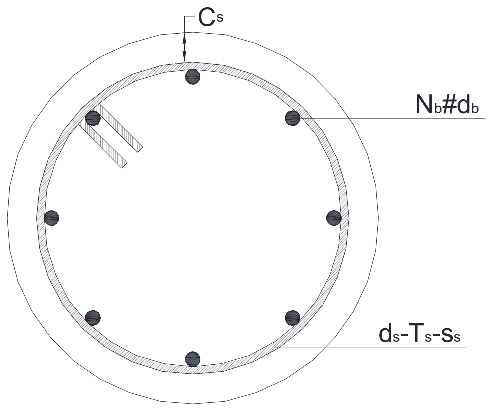
Element	Parameter	Description	Example
Spread Footing	Orientation - Dir 1	The orientation 1 relative to the project north. On most cases this value will be 0 for vertical direction and 90 for horizontal direction. The span direction shall be defined by the angle of the orientation.	90
	TopBars - Dir 1	There are 2 parameters for the top bars: Diameter and separation of bars.	#3-250
	TopBars - Dir 2		#3-250
	BotBars - Dir 1	There are 2 parameters for the bottom bars: Diameter and separation of bars.	#4-150
	BotBars - Dir 2		#4-200
	Cs	Top Cover.	60
	Ci	Bot Cover	60
	Cl	Lateral Cover	60
	Fy	Steel Strength for Rebar (Units by file).	420

C.6 Pile Cap

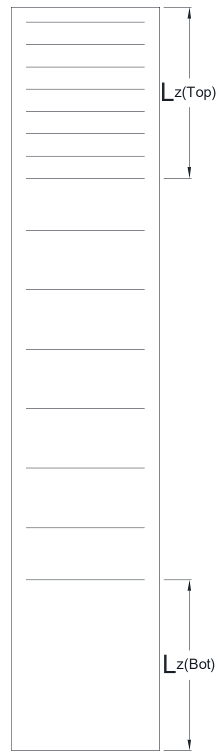


Element	Parameter	Description	Example
Pile Cap	Orientation - Dir 1	The orientation 1 relative to the project north. On most cases this value will be 0 for vertical direction and 90 for horizontal direction. The span direction shall be defined by the angle of the orientation.	90
	TopBars - Dir 1	There are 2 parameters for the top bars: Diameter and separation of bars.	#3-250
	TopBars - Dir 2		#3-250
	BotBars - Dir 1	There are 2 parameters for the bottom bars: Diameter and separation of bars.	#4-150
	BotBars - Dir 2		#4-200
	Ties - Dir 1	There are 2 parameters for the ties if the pile cap has them: Diameter and separation of ties.	#4-150
	Ties - Dir 2		#4-150
	Cs	Top Cover.	60
	Ci	Bot Cover	60
	Cl	Lateral Cover	60
	Fy - Rebar	Steel Strength for Rebar (Units by file).	420
	Fy - Ties	Steel Strength for Ties (Units by file).	420

C.7 Pile



Cross Section View
Pile



Longitudinal View

Element	Parameter	Description	Example
Pile	Longitudinal Bars - Top Pile	There are 2 parameters for the longitudinal reinforcement of a circular pile: number of bars and diameter of the bars	12#8
	Longitudinal Bars - Mid Pile		6#8
	Longitudinal Bars - Bottom Pile		0
	Ties - Top Pile	There are 3 parameters for the stirrups: diameter of stirrup, type (stirrup or spiral), spacing. There can be 3 different values, one for the top, one for the middle and one for the bottom of the pile.	#4-stirrup-100
	Ties - Mid Pile		#4-stirrup-200
	Ties - Bottom Pile		0
	Fy - Long. Bars	Steel Strength for Longitudinal Bars (Units by file)	420
	Fy - Stirrups	Steel Strength for Stirrups (Units by file)	420
	Cs	Column Cover	50
	Lz	Length of zones. 3 values: Top, middle, bottom length	5000,5000,5000

APPENDIX D. TEMPLATES FOR DESIGN INTENT PARAMETRIZATION

D.1 Beam

Beam								
Type Mark	B2							
Concrete Mix	C-28-Beam-A							
Width	300							
Height	600							
Length	5500			Store Type				
Top Cover	40							
Side Cover	40							
Bottom Cover	40							
Left Zone Length	800							
Right Zone Length	800							
Fy Long Bars	420							
Fy Stirrups & Ties	420							
Stirrups								Parameters
	Diameter	Number	Width (Auto)	Width (Input)	Width	Separation		
Start Beam	3	1	220		220	150		1#3-220-150
Middle Beam	3	1	220		220	300		1#3-220-300
End Beam	3	1	220		220	150		1#3-220-150
Ties								
	Diameter	Number	Separation					
Start Beam	3	1	150					1#3-150
Middle Beam	3	1	300					1#3-300
End Beam	3	1	150					1#3-150
Top Reinforcement								
	Diameter	Number	d'	Spacing (Input)	First (Input)	Spacing	First Bar	
Start Beam	5	3	57			93	57	3#5-543-93-57
						-201	50	0
Middle Beam	5	2	57			185	57	2#5-543-185-57
						-201	50	0
End Beam	5	3	57			93	57	3#5-543-93-57
						-201	50	0
Middle Reinforcement								
	Diameter	Number	d	Spacing (Input)	First (Input)	Spacing	First Bar	
Start Beam	4	2	300			188	56	2#4-300-188-56
						-201	50	0
Middle Beam	4	2	300			188	56	2#4-300-188-56
						-201	50	0
End Beam	4	2	300			188	56	2#4-300-188-56
						-201	50	0
Bottom Reinforcement								
	Diameter	Number	d	Spacing (Input)	First (Input)	Spacing	First Bar	
Start Beam	5	2	57			185	57	2#5-57-185-57
						-201	50	0
Middle Beam	5	4	57			62	57	4#5-57-62-57
						-201	50	0
End Beam	5	2	57			185	57	2#5-57-185-57
						-201	50	0

Concrete Mix Parameters	
Concrete Mix Row Location	2
Concrete - Mix Identifier	C-28-Beam-A
Concrete - Strength	4000
Concrete - Strength Age	28
Concrete - Min E	4350
Concrete - Cement Type	Portland I
Concrete - Aggregate Type	Normal
Concrete - Slump	2"
Concrete - Max Aggregate Size	1"
Concrete - W/C Ratio	0.45
Concrete - Durability Requirements	N/A

D.2 Column

Column	
Type Mark	C2
Concrete Mix	C-28-Column-A
Width	600
Height	600
Length	4500
Rebar Cover	40
Start Zone Length	1000
End Zone Length	1000
Fy Long Bars	420
Fy Stirrups & Ties	420

Store Type

Stirrups							Parameters
	Diameter	Number	Width (Auto)	Width (Input)	Width	Separation	
Top Column	4	1	520		520	100	1#4-520-100
Middle Column	4	1	520		520	200	1#4-520-200
Bottom Column	4	1	520		520	100	1#4-520-100

Vertical Ties				
	Diameter	Number	Separation	
Top Column	4	1	100	1#4-100
Middle Column	4	1	200	1#4-200
Bottom Column	4	1	100	1#4-100

Horizontal Ties				
	Diameter	Number	Separation	
Top Column	4	1	100	1#4-100
Middle Column	4	1	200	1#4-200
Bottom Column	4	1	100	1#4-100

Top Reinforcement								
	Diameter	Number	d	Spacing (Input)	First (Input)	Spacing	First Bar	
Top Column	8	3	535			235	65	3#8-65-235-65
	8	2	300			469	65	2#8-300-469-65
	8	3	65			235	65	3#8-535-235-65
						-495	53	0
						-495	53	0
Middle Column	8	3	535			235	65	3#8-65-235-65
	8	2	300			469	65	2#8-300-469-65
	8	3	65			235	65	3#8-535-235-65
						-495	53	0
						-495	53	0
Bottom Column	8	3	535			235	65	3#8-65-235-65
	8	2	300			469	65	2#8-300-469-65
	8	3	65			235	65	3#8-535-235-65
						-495	53	0
						-495	53	0

Concrete Mix Parameters	
Concrete Mix Row Location	13
Concrete - Mix Identifier	C-28-Column-A
Concrete - Strength	4000
Concrete - Strength Age	28
Concrete - Min E	4350
Concrete - Cement Type	Portland I
Concrete - Aggregate Type	Normal
Concrete - Slump	2"
Concrete - Max Aggregate Size	1"
Concrete - W/C Ratio	0.4
Concrete - Durability Requirements	N/A

D.3 Wall

Wall	
Wall Type Mark	W2
Concrete Mix	C-35-Wall-A
Wall Width	300
Wall Length	2500
Wall Hieght	3000
Length Border Element	0
Height Border Element	0
Border Elem Cover (Side)	0
Border Elem Cover (Extr)	0
Wall Cover	20
Fy Long Bars	420
Fy Stirrups & Ties	420
Fy Wall Reinforcement	420

Store Type

Stirrups - Border Element								Parameters
	Diameter	Number	Width (Auto)	Width (Input)	Width	Separation		
Total	0	1	300		300	150		0
Vertical Ties - Border Element								
	Diameter	Number	Separation					
Total	0	1	150					0
Horizontal Ties - Border Element								
	Diameter	Number	Separation					
Total	0	1	150					0
Border Element Reinforcement								
	Diameter	Number	d	Spacing (Input)	First (Input)	Spacing	First Bar	
Total	0	4	0			100	0	0
	0	4	0			100	0	0
						-300	0	0
						-300	0	0
						-300	0	0
Wall Reinforcement								
	Diameter	Separation						
Vertical - Right Side	3	250						#3-250
Horizontal - Right Side	3	250						#3-250
Vertical - Left Side	3	250						#3-250
Horizontal - Left Side	3	250						#3-250
Wall Ties								
	Diameter	Number	Separation					
Total	3	5	300					5#3-300

Concrete Mix Parameters	
Concrete Mix Row Location	24
Concrete - Mix Identifier	C-35-Wall-A
Concrete - Strength	5000
Concrete - Strength Age	28
Concrete - Min E	5500
Concrete - Cement Type	Portland I
Concrete - Aggregate Type	Normal
Concrete - Slump	2"
Concrete - Max Aggregate Size	1"
Concrete - W/C Ratio	0.4
Concrete - Durability Requirements	Additives A & B

D.4 Slab

Slab			
Slab Type Mark	S2		
Concrete Mix	C-21-General-A		
Orientation Span 1	90		
Slab Thickness	200		
Slab Dimension Dir 1	5500		
Slab Dimension Dir 2	5500		Store Type
Top Cover	20		
Bottom Cover	20		
Length of Start Zone Dir 1	1000		
Length of End Zone Dir 1	1000		
Length of Start Zone Dir 2	1000		
Length of End Zone Dir 2	1000		
Fy Uniform Mesh/Rebar	540		
Fy Additional Rebar	420		
Uniform Rebar/Mesh			Parameters
	Diameter	Separation	
Top - Dir 1	5mm	150	5mm-150
Top - Dir 2	5mm	150	5mm-150
Bottom - Dir 1	5mm	150	5mm-150
Bottom - Dir 2	5mm	150	5mm-150
Top Bars			
	Diameter	Separation	
Span 1 - Start	3	300	#3-300
Span 1 - Middle			0
Span 1 - End	3	300	#3-300
Span 2 - Start	3	300	#3-300
Span 2 - Middle			0
Span 2 - End	3	300	#3-300
Column Zone - 1 - Dir 1	3	300	#3-300-#3-300
Column Zone - 1 - Dir 2	3	300	
Column Zone - 2 - Dir 1	3	300	#3-300-#3-300
Column Zone - 2 - Dir 2	3	300	
Column Zone - 3 - Dir 1	3	300	#3-300-#3-300
Column Zone - 3 - Dir 2	3	300	
Column Zone - 4 - Dir 1	3	300	#3-300-#3-300
Column Zone - 4 - Dir 2	3	300	
Bottom Bars			
	Diameter	Separation	
Span 1 - Start			0
Span 1 - Middle	3	150	#3-150
Span 1 - End			0
Span 2 - Start			0
Span 2 - Middle	3	150	#3-150
Span 2 - End			0

Concrete Mix Parameters	
Concrete Mix Row Location	35
Concrete Slab - Mix Identifier	C-21-General-A
Concrete Slab - Strength	3000
Concrete Slab - Strength Age	28
Concrete Slab - Min E	3500
Concrete Slab - Cement Type	Portland I
Concrete Slab - Aggregate Type	Lightweight
Concrete Slab - Slump	2"
Concrete Slab - Max Aggregate Size	1"
Concrete Slab - W/C Ratio	N/A
Concrete Slab - Durability Requirements	N/A

D.5 Footing

Spread Footing			
Spead Fooring Type Mark	SpF2		
Concrete Mix	C-21-General-A		
Orientation Dir 1	90		Store Type
Footing Thickness	450		
Footing Dimension Dir 1	1800		
Footing Dimension Dir 2	1200		
Top Cover	75		
Bottom Cover	75		
Side Cover	75		
Fy Rebar	420		
Top Bars			Parameters
	Diameter	Separation	
Dir 1	3	300	#3-300
Dir 2	3	300	#3-300
Bottom Bars			
	Diameter	Separation	
Dir 1	5	200	#5-200
Dir 2	5	250	#5-250

Concrete Mix Parameters	
Concrete Mix Row Location	35
Concrete - Mix Identifier	C-21-General-A
Concrete - Strength	3000
Concrete - Strength Age	28
Concrete - Min E	3500
Concrete - Cement Type	Portland I
Concrete - Aggregate Type	Lightweight
Concrete - Slump	2"
Concrete - Max Aggregate Size	1"
Concrete - W/C Ratio	N/A
Concrete - Durability Requirements	N/A

StripFooting			
Strip Footing Type Mark	StF2		
Concrete Mix	C-21-General-A		
Footing Thickness	450		
Footing Length	7000		Store Type
Footing Width	1200		
Top Cover	75		
Bottom Cover	75		
Side Cover	75		
Fy Rebar	420		
Top Bars			Parameters
	Diameter	Separation	
Spread Direction	3	300	#3-300
Short Direction	3	300	#3-300
Bottom Bars			
	Diameter	Separation	
Spread Direction	4	150	#4-150
Short Direction	5	250	#5-250

Concrete Mix Parameters	
Concrete Mix Row Location	35
Concrete - Mix Identifier	C-21-General-A
Concrete - Strength	3000
Concrete - Strength Age	28
Concrete - Min E	3500
Concrete - Cement Type	Portland I
Concrete - Aggregate Type	Lightweight
Concrete - Slump	2"
Concrete - Max Aggregate Size	1"
Concrete - W/C Ratio	N/A
Concrete - Durability Requirements	N/A

D.6 Pile Cap

Pile Cap			
PileCap Type Mark	PC1		
Concrete Mix	C-21-General-A		
Orientation Dir 1	90		
Footing Thickness	600		
Footing Dimension Dir 1	1800		Store Type
Footing Dimension Dir 2	1800		
Top Cover	75		
Bottom Cover	75		
Side Cover	75		
Fy Rebar	420		
Fy Ties	420		
Top Bars			Parameters
	Diameter	Separation	
Dir 1	4	300	#4-300
Dir 2	4	300	#4-300
Bottom Bars			
	Diameter	Separation	
Dir 1	7	150	#7-150
Dir 2	7	150	#7-150
Ties			
	Diameter	Separation	
Dir 1	4	300	#4-300
Dir 2	4	300	#4-300

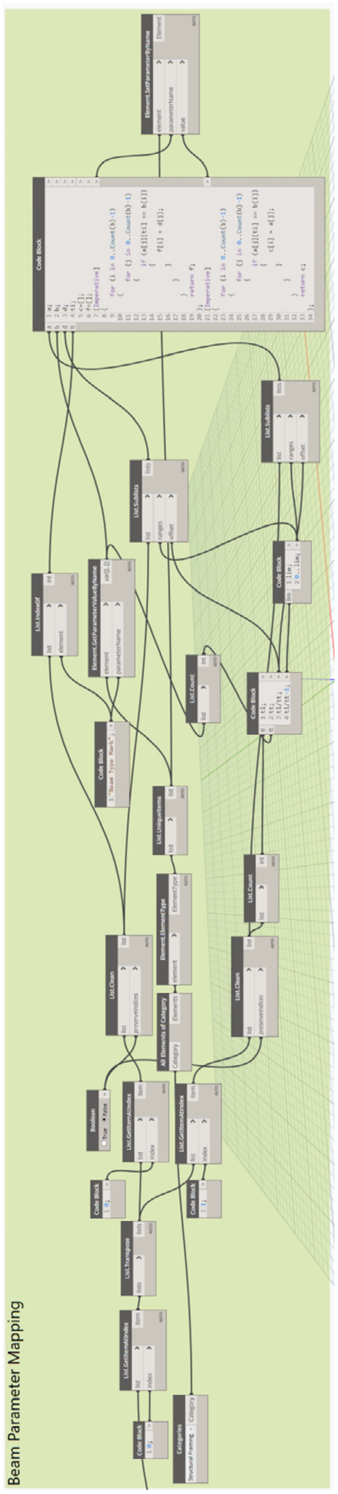
Concrete Mix Parameters	
Concrete Mix Row Location	35
Concrete - Mix Identifier	C-21-General-A
Concrete - Strength	3000
Concrete - Strength Age	28
Concrete - Min E	3500
Concrete - Cement Type	Portland I
Concrete - Aggregate Type	Lightweight
Concrete - Slump	2"
Concrete - Max Aggregate Size	1"
Concrete - W/C Ratio	N/A
Concrete - Durability Requirements	N/A

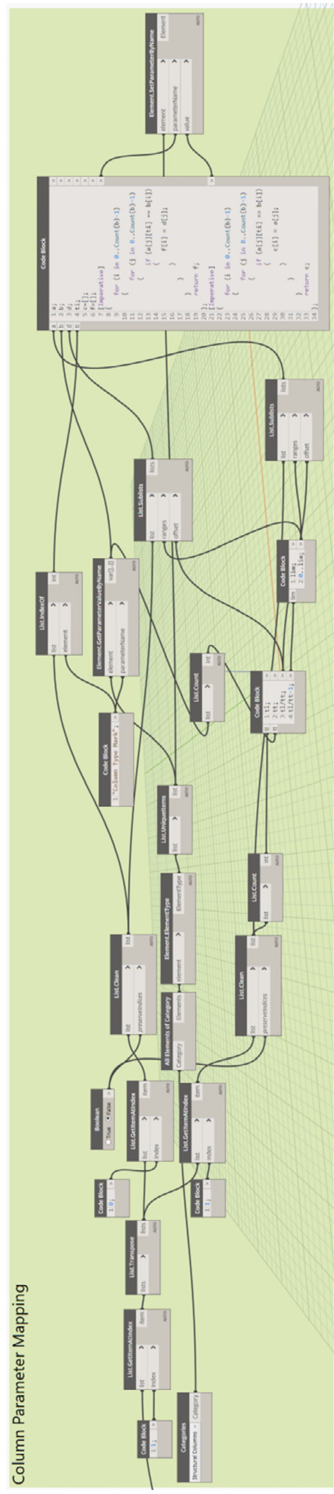
D.7 Pile

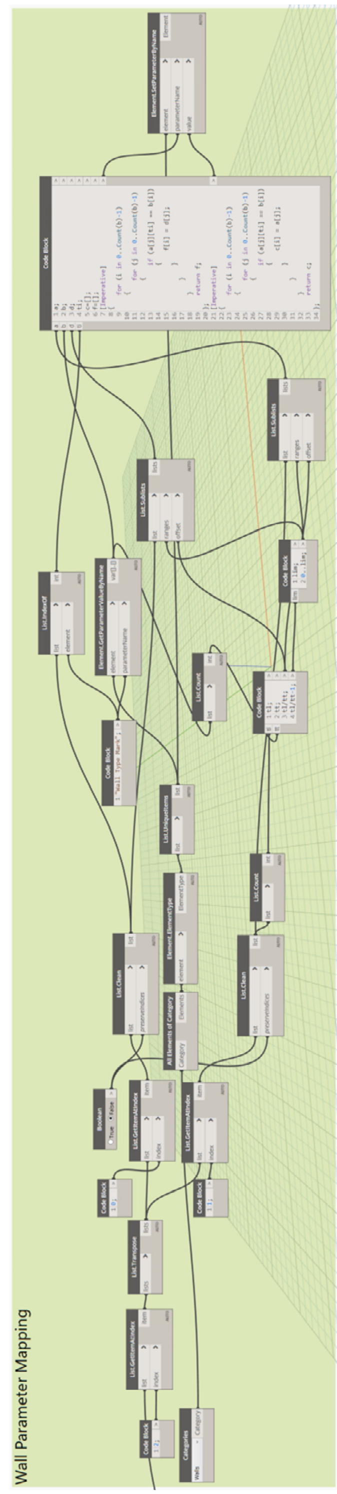
Pile				
Pile Type Mark	P2			
Concrete Mix	C-21-General-A			
Diameter	300			
Depth	5000			Store Type
Rebar Cover	75			
Top Zone Length	2000			
Bottom Zone Length	4000			
Fy Long Bars	420			
Fy Stirrups	420			
Stirrups				Parameters
	Diameter	Type	Separation	
Top Pile	4	Spiral	150	#4-Spiral-150
Middle Pile	4	Spiral	300	#4-Spiral-300
Bottom Pile				0
Longitudinal Reinforcement				
	Diameter	Number		
Top Pile	8	8		8#8
Middle Pile	8	4		4#8
Bottom Pile				0

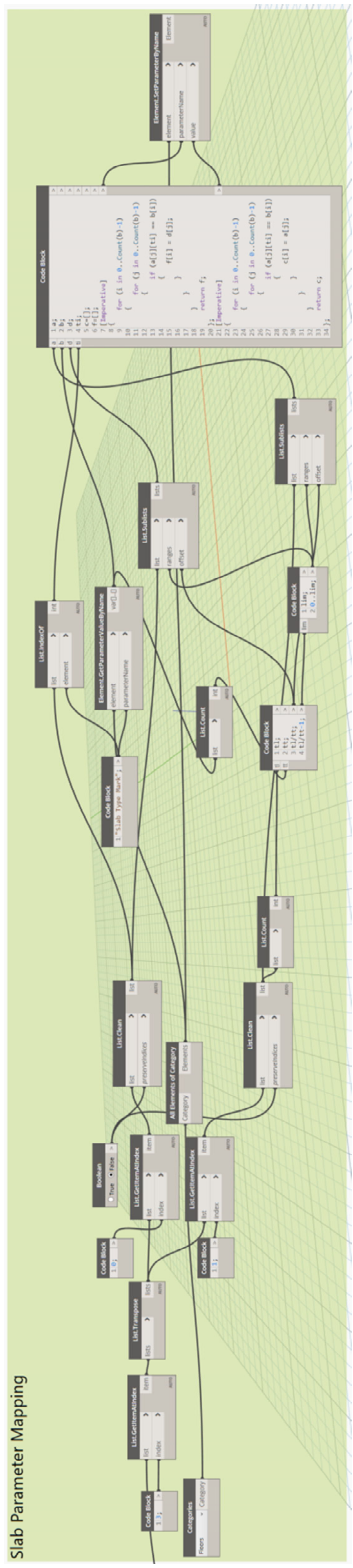
Concrete Mix Parameters	
Concrete Mix Row Location	35
Concrete - Mix Identifier	C-21-General-A
Concrete - Strength	3000
Concrete - Strength Age	28
Concrete - Min E	3500
Concrete - Cement Type	Portland I
Concrete - Aggregate Type	Lightweight
Concrete - Slump	2"
Concrete - Max Aggregate Size	1"
Concrete - W/C Ratio	N/A
Concrete - Durability Requirements	N/A

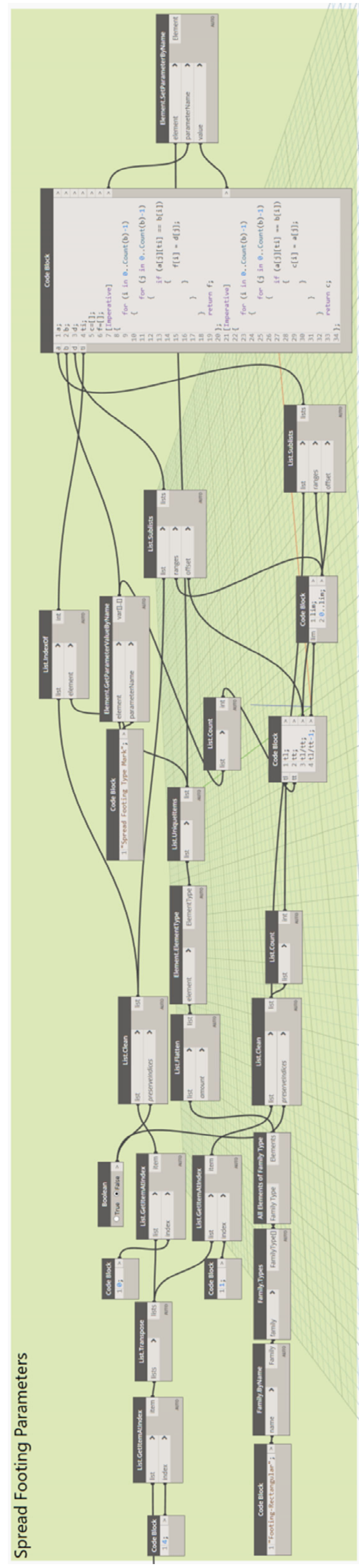
APPENDIX E. DYNAMO CODES FOR DESIGN INTENT INFORMATION MATCHING AND MAPPING

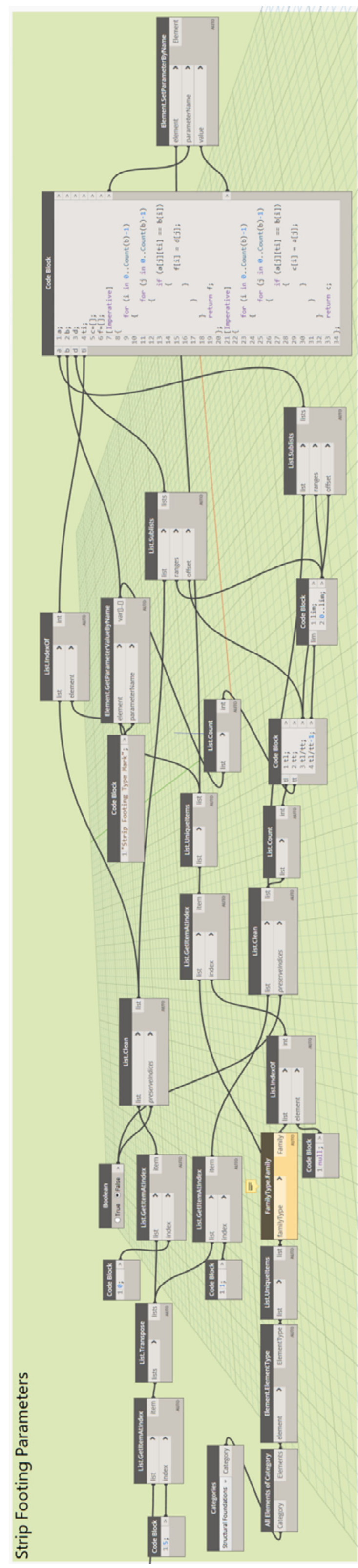


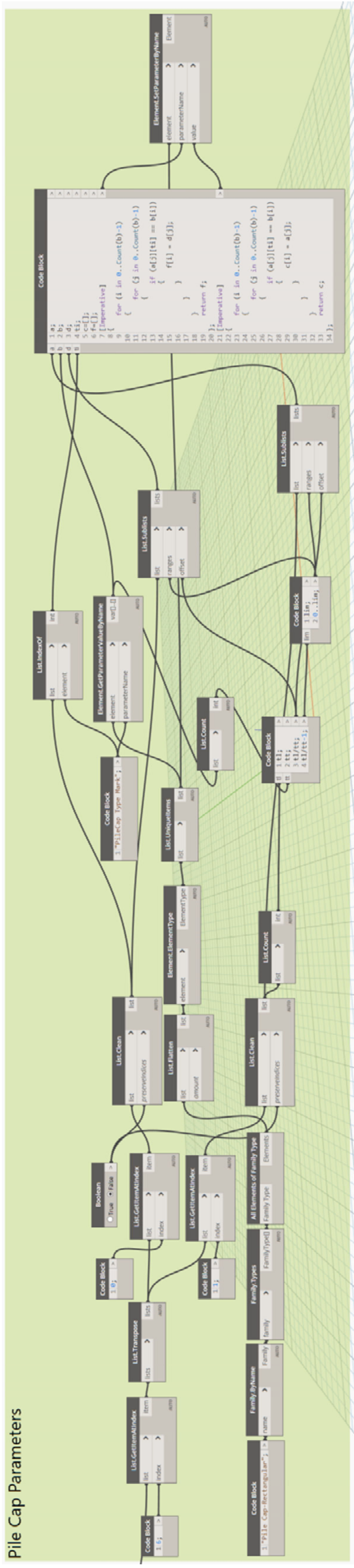


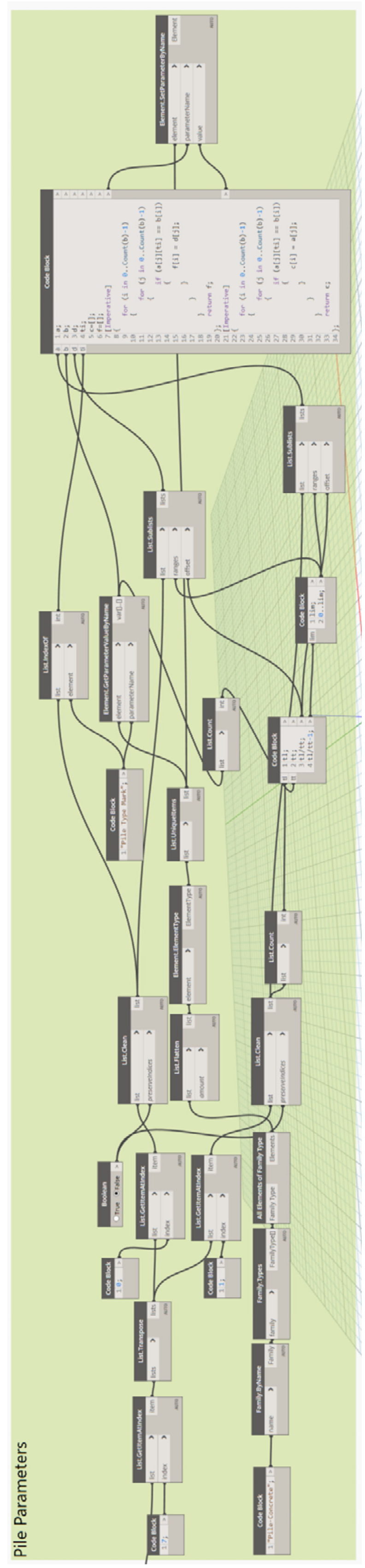



Slab Parameter Mapping

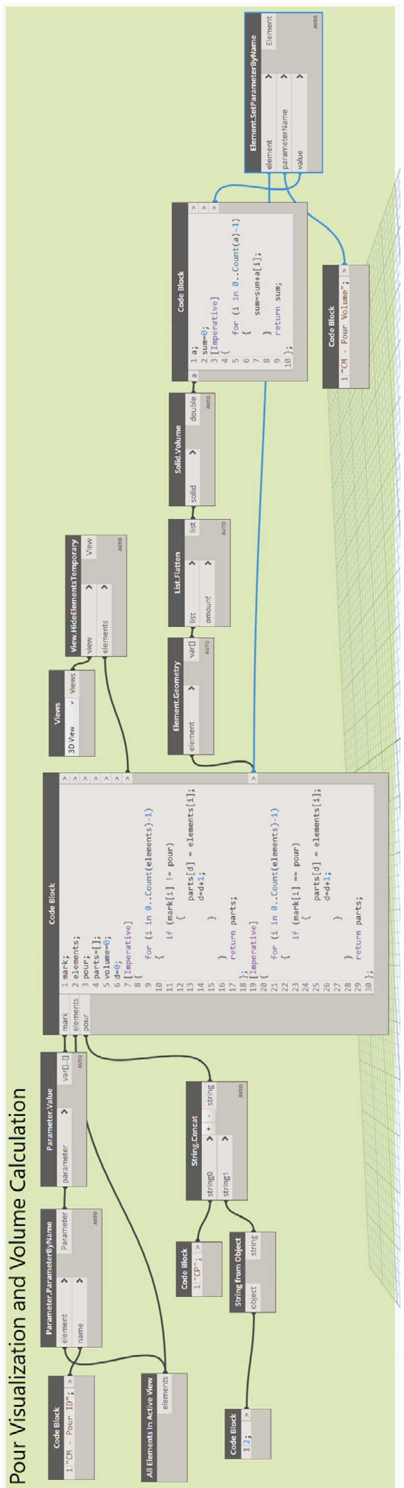

Spread Footing Parameters

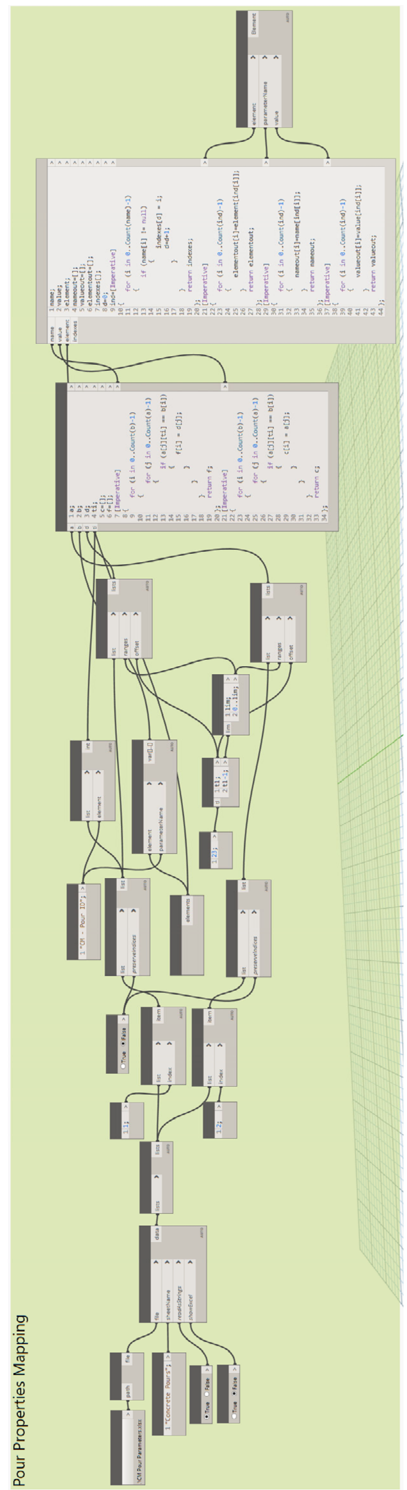

Strip Footing Parameters


Pile Cap Parameters


Pile Parameters

APPENDIX F. DYNAMO CODES FOR CONSTRUCTION PLANNING INFORMATION MATCHING AND VISUALIZATION





APPENDIX G. BEAM, COLUMN AND SLAB SECTIONS FOR TRAINING DATABASE

G.1 Beams

Width	Height	Cover	Top bar ϕ row 1	# top bar row 1	Top bar ϕ row 2	# top bar row 2	Top bar ρ	Top bar S	Bot bar ϕ row 1	# bot bar row 1	Bot bar ϕ row 2	# bot bar row 2	Bot bar ρ	Bot bar S	Shear S	Shear bar ϕ	# shear bar	Shear bar Sep
8	12	2	4	2	0	0	0.5%	3.50	5	3	0	0	1.1%	1.38	6	3	2	3.63
8	12	2	4	2	0	0	0.5%	3.50	5	3	0	0	1.1%	1.38	12	3	2	3.63
8	12	2	4	2	0	0	0.5%	3.50	6	2	0	0	1.1%	3.25	6	3	2	3.63
8	12	2	4	2	0	0	0.5%	3.50	6	2	0	0	1.1%	3.25	12	3	2	3.63
8	12	2	4	2	0	0	0.5%	3.50	7	3	0	0	2.3%	1.13	6	3	2	3.63
8	12	2	4	2	0	0	0.5%	3.50	7	3	0	0	2.3%	1.13	12	3	2	3.63
8	12	2	4	2	0	0	0.5%	3.50	8	2	0	0	2.0%	3.00	6	3	2	3.63
8	12	2	4	2	0	0	0.5%	3.50	8	2	0	0	2.0%	3.00	12	3	2	3.63
8	12	2	5	3	0	0	1.1%	1.38	4	2	0	0	0.5%	3.50	3	3	2	3.63
8	12	2	5	3	0	0	1.1%	1.38	4	2	0	0	0.5%	3.50	6	3	2	3.63
8	12	2	6	2	0	0	1.1%	3.25	4	2	0	0	0.5%	3.50	3	3	2	3.63
8	12	2	6	2	0	0	1.1%	3.25	4	2	0	0	0.5%	3.50	6	3	2	3.63
8	12	2	7	3	0	0	2.3%	1.13	4	2	0	0	0.5%	3.50	3	3	2	3.63
8	12	2	7	3	0	0	2.3%	1.13	4	2	0	0	0.5%	3.50	6	3	2	3.63
8	12	2	8	2	0	0	2.0%	3.00	4	2	0	0	0.5%	3.50	3	3	2	3.63
8	12	2	8	2	0	0	2.0%	3.00	4	2	0	0	0.5%	3.50	6	3	2	3.63
16	24	2	7	3	0	0	0.5%	5.13	6	4	6	4	1.0%	3.25	6	3	3	5.63
16	24	2	7	3	0	0	0.5%	5.13	6	4	6	4	1.0%	3.25	12	3	3	5.63
16	24	2	7	3	0	0	0.5%	5.13	6	4	6	4	1.0%	3.25	24	3	3	5.63
16	24	2	7	3	0	0	0.5%	5.13	8	4	8	2	1.3%	3.00	6	3	3	5.63
16	24	2	7	3	0	0	0.5%	5.13	8	4	8	2	1.3%	3.00	12	3	3	5.63
16	24	2	7	3	0	0	0.5%	5.13	8	4	8	2	1.3%	3.00	24	3	3	5.63
16	24	2	7	3	0	0	0.5%	5.13	8	5	8	5	2.2%	2.00	6	3	3	5.63
16	24	2	7	3	0	0	0.5%	5.13	8	5	8	5	2.2%	2.00	12	3	3	5.63
16	24	2	7	3	0	0	0.5%	5.13	8	5	8	5	2.2%	2.00	24	3	3	5.63
16	24	2	7	3	0	0	0.5%	5.13	9	4	9	4	2.3%	2.88	6	3	3	5.63
16	24	2	7	3	0	0	0.5%	5.13	9	4	9	4	2.3%	2.88	12	3	3	5.63
16	24	2	7	3	0	0	0.5%	5.13	9	4	9	4	2.3%	2.88	24	3	3	5.63
16	24	2	6	4	6	4	1.0%	3.25	7	3	0	0	0.5%	5.13	3	3	3	5.63
16	24	2	6	4	6	4	1.0%	3.25	7	3	0	0	0.5%	5.13	6	3	3	5.63
16	24	2	6	4	6	4	1.0%	3.25	7	3	0	0	0.5%	5.13	12	3	3	5.63
16	24	2	8	4	8	2	1.3%	3.00	7	3	0	0	0.5%	5.13	3	3	3	5.63
16	24	2	8	4	8	2	1.3%	3.00	7	3	0	0	0.5%	5.13	6	3	3	5.63
16	24	2	8	4	8	2	1.3%	3.00	7	3	0	0	0.5%	5.13	12	3	3	5.63
16	24	2	8	5	8	5	2.2%	2.00	7	3	0	0	0.5%	5.13	3	3	4	3.63
16	24	2	8	5	8	5	2.2%	2.00	7	3	0	0	0.5%	5.13	6	3	4	3.63
16	24	2	8	5	8	5	2.2%	2.00	7	3	0	0	0.5%	5.13	12	3	4	3.63
16	24	2	9	4	9	4	2.3%	2.88	7	3	0	0	0.5%	5.13	3	3	4	3.63
16	24	2	9	4	9	4	2.3%	2.88	7	3	0	0	0.5%	5.13	6	3	4	3.63
16	24	2	9	4	9	4	2.3%	2.88	7	3	0	0	0.5%	5.13	12	3	4	3.63
24	36	2	8	4	8	2	0.6%	5.67	9	6	9	4	1.2%	2.88	6	4	4	6.17
24	36	2	8	4	8	2	0.6%	5.67	9	6	9	4	1.2%	2.88	12	4	4	6.17
24	36	2	8	4	8	2	0.6%	5.67	9	6	9	4	1.2%	2.88	24	4	4	6.17
24	36	2	8	4	8	2	0.6%	5.67	10	4	10	4	1.2%	5.42	6	4	4	6.17
24	36	2	8	4	8	2	0.6%	5.67	10	4	10	4	1.2%	5.42	12	4	4	6.17
24	36	2	8	4	8	2	0.6%	5.67	10	4	10	4	1.2%	5.42	24	4	4	6.17
24	36	2	8	4	8	2	0.6%	5.67	9	8	9	8	1.9%	1.73	6	4	4	6.17
24	36	2	8	4	8	2	0.6%	5.67	9	8	9	8	1.9%	1.73	12	4	4	6.17
24	36	2	8	4	8	2	0.6%	5.67	9	8	9	8	1.9%	1.73	24	4	4	6.17
24	36	2	8	4	8	2	0.6%	5.67	10	6	10	6	1.8%	2.75	6	4	4	6.17
24	36	2	8	4	8	2	0.6%	5.67	10	6	10	6	1.8%	2.75	12	4	4	6.17
24	36	2	8	4	8	2	0.6%	5.67	10	6	10	6	1.8%	2.75	24	4	4	6.17
24	36	2	9	6	9	4	1.2%	2.88	8	4	8	2	0.6%	5.67	3	4	4	6.17
24	36	2	9	6	9	4	1.2%	2.88	8	4	8	2	0.6%	5.67	6	4	4	6.17
24	36	2	9	6	9	4	1.2%	2.88	8	4	8	2	0.6%	5.67	12	4	4	6.17
24	36	2	10	4	10	4	1.2%	5.42	8	4	8	2	0.6%	5.67	3	4	4	6.17
24	36	2	10	4	10	4	1.2%	5.42	8	4	8	2	0.6%	5.67	6	4	4	6.17
24	36	2	10	4	10	4	1.2%	5.42	8	4	8	2	0.6%	5.67	12	4	4	6.17
24	36	2	9	8	9	8	1.9%	1.73	8	4	8	2	0.6%	5.67	3	4	5	4.50
24	36	2	9	8	9	8	1.9%	1.73	8	4	8	2	0.6%	5.67	6	4	5	4.50
24	36	2	9	8	9	8	1.9%	1.73	8	4	8	2	0.6%	5.67	12	4	5	4.50
24	36	2	10	6	10	6	1.8%	2.75	8	4	8	2	0.6%	5.67	3	4	5	4.50
24	36	2	10	6	10	6	1.8%	2.75	8	4	8	2	0.6%	5.67	6	4	5	4.50
24	36	2	10	6	10	6	1.8%	2.75	8	4	8	2	0.6%	5.67	12	4	5	4.50

G.2 Columns

Width	Depth	Cover	Bar ϕ	# Bars	Column ρ	Bar/Face	S Bars	Shear S	Shear bar ϕ	# shear bar	Shear bar Sep	Shear ρ
12	12	2	4	12	1.6%	3	4.0	2	3	2	7.63	0.9%
12	12	2	4	12	1.6%	3	4.0	4	3	2	7.63	0.5%
12	12	2	4	12	1.6%	3	4.0	6	3	2	7.63	0.3%
12	12	2	5	8	1.7%	2	8.0	2	3	2	7.63	0.9%
12	12	2	5	8	1.7%	2	8.0	4	3	2	7.63	0.5%
12	12	2	5	8	1.7%	2	8.0	6	3	2	7.63	0.3%
12	12	2	6	16	4.9%	4	2.7	2	3	2	7.63	0.9%
12	12	2	6	16	4.9%	4	2.7	4	3	2	7.63	0.5%
12	12	2	6	16	4.9%	4	2.7	6	3	2	7.63	0.3%
12	12	2	7	12	5.0%	3	4.0	2	3	2	7.63	0.9%
12	12	2	7	12	5.0%	3	4.0	4	3	2	7.63	0.5%
12	12	2	7	12	5.0%	3	4.0	6	3	2	7.63	0.3%
12	12	2	7	16	6.7%	4	2.7	2	3	2	7.63	0.9%
12	12	2	7	16	6.7%	4	2.7	4	3	2	7.63	0.5%
12	12	2	7	16	6.7%	4	2.7	6	3	2	7.63	0.3%
12	12	2	8	12	6.5%	3	4.0	2	3	2	7.63	0.9%
12	12	2	8	12	6.5%	3	4.0	4	3	2	7.63	0.5%
12	12	2	8	12	6.5%	3	4.0	6	3	2	7.63	0.3%
18	18	2	6	12	1.6%	3	7.0	2	3	2	13.63	0.6%
18	18	2	6	12	1.6%	3	7.0	4	3	2	13.63	0.3%
18	18	2	6	12	1.6%	3	7.0	6	3	2	13.63	0.2%
18	18	2	7	8	1.5%	2	14.0	2	3	2	13.63	0.6%
18	18	2	7	8	1.5%	2	14.0	4	3	2	13.63	0.3%
18	18	2	7	8	1.5%	2	14.0	6	3	2	13.63	0.2%
18	18	2	8	20	4.8%	5	3.5	2	3	3	6.63	0.9%
18	18	2	8	20	4.8%	5	3.5	4	3	3	6.63	0.5%
18	18	2	8	20	4.8%	5	3.5	6	3	3	6.63	0.3%
18	18	2	9	16	4.9%	4	4.7	2	3	2	13.63	0.6%
18	18	2	9	16	4.9%	4	4.7	4	3	2	13.63	0.3%
18	18	2	9	16	4.9%	4	4.7	6	3	2	13.63	0.2%
18	18	2	8	32	7.8%	8	2.0	2	3	4	4.29	1.2%
18	18	2	8	32	7.8%	8	2.0	4	3	4	4.29	0.6%
18	18	2	8	32	7.8%	8	2.0	6	3	4	4.29	0.4%
18	18	2	10	20	7.6%	5	3.5	2	3	3	6.63	0.9%
18	18	2	10	20	7.6%	5	3.5	4	3	3	6.63	0.5%
18	18	2	10	20	7.6%	5	3.5	6	3	3	6.63	0.3%
24	24	2	6	20	1.5%	5	5.0	3	3	3	9.63	0.5%
24	24	2	6	20	1.5%	5	5.0	6	3	3	9.63	0.2%
24	24	2	6	20	1.5%	5	5.0	12	3	3	9.63	0.1%
24	24	2	8	12	1.6%	3	10.0	3	3	3	9.63	0.5%
24	24	2	8	12	1.6%	3	10.0	6	3	3	9.63	0.2%
24	24	2	8	12	1.6%	3	10.0	12	3	3	9.63	0.1%
24	24	2	9	28	4.8%	7	3.3	3	3	4	6.29	0.6%
24	24	2	9	28	4.8%	7	3.3	6	3	4	6.29	0.3%
24	24	2	9	28	4.8%	7	3.3	12	3	4	6.29	0.2%
24	24	2	10	24	5.1%	6	4.0	3	3	3	9.63	0.5%
24	24	2	10	24	5.1%	6	4.0	6	3	3	9.63	0.2%
24	24	2	10	24	5.1%	6	4.0	12	3	3	9.63	0.1%
24	24	2	10	36	7.7%	9	2.5	3	3	5	4.63	0.8%
24	24	2	10	36	7.7%	9	2.5	6	3	5	4.63	0.4%
24	24	2	10	36	7.7%	9	2.5	12	3	5	4.63	0.2%
24	24	2	11	28	7.2%	7	3.3	3	3	4	6.29	0.6%
24	24	2	11	28	7.2%	7	3.3	6	3	4	6.29	0.3%
24	24	2	11	28	7.2%	7	3.3	12	3	4	6.29	0.2%

G.3 Slabs

Depth	Cover	Top Bar ϕ	Top S Bars	Bot Bar ϕ	Bot S Bars	Slab ρ	Slab ρ top	Slab ρ bot
4	1	2	4	2	12	0.4%	0.4%	0.1%
4	1	3	8	2	12	0.4%	0.5%	0.1%
4	1	4	12	2	12	0.5%	0.5%	0.1%
4	1	3	4	2	12	0.8%	0.9%	0.1%
4	1	4	8	2	12	0.7%	0.8%	0.1%
4	1	6	12	2	12	1.0%	1.2%	0.1%
4	1	4	4	2	12	1.3%	1.6%	0.1%
4	1	5	8	2	12	1.1%	1.3%	0.1%
4	1	7	12	2	12	1.4%	1.7%	0.1%
6	1	3	4	2	12	0.5%	0.6%	0.1%
6	1	4	6	2	12	0.6%	0.7%	0.1%
6	1	6	12	2	12	0.7%	0.7%	0.1%
6	1	4	4	2	12	0.9%	1.0%	0.1%
6	1	5	6	2	12	0.9%	1.0%	0.1%
6	1	7	12	2	12	0.9%	1.0%	0.1%
6	1	5	4	2	12	1.3%	1.5%	0.1%
6	1	6	6	2	12	1.3%	1.5%	0.1%
6	1	8	12	2	12	1.2%	1.3%	0.1%
8	1	3	4	2	12	0.4%	0.4%	0.1%
8	1	4	6	2	12	0.5%	0.5%	0.1%
8	1	6	12	2	12	0.5%	0.5%	0.1%
8	1	5	4	2	12	1.0%	1.1%	0.1%
8	1	6	6	2	12	1.0%	1.1%	0.1%
8	1	8	12	2	12	0.9%	0.9%	0.1%
8	1	6	4	2	12	1.4%	1.6%	0.1%
8	1	7	6	2	12	1.3%	1.4%	0.1%
8	1	9	12	2	12	1.1%	1.2%	0.1%

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