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Automated Generation and Visualization of Initial Construction Schedules from Building Information Models

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AUTOMATED GENERATION AND VISUALIZATION OF INITIAL CONSTRUCTION SCHEDULES FROM BUILDING INFORMATION MODELS

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I dedicate this dissertation to my parents Rediet & Weldemihret ,

my wife Dr. Zinash Tesfaye, my son Ezana and my siblings Alganesh, Aklilu, Abel & Roza.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Recent advances in digital technology have had a significant influence on the quality and speed of sharing and communicating project information in the architecture, engineering, and construction (AEC) industry. The process of acquiring the design intent in order to develop and communicate project schedules, as critical components of project delivery, have similarly been benefitting from such progress. With the relatively recent techniques of Building Information Modeling (BIM) and its capability to integrate the facility design with its construction schedule, meaningul strides have been made in improving the information flow and eventually visualizing the final schedule in 4D. However, the need for faster and more efficient ways of generating both the schedule and its 4D visualization has been growing as it directly impacts the overhead cost, and hence the bottomline, of projects. Lack of direct integration and logical interoperability between the various computer systems used for these processes deprives the industry of the power of synergy that could have resulted from such explicit assimilation of the product and process models and their respective sub-processes.

This research develops an approach that interprets 3D building information models into a source of direct input information to generate initial construction schedules for commercial building projects, which ultimately leads to automated visualization of the produced schedule in 4D BIM. By integrating an intermediate product model and generically predefined activities at domains level, it generates initial activities that capture the scope of the work in the design. The method also incorporates semi-automated sequencing algorithms that take into account the logic of support in structural construction and other factors related to work access and user preferences.

The methodology has been implemented in a computer application built to substantiate its feasibility and then evaluated with the help of volunteer professionals in the industry by using test cases. The implementation and the tests conducted demonstrated that the developed methodology is feasible and can be considered as a step forward towards complete automation in the industry, while there are still various aspects open for improvement.

CHAPTER 1- INTRODUCTION

1.1 Background

Planning and scheduling play key roles in project delivery by optimizing the time and cost components of project management. Therefore, to make this important phase more efficient, the architecture, engineering and construction (AEC) industry has been adopting new technologies for faster and more efficient ways of producing schedules, in terms of the quality and quantity of information they convey. Research and development in this area have introduced various computer models ranging from fully functional systems to simple proof of concept prototypes in attempts to automate different aspects of the scheduling process. Recent trends of integration and automation in this critical aspect of the project implementation have focused on visualizing schedules with the aid of Building Information Models (BIM).

As a matter of practice, the design of a facility is completed first by professionals such as architects, structural engineers, mechanical and electrical engineers before the construction team can begin the actual work of materializing the physical facility on the ground using blue prints as a guide. In that sense, construction professionals need the design to plan the actual construction work. Historically, incompatibility between the design representation and construction process models required the manual transfer of information from the design documents into the scheduling process through the interpretation of the construction expert. Interoperability between the two models must be realized to facilitate a systematic data flow and information sharing through an integrated computer model. Such integration is expected to result in some degree of automation in the overall scheduling process. An intermediary product model of the designed facility should be used to transfer this relevant data from the product model to the process model.

BIM takes this effort of integration and information exchange to a new level. At its current stage, the application of BIM is mainly used as a medium of communication, and collaboration between the various professionals involved in a shared project delivery endeavor. In this regard, it has brought about some level of a paradigm shift in the industry, which in turn has increased productivity and efficiency through better collaboration(Takim, Harris, & Nawawi, 2013). In general, although there is no universal definition for BIM, it is associated with a software-based unified means of bringing all stakeholders to quickly share information and collaborate effectively. These models are described by intelligent building components, parametric rules and data that characterize their behavior (Eastman, Teicholz, Sacks, & Liston, 2008). It is associated with the facility's digital representation and maintenance considering its lifecycle(Gu & London, 2010), (Sciences, 2007). The scope of its application in the industry is expanding to various aspects of project management such as risk analysis (Zou, Kiviniemi, & Jones).

However, this technology is still far from being ideal in addressing many of the long-running inefficiencies in the industry. Research and development have continued to extend the relevance and effectiveness of BIM in addressing specific problems the industry is currently facing. The following sections briefly summarize prominent research

areas and their contributions to the endeavors of automating the process of scheduling, and the 4D aspects of BIM, which are the major targets of this research.

1.2 Overview of Systems for Automating Construction Schedules

Planning, according to (R.-.-J. Dzeng & Tommelein, 2004), involves defining construction activities and their logic of construction, which is expressed in terms of their precedence relationships. It also involves determining the resources and duration associated with the respective activities, which are the main inputs for the critical path method (CPM) to calculate start and finish dates as well as floats of inputs for the activities.

Many systems of information technology have been developed in such a way that creating a new schedule can be reduced to requiring as fewer inputs as possible by reusing experience and information gained from already completed similar projects and stored in different knowledge-based systems. Some of the knowledge-based systems used so far include templates, Case-based reasoning (CBR), rule-based approaches, and expert systems. Such systems depend on three main factors (W. Huhnt & Enge, 2006): the context(the project information), the inference mechanism and the knowledge source(human expertise). It is also noted that due to the uniqueness of construction processes, complete automations of schedules that disregard input from construction experts are not feasible. Among the numerous knowledge-based expert systems developed so far include GHOST (Navinchandra, Sriram, & Logcher, 1988), Construction-Planex (Hendrickson, Zozaya-Gorostiza, Rehak, Baracco-Miller, & Lim, 1987), BUILDER (Cherneff, Logcher, & Sriram, 1991), CONSCHED (Shaked & Warszawski, 1992). Construction-Planex and GHOST produce component level sequencing of construction processes while OARPLAN (Darwiche, 1989) generates activities. In these systems, the activities per applied construction technologies are predefined and their precedence is either predefined (Zozaya-Gorostiza, Hendrickson, & Rehak, 1990) or described from physical relationships between the components such as support and covered-in.(Echeverry, Ibbs, & Kim, 1991), and such relationships need to be supplied to the systems manually. These systems are also referred to as model-based systems (Aalami, Fischer, & Kunz, 1998).

Knowledge-based systems generally require similarity comparisons between the projects to result in exact or very close matches in order to be adopted as solutions. The stored solution for the elements with the highest degree of similarity, to the elements at hand are adopted (Mikulakova, König, Tauscher, & Beucke, 2010). However, some level of intervention from the project manager is necessary to modify and adopt the schedule generated from such systems. The assumed similarity match depends much on the comprehensiveness of the stored cases, which cannot be guaranteed considering the uniqueness of construction projects. To summarize the concepts and applications (Watson & Perera, 1997) has presented a comprehensive review of case based design. In CasePlan (R.-.-J. Dzeng & Tommelein, 2004) developed a generic boiler product model as a case study to reuse its schedules in the developed system. (Mikulakova et al., 2010) used a knowledge-based scheduling system that uses case based reasoning to compare new project components against cases that are solved and stored. Converting functional requirements of each component into temporal sequence has also been (David K. H. Chua, Nguyen, & Yeoh, 2013) applied to generate schedule

sequence. As discussed below, there are various problems that arise from the uniqueness of construction projects, and hence their designs, which are not addressed by these works. More importantly, these systems do not offer an opportunity for automated 4D visualization, which is at the heart of this research.

The unique and dynamically changing nature of construction projects require frequent expansion and updates to the information stored in knowledge-based and case-based systems. As time goes by, such a precondition makes these systems less useful and more dependent on the availability of historical data and the need to update them continuously. A system of automation that can interpret the actual design of new projects and generate solutions based on the reality embodied in the actual design, instead of inferring from indirect relationships has the potential to make the whole process of generating construction activities contextually more meaningful to the project at hand. Therefore, such a computer system is already up-to-date as far as handling the uniqueness of construction designs is concerned since it precludes any possible problems arising from the mismatch in similarity, as in the case of knowledge-based systems. It also nullifies the need to store the schedules of old projects that would have been needed for comparison.

Since the dominant form of product model used in the construction industry is still 2D CAD, the input of information from product model into the scheduling process is mainly manual and therefore, previous methods that attempted to automatically generate activities emphasized the need to minimize the amount of product information the user has to input as part of this automation(Chevallier & Russell, 1998). Even if the required input is limited, one of the drawbacks of these systems is that the information should be analyzed by the project manager and be entered manually. This input of information does not completely capture the uniqueness of the project at hand, as there is a tradeoff between the amount of project-specific information and the level of unique details of the project that can be included in the schedule. Therefore, the systems have varying degrees of accuracy in their reasoning capabilities. As a result, they do not completely automate the practice of generating activities and their constraints.

The need for electronic integration of design and construction information has been an area of research for quite some time. The meaning and extent as well as form of integration of this information has been elaborated by (Luiten, Tolman, & Fischer, 1998; A. Russell & Chevallier, 1998), which introduces a building project model(BPM) as an explicit integration of these models, in which the different professionals effect the populating of the various information at different phases of the project development.

Limited numbers of tools and research systems have used electronically extracted information from 3D CAD models and use it as input for scheduling or even better generate the schedule from it (Kim, Anderson, Lee, & Hildreth, 2013; Liu, Al-Hussein, & Lu, 2015). Using ifcXML data format, (Kim et al., 2013) presents a research work that extracts basic object information such as name, quantity and manually assigned zone location information. Even though this work discusses simple sequencing rules previously introduced by (Echeverry et al., 1991) and others, it fails to discern how such information can be deduced from the extracted BIM data. In addition, the generated activities are merely a concatenation of the object names and the manually identified locations.

Another research (de Vries & Harink, 2007) used a geometric approach to infer the topological relationship between components. The method first converts CAD models into solid models and then employs a technique of moving each building object in different directions to check the adjacent objects. Based on the detected objects and using the intersection operation of constructive solid geometry, it lists out the components adjacent to it and their relative position. This information is stored in a log file and exported into planning tools such as Microsoft Project in the form of an automatically generated schedule. Such directly extracted data has been used to improve various aspects of scheduling such as the problem of activity overlap, and hence, resource over-allocation has been analyzed with a system that uses BIM data (Moon, Kim, Kamat, & Kang, 2015).

The importance of directly capturing the actual project information from the CAD model has been emphasized in earlier research (Echeverry et al. 1991). The previous systems have limited capabilities in capturing the unique data about the designed facility. Therefore, computer-interpretable 3D CAD models are expected to solve part of the problem. As the future of the PDM++ system, (D. K. H. Chua & Yeoh, 2011) promised to integrate building information models to automatically produce a construction requirement-driven schedule. In an effort to ease the process of linking product and process models (Alan Russell, Staub-French, Tran, & Wong, 2009; S. Staub-French, Alan Russell, & Ngoc Tran, 2008), developed a product-process integration model that links the two so as to provide contextual information about the project to determine productivity, production rates, etc. at different locations of a linearly repetitive projects. However, many of the intermediate processes in these models, including the characterization of the projects in terms of the activity description, location etc. are manual, hence limiting the power of the intended integration.

1.3 Construction Schedules and BIM

The rich information content in BIM models is leading many applications that add value to the construction process, although there are still significant limitations in exploiting this information (Liu et al., 2015). The integration of construction schedules with 3D design models has resulted in 4D visualization of the schedule and the AEC industry is witnessing their benefits, as they improve communication between the project actors. They also help to easily detect conflicts and incompleteness of the models before the start of the actual construction, a stage at which the correction of these errors is usually expensive(Mahalingam, Kashyap, & Mahajan, 2010), (Koo & Fischer, 2000). However, currently, the approach to link the activity-based schedules to the BIM objects in order to generate these visual schedules is mainly manual and very tedious. In the past various methods have been implemented to automate the process to different degrees of success(Chau, Anson, & Zhang, 2005),(Kang, Moon, Park, Kim, & Lee, 2010), (Mikulakova et al., 2010), (Tauscher, Mikulakova, Beucke, & Konig, 2009). These developments are briefly discussed below.

Different models have been developed to semi-automate the mapping between product and process models and hence, tackle the challenge of tedious manual linking. In an effort to minimize the number of manual linking (Alan Russell et al., 2009; S. Staub-French et al., 2008) integrated 3D ADT drawings with a project structure they developed and named REPCON, using database systems for mapping attributes with the physical

component breakdown structure (PCBS) in REPCON. This structure consists of location, product description and attributes hierarchically. Here, generic and hence fewer, links between the REPCON and the ADT style attributes has to be made manually. After such linkage is created, updates for changes are mostly automated.

Work break down structure (WBS) has also been used as a nexus for linking schedule activities and objects of 3D models (Chau et al., 2005; Kang et al., 2010). It was also used as the main connector of other attributes of the schedule such as resources, cost, etc. WBS is used as a means of information project exchange between the various processes in construction projects (R.-.-J. Dzeng & Tommelein, 2004). The application of work break down structures (WBS) to automate the generation of 4D CAD model requires the creation of both the 3D as well as the activity-based schedules separately and manually synchronizing the corresponding WBS IDs. Even if the common WBS used in both the schedule and the 3D modeling automates the generation of the 4D simulation, this and other methods that require the creation of both 3D and the complete schedule for the 4D to be generated reverse some of the research advances in automating the generation of CPM schedules. Consequently, there is a need for continuing the progress already made in automating the scheduling process, as the enhancement with the 4D approach should not necessitate a tradeoff. Thus, a 4D CAD method that can also generate the activity-based schedule automatically is expected to provide more value to the process. Besides, it solves the costs and errors related to data re-entry very commonly observed in the construction industry when moving data from one system to the next.

According to (Tulke & Hanff, 2007), today's 4D tools lack the ability to create 4D in parallel with scheduling as the available 4D tools require a completed schedule. However, after the separate creation of both schedule and 3D CAD model, there are manual or semi-automatic methods in current tools to create a 4D model. A research (Feng, Chen, & Huang, 2010) presented a multi_CAD model-based project scheduling system(MD_PSS) in which work items from CAD-based 3D model are exported into a project database and sequenced based on a developed genetic algorithm and then integrated with detail activities, production rate and related cost from existing Taiwan standard. The system considers only inflexible constraints described as direct support, indirect support and direct dependence between building elements. However, this initial topological information from the 3D objects is populated manually to form the object-sequencing matrix (OSM).

Earlier works aimed at automatically generating activity-based schedules were mostly demonstrations of the possibilities and the necessities in the industry. However, they lacked fully automated means of extracting product information from the design data. Therefore, the required information is either supplied by the user or indirectly inferred from other inputs, which make the systems more academic than practical. More recent works such as (Chen, Griffis, Chen, & Chang, 2013), (Liu et al., 2015) and (Kim et al., 2013) have developed computer prototypes to describe the possibilities of using BIM models as a direct source of input information to generate construction schedules. (Chen et al., 2013)

The main focus of (Liu et al., 2015) was in optimizing a resource utilization and minimizing the overall duration of the project by integrating particle swarm optimization

and discrete event simulation techniques while applying geometric adjacency of components is utilized to deduce precedence in the construction of panelized light gauge steel. This scheduling approach is very limited in scope and cannot be implemented in commercial construction projects as pure geometric adjacency and proximity do not necessarily determine the sequence of construction. Focus of this system was more on optimizing the resources in schedules rather than advancing the process of automating or speeding up the process of generating schedules.The process of (Moon et al., 2015) developed a system that applies fuzzy logic and genetic algorithm to minimize overlap of activities and hence minimize the risk of delay.

Whereas these can be considered as the most recent advances in this topic, they fail to represent the actual reality and in actually designed projects as they are either too simplistic, limited in scope or incomplete in their attempt to exploit the benefits of BIM for a robust and comprehensive scheduling generation, followed by visualization using 4D. To this end, a very critical step in the integration of BIM models with construction schedules is the automation of 4D visualization, which in many of the works is considered a separate topic and a separate problem.

1.4 Activity Modeling and Generation

Activities, as the basic elements for working schedules, are defined and sequenced to determine the overall blueprint of the project execution. Due to their lower level of details compared to the design of the product, the number of activities to be defined or generated and arranged in a certain sequence is usually significant. Therefore, computer systems that facilitate the modeling and generation of activities in a systematic way can add value to this important portion of the project planning phase.

Various authors have proposed general approaches to model the representation of activities. In their model-based planning systems (Darwiche, Levitt, & Hayes-Roth, 1989) represented construction activities as a function of the building components they act on, the action and the resource they use in the form of <CAR> tuple where C=component, A=action, R=resource. This abstracts the reasoning behind the activities and their sequence (Aalami et al., 1998). The construction method model template (CMMT) system was developed to represent the reasoning behind activities by allowing the user to explicitly enter the constraints into each activity reflecting the selected construction methods (Aalami et al., 1998). This elaborates the reasoning down to the activity level, thereby addressing the challenge of abstracted knowledge representation in activities.

Most of the research in this area has focused on refining case-based reasoning, knowledge based systems, expert systems….etc. to regenerate activities from past knowledge or data (R.-J. Dzeng & Lee, 2004; Mikulakova et al., 2010; Tauscher et al., 2009), rather than syntactical modeling like <CAR> discussed above.

Domain specific characterization of construction activities can be generically predefined regardless of the product model. Considering the basic nature of repetitiveness in material and methods of construction at different locations of a building, these generic activities can be applied. We argue here that, the uniqueness of construction projects is due partly to the possibility to design facilities with various combinations of these subareas. However, the variation between individual subareas or domains does not

vary greatly that it is feasible to generically classify and characterize through predefinition of their sub processes. Therefore, the practice of scheduling in the industry can gain some improvements through the generic categorization into different domains and integration into the proposed system of the activities per domain and per method of construction. This project and context-independent knowledge base approach is expected to benefit companies by reusing the information they once tailored to suit their preferred level of detail and technologies. Automated integration of project-specific data from 3D model to this knowledge base would result in a speedy generation of working schedules.

Many of the above research works have served as the stepping-stones for further advances in the development of better commercial solutions. In that regard, these older works are more of theoretical frameworks than currently relevant solutions to the challenges faced by the industry today. Additionally, most of these research level assertions and the prototypes developed to validate their claims would generally be incompatible, if not irrelevant, to the technology and tools currently in use in the industry. As a result, most of these computer models serve more as theoretical backgrounds of development than relevant solutions to the current challenges in the industry. Therefore, this research aims at bringing the current stage of practice in model-based scheduling and 4D visualization to the forefront of the challenges the industry is facing.

1.5 Problem Statement

The following interrelated problems have been identified and set as important targets for this research.

1. While the advent of 4D CAD into the construction scheduling has added more value to the AEC, through better communication and visualization, the endeavors to automate both activity generation and 4D visualization have not necessarily complemented each other. As a result, improvement in one has not led to improvements in the other. Advances in automating scheduling process have not been built upon when the new focus on 4D came to play in the industry. This disconnect between the two processes arises from the lack of basic interoperability between their sub processes and lack of integration in their respective inputs. In the current state, 4D visualization requires a completed schedule to be linked with the 3D product model. Creating the schedule, on the other hand, considers the product design as its implicit input. Therefore, automating the process of generating activities that uniquely and sufficiently describe the physical scope of the designed project at hand is still a challenge.
2. Construction sequencing of building components based on their physical relationship, notably support constraints, has been described in previous research as one of the main factors for sequencing their construction activities. However, these descriptions are mainly formalizations of the overall reasoning behind scheduling, without a generalized approach to acquiring and utilizing such logic from the product model and use them in generating actual project scheduling (Norbert Paul & Borrmann, 2009). Different researchers have proposed a variety of techniques and tools to address this issue. However, they are either limited in scope or require significant user input. Some attempted to address the problem at

the individual building element level, but it is impractical to schedule activities that refer to individual instances of components in the project design.

3. Visualizing the construction process has been proven effective in boosting the level and clarity of communication between the actors in the project and creating the opportunity to prevent costly mistakes at the early stage of the process. Linking the process model, the activity-based schedule, and product model, the 3D CAD, is however still mainly a manual process, which is hindering the adoption of the technology. Currently available automation techniques still involve a significant degree of manual processes.

1.6 Research Objectives

The overall objective of this research is to generate draft project schedules from the 3D design of the facility, thereby integrating the two with the ultimate goal of automating the currently manual and painstakingly long process of visualizing the schedule in 4D. More specific targets of this research are outlined below:

1. To define a general activity model for high-rise commercial buildings, with the option for each company to assign the projects they undertake a certain project type group based on broad similarity in their schedules. The model should be extensible to include different domains of construction and new methods under each domain.
2. To design an intermediate product model that extracts, restructures and stores data from 3D models in a way that can be used for seamless and explicit integration of the generic activity model with the contextual design information, to facilitate the generation of a draft schedule and 4D linking. It is called "intermediate" as it lies between the design of the facility and the work plan, schedule, to serve as a bridge between the two.
3. To develop and implement a method for mapping construction activities to the BIM model components so that 4D visualization of the schedule produced can be automated.
4. To develop a semi-automated method for generating initial activities and their sequences by blending information from the general activity model and the specific BIM model of the project under consideration. The logic considers relationships between building components such as physical support, location, and other constraints that practically determine the sequence of activities.
5. To validate and test the capability of the developed system in performing the stipulated purposes of model extraction, draft schedule generation and automating the linking of activities to their 3D objects in the model, by using actual commercial concrete construction project and getting feedback with the help of professionals in the industry.

CHAPTER 2- RELATED WORKS

In this chapter, we discuss previous approaches related to automating schedule generation and the developments in the context of generating 4D views. To lay the ground for the methodology in this research, the progress made so far in the area have been discussed under activity generation, sequencing methods and the techniques and state of the art of producing 4D visualization from 3D building information models. The relevance of the industry foundation classes (IFCs) to the scheduling process has also been briefly summarized.

2.1 Approaches to Automate Activity Generation

Efforts to improve the speed and quality of the scheduling process in the industry have been in progress for decades. Many computer applications have been developed for commercial and research purposes. Automating several aspects of the scheduling process such as generating the activities, calculating the duration, the sequence logic etc. have been areas of interest and research for a long time. The goal of most of such systems is to minimize the duplication of efforts and time spent in recreating this information for new projects. To accomplish the objectives of these systems, detailed information about the project at hand has usually been a critical input. Since the dominant form of product model used in the construction industry is 2D CAD, scheduling systems required manual extraction of the relevant information from the CAD drawings and used as inputs. Some of the inputs included are discussed as follows.

Listing the design components manually for rule-based sequencing and other analyses was implemented in GHOST (Navinchandra et al., 1988). In a model called SIPE, hierarchy of physical components(Levitt, Kartam, & Kunz, 1988) was also used as input to generate a network of work schedule with single activities per component.

Using a seed activity, which is a major task that abstracts the lower tasks that construct a part of the whole facility was developed (Fischer & Aalami, 1996). The detailing of this seed activity required further integration with other project data. Project parameters such as the number of floors, floor size, type of structure project characteristics(R.-J. Dzeng & Tommelein, 1995) were also used in case-based reasoning technique that reuses old schedules. The use of 3D CAD MODELS has also been used for the purpose of minimizing the effort of activity generation and linking to 3D objects (Alan Russell et al., 2009; Sheryl Staub-French, Alan Russell, & Ngoc Tran, 2008). This model still involves significant manual component in its implementation.

In using old schedules, (Chevallier & Russell, 1998) presents a technique that keeps the role of a construction engineer active in defining project templates with proper breakdown structure, the logic, and rules of sequencing. Such templates for complete projects are stored as rules and are applied to adopt them to upcoming ones. By using physical views (PCBS) and process-view, the system queries the user for project specific information to adapt to the scale of the new project. It also discusses earlier approaches to automate construction schedule generation by using different artificial intelligence methods to develop expert systems. A related work by (Fischer & Aalami,

1996) presented a mechanism that uses predefined sub-networks of activities, where details of activities are accessed from a predefined storage, based on the selection of higher level aggregated activities. The prototype developed as a proof of concept requires the user to input the high-level seed activities for the product model and method of construction. This leads to the generation of detail activities.

The research presented by (Tauscher et al., 2009) uses the information in IFC models to generate activities but it requires a manual creation of elementary schedule, which includes tasks and their related pre-requisites and their results, which are the final products. The study assumes the availability of stored cases of similar structure, as confirmed using the physical similarity calculation provided on individual elements with similar methods of construction and generates the schedules from those similar cases. The need for the manual creation of the elementary schedule elements can be considered as a drawback as in the other case-based reasoning method. Besides, the matching between the new and old elements based on similarities has some degree of uncertainty.

More recent studies have proved the feasibility of open standard BIM data models such as IFC and BIM in general, in supporting the automated generation of construction schedules (Kim et al., 2013; Moon et al., 2015) and relevant data such as material properties and quantities that can be utilized to further enhance the scheduling process through richer information.

Despite their significant contribution to the progress on the topic, these systems have very limited scope and usually consider basic building element types such as walls, columns, beam….etc. to test their prototypes work. Their frameworks are not general enough to handle all the variations in 3D designs of real world projects and integrate user preferences without making the whole process significantly manual. These works also fail to establish a mechanism to utilize such information to improve the 4D process, which is considered as the state-of the art technology in communicating project schedules.

2.2 Methods to Automate Construction Sequencing

The relative temporal order in which the activities of a schedule are carried out is dictated by the constraints that control their execution, and such constraints arise from various factors in each project. In formalizing the sequencing factors for activities that directly act on building components(Echeverry et al., 1991) identifies four main factors: physical factors, trade interaction, path conflict and regulation codes. (Hinze, 1998) classifies these as physical, resource, safety, financial, environmental, management and contractual. In the GHOST system (Navinchandra et al., 1988) applies support and connection of components to sequence activities.

As a general practice of sequencing activities in schedules in the construction industry, experienced personnel create the schedules for new projects by using any information about the project that they have and their own experience. This makes the experience personal (Adjei-Kumi & Retik, 1997; Büchmann-Slorup & Andersson, 2010) and limits knowledge transfer from project to project. Knowledge-based systems have been used to close this gap. In addition, many researchers that aimed at automating the visualization of project schedules through the integration of the activity-based schedules

and 3D product models have made use of similar knowledge-based systems and case-based reasoning.

Even though these approaches have produced good results for projects that have exact or very similar matches, the uniqueness of construction projects is generally an ever-evolving reality that can limit their effectiveness. Even if two projects are exactly the same from the design point of view, differences in other factors such as the interest of project actors such as contractors, subcontractors and owners, contractual limitations, etc. do generally require different approaches in the construction process, and hence, in the schedules.

The need for integration of domain-specific standalone computer applications in the AEC as a way to increase efficiency in data exchange between different tools has been demonstrated by (Parfitt, Syal, Khalvati, & Bhatia, 1993). This work envisions an ideally integrated system to have a two-way data flow.

In CMMT (Aalami et al., 1998) an activity is defined per and for every building component and further elaborated depending on the predefined method of construction. Component-based and process-based constraints are used as means of sequencing the work. Component based constraints are further divided into support and part-of constraints. In CONPLA-CBR, (Han-Guk, Hyun-Soo, & Moonseo, 2007) considered a cased-based approach that considers very high level descriptions of projects such as the number of floors, soil type and project cost to determine similarity.

Some researchers have attempted to automate the schedule creation from information in the 3D model of the project(de Vries & Harink, 2007; Tauscher et al., 2009), (Kataoka, 2008). The work by (Kataoka, 2008) used an approach that first converts CAD models into solid models and then a technique of moving each building object in different directions to check the adjacent objects. Based on the detected objects and using the intersection operation of constructive solid geometry, it lists out the components adjacent to it and their relative position. This information is stored in a log file and exported into planning tools such as Ms. Project in the form of an automatically generated schedule. This approach also requires predefining the types of movements for each building component to minimize the number of movements per component. By using the topological information in industry foundation classes(IFCs) the need for the movement of individual elements can be eliminated because in the latter case, each building component ‘knows’ what component it is connected to in every direction. The construction analysis subsystem of the above method requires predefining the types of movements appropriate for each building component. The goal was to generate schedules from preliminary 3D design using geometric information and various known methods of construction for structural frame of a building.

Even though many of the systems discussed earlier needed inputs about the design from the user, logics such as physical support, trades, space and other resources are generally applied like rules. Systems that adapt schedules from old projects inherit the sequence of the same schedules.

2.3 BIM Interoperability and Scheduling

The ability to exchange data between various software applications has been an area of significant interest in the construction industry for a long time as it affects the efficiency and profitability of projects. The industry foundation classes (IFC) is an internationally recognized neutral file format developed to facilitate such an exchange between heterogonous proprietary BIM applications. With such a common medium, various professionals such as architects and engineers can exchange 3D data while they are running applications from various vendors, even though IFCs still present practical challenges in meeting expected levels of efficiency and flexibility (Jeong, Eastman, Sacks, & Kaner, 2009), which are expected to be addressed gradually through subsequent developments and releases.

According to (Fu, Aouad, Lee, Mashall-Ponting, & Wu, 2006) currently, there are two methods of specification for building information models-STEP and the industry foundation classes (IFC). While both are written in EXPRESS language, STEP is more general for many industries while IFC is specifically detailed to represent different process as well as product aspects of the AEC industry. Developed by International Alliance for Interoperability (IAI), IFC shows product components and their properties in the form of relationships and attributes.

Today's major BIM software applications available in the market support export into different forms of IFC as a means of interoperability. These are application-independent set of specification and the representation (Gang, Zhiping, Xiaodong, & Yuken, 2010; Hu, Zhang, & Deng, 2008), believed to be efficient mechanisms for the implementation of BIM. Entities described in IFC are parametric. Different researches have shown that IFC schema is extensible to represent information elements not readily available in the schema(Eastman, Jeong, Sacks, & Kaner, 2010; Ma, 2011).In another study (Staub-French & Fischer, 2000) have described how the information content in IFC can be used for determining actual cost estimating of construction components.

IFC has been used in various researches to support the scheduling process using BIM (Kim et al., 2013; Tauscher et al., 2009) and a case-based reasoning was used to retrieve scheduling tasks from stored projects and assign them to the building elements of the model based on calculated similarities between the object at hand and the respective elements from the stored database. This study defines the attributes of building elements as the constraints of their corresponding tasks. These required constraints are obtained from the IFC model. In an effort to automate the generation of construction schedules (Mikulakova et al., 2010) integrated knowledge-based system with IFC parser. This study emphasizes the advantages of standardized data structure such the IFC for an efficient storage and retrieval of information from database systems for the case-based reasoning (CBR). The IFC-parser is used to extract design information from the 3D model. Detailed building information such as geometric and material properties of the IFC model can be applied for elaborate reasoning.

Currently available IFC compliant authoring tools such as Revit and ArchiCAD have built-in modules to map the modelled 3D building elements into the standard specification of IFC 2x3 schema. Table 1- is an example of such a mapping as

implemented in Graphisoft's ArchiCAD, one of the commercially available 3D authoring tools in the market today.

Table 1- IFC mapping of building elements in ArchiCAD

ArchiCAD Element	Mapped IFC Element Type
Wall	IfcWall or IFcStandardCase
Door	IfcDoor
Window	IfcWindow
Skylight	IfcWindow
Roof	IfcSlab
Shell	IfcSlab
Beam	IfcBeam
Column	IfcColumn
Slab	IfcSlab
Stair	IfcStair
Morph	IfcBuildingElementProxy
Ramp	IfcStair
Mesh	IfcBuildingElementProxy

2.4 Model-Based Scheduling and 4D BIM

The introduction of Building Information Modeling has created more challenges and opportunities in the construction industry. The semantically rich and computable information in these models has enabled more integration of information usable for different stages of a facility's life cycle. The integration of 3D BIM with construction schedules to give rise to 4D has had many applications and implications in the way the AEC industry is improving project delivery.(Trebbe, Hartmann, & Dorée, 2015) have conducted a qualitative study to show the benefits of 4D in train-station renovation by coordinating various co-builders in achieving their common goal.

During the process of developing, communicating and monitoring of construction schedules, better visualization, detection of schedule incompleteness have been demonstrated to be few of the advantages of 4D CAD (Koo & Fischer, 2000; Mahalingam et al., 2010). The significance of 4D CAD in coordinating construction activities in the actual building process and communicating the content and intent of the work plan as embodied in the schedule has been proven to be instrumental (Staub, Fischer, & Spradlin, 1999) for a plant construction. Using 4D, optimal equipment layout and operations in liquefied natural gas plant construction were confirmed by (Zhou, Ding, Wang, Truijens, & Luo, 2015).

Despite the clear and revolutionary impacts of the 4D technology for understanding and communication of project schedules, various drawbacks have also been pointed out by the industry and research community. Among such major problems, the manual process of integrating the activity-based schedule with the 3D models has been cited as critically hindering the speed at which this technology can be deployed to every construction project. Improved approaches to the methods of linking activities to the 3D CAD objects have been introduced through a shared work breakdown structure (Chau et al., 2005), (Kang et al., 2010).

The integration of the three-dimensional BIM objects of the buildings with schedules has solved part of the problem, i.e. rendering the schedule visual and hence easy to understand for all stakeholders. However, the contemporary methods of developing the 4D model are through a manual and tedious linking of activity-based schedules with object components of the 3D mode. This again gives rise to another set of problems, which is the need to automate the linking process. In general, the progress in this direction towards the stage of automation and value adding can be summarized in four different phases.

Figure 1 shows one way of summarizing what is considered here as the different phases of development in the efforts to automate construction schedule generation and visualization, although not necessarily in precise chronological order(Weldu & Knapp, 2012). The first generation of progress shown in the diagram have mainly been research and development undertakings that aimed at generating construction activities by blending various techniques such as the utilization of historical records, knowledge base systems and expert systems. In this regard, (Chevallier & Russell, 1998) has published an extensive literature review of research starting in the early 1980s, which mainly fall under this phase of development. The focus in this phase has been to minimize the tedious process of re-producing similar construction schedules repeatedly and capturing the knowledge and experience of construction and model this experience in computer applications that try to simplify the process of reusing this experience.

Speeding up the process of generating construction schedules is just one aspect of improving this important segment of project management. Finding better ways of visualizing and communicating its content with all the involved parties has been another important part of its evolution. This need gave rise to the 4D CAD models, which can be considered as the second stage. Literature recognizes early 1990s research at Stanford University to be the origin of 4D CAD (Wolfgang Huhnt, Richter, Wallner, Habashi, & Krämer, 2010). Using 4D has enabled better project communication and conflict detection in work sequence, among many other benefits. However, the manual process of linking construction activities to the 3D CAD introduced additional challenges. Different approaches, categorized as 3rd generation in Figure 1 have been introduced to automate the linking process. Among the proposed techniques to solve this challenge, was the use of work breakdown structures(WBS)(Chau et al., 2005) implemented by developing 4DSMM, which involved manually creating WBS structures for dynamic 4D visualization.

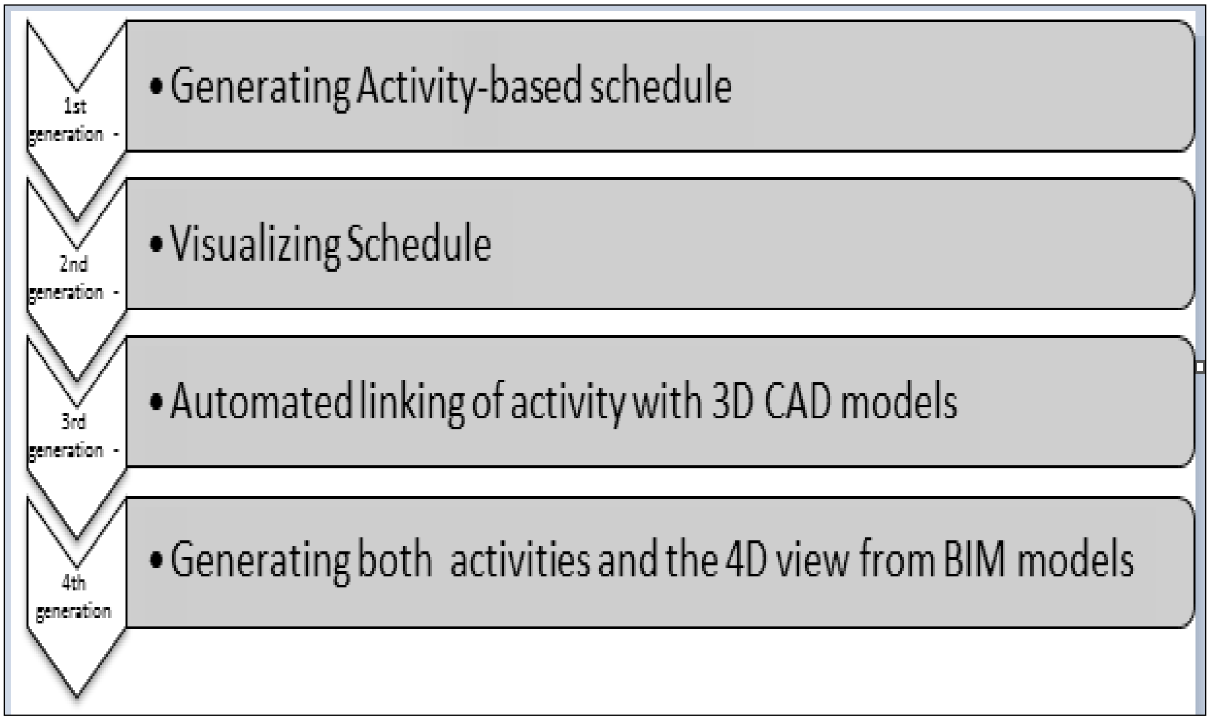


Figure 1- Different phases of schedule generation and visualization

The need for faster linking of activities to their 3D objects has been emphasized (Heesom & Mahdjoubi, 2004). Endeavors in automatic generation of 4D models had focused more on ways of linking 3D CAD with schedules produced. Therefore, approaches that merely aim at linking the two models, the schedule, and 3D CAD, lack the ability to build on the previous successes of automating the schedule production itself. Such a gap gave rise to what is named here as the 4th generation of efforts to produce both the schedule and the 4D CAD simultaneously and automatically. An ideal system would enterprise on the development of both endeavors so that the introduction of 3D models as an input to the scheduling process would not hamper the advances already achieved in automating the activity-based scheduling. Critic-based sequencing of activities is one approach but doesn't support specialization to represent methods (Navinchandra et al., 1988).

Work break down structure (WBS) has been used as a key for linking schedule activities and objects of 3D models (Chau et al., 2005; Kang et al., 2010). It was also used as the main connector of other attributes of the schedule such as resources, cost, and so forth. WBS is used as a means of information exchange between the various processes in construction projects (R.-.-J. Dzeng & Tommelein, 2004). The application of work break down structures (WBS) to automate the generation of 4D CAD model requires the creation of both the 3D as well as the activity-based schedules separately. Even if the common WBS used in both the schedule and the 3D modeling automates the generation of the 4D simulation, this and other methods that require the creation of both 3D and the complete schedule for the 4D to be generated reverse some of the research advances in automating the generation of CPM schedules. Therefore, there is a need for continuing the progress already achieved in automating the scheduling

process, as the enhancement that results from the addition of 4D should not necessitate the tradeoff. Therefore, a 4D CAD method that can also generate the activity-based schedule automatically is expected to provide more value to the process. Besides, it solves the costs and errors related to data re-entry very commonly observed in the construction industry.

According to (Tulke & Hanff, 2007), today's 4D tools lack the ability to create 4D in parallel with scheduling as it requires a completed schedule. However, after the separate creation of both schedule and 3D CAD model, there are manual or semi-automatic methods in current tools to create a 4D model. A research (Feng et al., 2010) developed a computer system called a multi_CAD model-based project scheduling system(MD_PSS).In this system, work items from CAD-based 3D model are exported into a project database and sequenced based on a developed genetic algorithm and then integrated with detail activities, production rate and related cost from existing Taiwan standard. After sequencing of the work items from the CAD model, detail activities, cost and duration are automatically populated by the integration of the project specific database and available construction standards for the work items. The purpose of the developed system is not only to sequence the work items automatically from the CAD to create the 4D visualization but also to produce useful information such as cost and resource distribution which is critical for practical project management but generally not available from available 4D CAD models. This research considers only the sequencing of work items that have inflexible sequence relationships in the model. These relationships are described as direct support, indirect support and direct dependence between building elements. It does not, however, include building elements that do not have such hard-coded sequencing requirements. Besides, it does not have a means to generate detail activities for each work item. Additionally, (Chen et al., 2013) combines simulation techniques and BIM data to generate resource-optimal schedules.

CHAPTER 3- RESEARCH METHODOLOGY

The main objectives of this research are outlined in chapter 1. This chapter introduces details of the research methodology employed in achieving those objectives. The various parts of the methodology are discussed below in the order they were introduced in chapter 1. The details of implementation of these methods in a computer application also follow the sequence presented here at a high level. The approach followed to generate construction activities is presented first, followed by the intermediate product information representation and integration with the scheduling process. The next two sections discuss the logic of construction sequencing and automating the process of linking the product and process models in order to speed up the generation of 4D visualization. Implementation details of the framework into a computer application are then covered. The final section discusses the route followed to test and validate the developed computer model and obtain feedback from experts in the industry.

3.1 Discipline Specific Generic Activity Modeling

The approach to generating draft schedules based on available BIM models of a facility as presented in this research depends on a domain specific predefinition and storage of activities. However, this predefined list of activities per domain is not universal to the whole construction industry. A variety of factors contributes to the fact that there cannot be a uniform definition of activities across the industry, among which are company types, project sizes, types of contract and type of schedule, location, company culture, user preference. Therefore, the system makes several assumptions and expectations from the end user to account for such variations and hence limit the applicability to individual companies in order to make it contextually more relevant to the company and the project type considered. To that end, the following two assumptions are considered and hence incorporated into the project information queried from the user.

1. Companies usually group their projects into few categories of business practice based on the type of construction involved or business area. For instance, a commercial contractor may group projects based on the size and type of facilities to be built. It is assumed that for a company to be able to utilize the system presented here, the company needs to create limited categories of projects to reflect their domain of business and hence the types of projects they undertake. This grouping should be able to accommodate both the past and future projects.
2. There are generic similarities between the activities at the discipline level in each group of projects that can be reused in new projects to avoid the need to recreate the whole package. Similarities in the type of activities and thus, method of construction are due to the level of detail, types of schedules (such as master construction schedule, proposal schedule and commissioning schedule). Such similarities make the reuse of these activities possible.

The above classification of projects, however, does not guarantee absolute similarity in the schedules of each project even if they are within the same group. There are usually scope differences between one project and the next, and hence, the need to limit the generated draft schedule to reflect that particular project is mandatory. A simple example of such a change could be two similar design buildings but with a different number of floors. Based on the above assessment the proposed generic activity model

focuses on breaking down of the project to discipline levels and then to the activities per discipline. This generic, discipline level elaboration of activities is meant to be comprehensive enough for current and future works, and dynamic enough to accommodate new additions. Therefore, the system can be updated based on new needs, technologies or preferences.

Figure 2 summarizes the overall information flow and components of the system developed in this research.

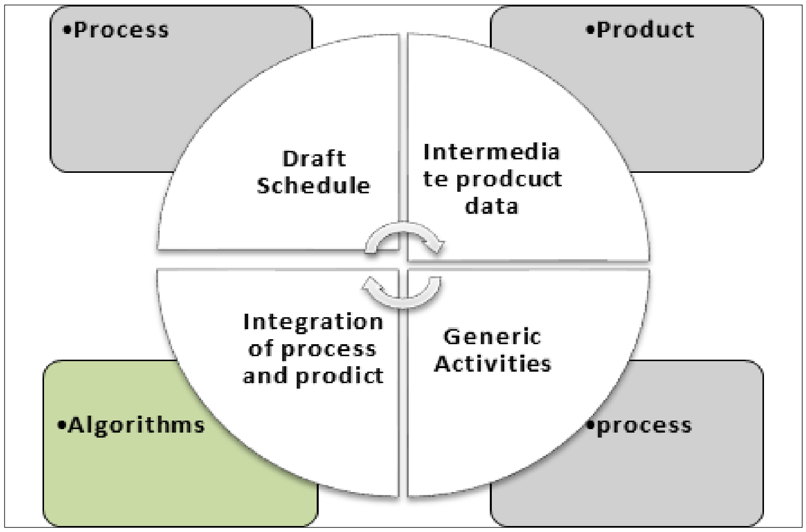


Figure 2- High-level overview of intermediate components and processes

3.2 Extraction of 3D Model and Intermediate Product Information

The matching of the Industry Foundation Classes (IFCs) to their respective domains of construction as shown in Table 2 is a precursor for the explicit integration of the BIM information with the generic activity model discussed in the previous section.

The term *product data* here refers to the drawing or 3-D model developed by professionals such as architects, structural or mechanical engineers to represent the final product or facility before the actual construction is carried out. On the other hand, the term *process model* refers to the work plan or schedule developed to guide the actual process of constructing the facility according to the design and other requirements included as part of the project specifications.

In this section, a method is developed for a general and extensible mapping model between BIM objects and scheduled construction activities. The framework is applicable in building construction projects with concrete structures. The practicality of the framework is validated using a model and activities in commercial concrete construction. Table 2 summarizes the major construction domains identified, and the IFC elements expected to fall under each domain.

Table 2-IFC elements considered per each domain of work

Domains	Components
Structural Concrete	IfcBeam, IfcColumn, IfcFooting, IfcSlab, IfcRoof, IfcMember,IfcPile, IfcRamp,IfcRampFlight, IfcStairFlight, IfcReinforcingBar
Masonry	IfcWall, IfcWallStandardcase, IfcFeatureElement, IfcCurtainWall
Thermal and Moisture Protection	-
Doors and windows	IfcWindow, IfcDoor
Electrical	IfcElectricalElement, IfcElectricDistributionPoint, IfcCableCarrierFittingType, IfcCableCarrierSegmentType, IfcSwitchingDevice
Mechanical	IfcDistributionFlowElement, IfcPipeFitting IfcPipeSegment, IfcUnitaryEquipmentType, IfcFlowTerminal
Roofing	IfcRoof, IfcMemember
Finishes	IfcCovering, IfcRailing
Specialties	-
Equipment	IfcEquipmentElement
Furnishings	IfcFurnishingElement
Conveying Systems	IfcTransportElement

On the other hand, Table 3 presents a basic structure of the domain-method-activity relationship considering three domains of construction as an example.

The common field “Domains” between the two tables means that the IFC elements will be matched to their activities. The purpose of the generic activity model is not to prescribe a complete list of activities for every method per the domain to be used throughout the industry. That would amount to unrealistic and impractical oversimplification of the complexity that exists in the industry. Instead, the purpose here is to create the platform that each company would be able to populate depending on their projects and their preferences. The activities provided here are simply examples that consider a certain scenario. For each domain, alternative construction methods and major activities per each assumed default method are provided from various sources

(Olin, Schmidt, & Lewis, 1980),(Hutchings, 2004), (Weber, 2005). Domains, the work items that divide the schedule into smaller work packages, can be broken down into further details in terms of their activities, which are more practical. They are also referred to as sub-networks of the whole schedule (Callahan, Quackenbush, & Rowing, 1992).

Table 3-Activities per domain and methods of construction

Domains	Alternative Methods	Activities per default method
Structural Concrete	1. Cast-in-situ 2. Precast	1. Erect form 2. Install reinforcement 3. Concrete accessories 4. Place concrete 5. Cure concrete 6. Remove form and temporary support 7. Concrete restoration and cleaning
Masonry	1. Hollow concrete blocks(HCB) 2. Brick	1. Prefabricate HCB 2. Build masonry 3. Cure masonry
Doors and windows	1. wooden doors 2. Metal doors and windows	1. Install door opening assemblies 2. Install doors and windows 3. Install glasses

For the purpose of this research, a modified version of the 16 division 1995 MasterFormat (Miller & Newitt, 2005) classification has been applied. This division is neither complete nor universal industry standard that every company adheres to when it comes to organizing work packages, but it is considered sufficient to represent the data structure sought in this implementation. Several modifications were also necessary to the categorization of the different work items with regard to their place in the domains. For example, “roof” as work package is included in the “structural concrete” division here, even though the standard classification places it under Thermal and Moisture Protection.

Whereas the elements assigned to the different domains in Table 2 can be predicted beforehand, there are various generic elements such as *IfcElementAssembly, IfcFeatureElement, IfcBuildingElementPart* which can fall anywhere in the domain classification depending on what major building element they are associated with. Therefore, domain assignment for these generic items in the design is decided based on the domains of major elements associated with them or through visual inspection by the user.

The scope of this research is limited to part of the construction segments that constitute the final product of the facility including the substructure and superstructure works. Some common work breakdown structure (WBS) segments of a typical project schedule such as procurement, earthwork, commissioning and other administrative

works, which are not directly related to the installation of physical building elements are considered beyond the scope of this work since the relevant information is not readily available in the 3D models.

The various disciplines of work listed above can be built on the actual site using different techniques and material of construction depending on the design and preference or availability of resources. It is the contractor's sole responsibility to choose the methods of construction and sequence of the work (AIA, 2015).

The IFC classes covered in this research are subtypes of the entity IfcElement, which comprises all objects that make up any AEC product(Thomas Liebich et al., 2006). In Table 4, the eight immediate subtypes are numbered and listed in the merged cells.
IfcBuildingElement, IfcFurnishingElement, IfcElectricalElement, IfcDistributionElement,IfcTransportElement, IfcEquipmentElement, IfcFeatureElement, IfcElementAssembly), followed by their respective subtypes. Among the subtypes of this container class, IfcVirtualElement has been omitted because it does not represent any physical element that becomes part of the final product.

Table 4-Description of IFC elements considered

Component	Description
1) IfcBuildingElement: major functional components of a building	
IfcBeam	A horizontal structural building element that supports load beyond point of support
IfcBuildingElementComponent	Smaller sub-elements of building elements usually added for reinforcement and strengthening. E.g. reinforcing elements, components added as part of a layer
IfcBuildingElementProxy	A general name given to building elements, for which the current version of the IFC structure does not have a specific definition. Therefore, in the system developed here, the user is required to give more specific description while matching them with their specific methods and domains
IfcColumn	A vertical structural member that transmits load to its base, usually in the form of compression
IfcCovering	Refers to elements that cover other elements. Examples include wall claddings, floorings, and suspended ceilings
IfcCurtainWall	Exterior walls of a building
IfcDoor	Building element that provides controlled access to a building
IfcFooting	Part of the foundation which transmits load to the soil either directly or via piles
IfcMember	A structural element designed to support Load between and beyond points of supports but, it is not necessarily load bearing
IfcPile	A slender timber, concrete, or steel structural element, driven, jetted, or otherwise embedded on end in the ground for the purpose of supporting a load

(Table 4-Continued-1)

Component	Description
IfcPlate	Refers to metal or other material which is planar and often flat part of building elements
IfcRailing	A frame assembly as handrails in staircases
IfcRamp	Vertical passageway for humans between different floor levels
IfcRampFlight	Slanted segment of a stair usually aggregated with IfcRamp
IfcRoof	This acts as an aggregate description of all roof components such as slabs, rafters, and purlins (IfcBeam). This aggregation is expected to be found as parent-child relationship considered in the Navisworks application used in this implementation
IfcSlab	Component of construction that normally acts as vertical space division and also acts as lower support such as floor or upper such as roof
IfcStair	An entity that aggregates all components of the stair it represents including IfcStairFlight and landing (ifcSlab)
IfcStairFlight	Parts of a stair in single run not interrupted by a landing, including steps and stringers
IfcWall	Vertical construction that divides or bounds a space
IfcWallStandardcase	A wall occurrence that has non-changing thickness
IfcWindow	Defines occurrence of a window in the design
2) *IfcFurnishingElement*: - these are furniture related objects, which are generally manufactured off site.	
*3) IfcDistributionFlowElement**: -*** Elements that facilitate the distribution of elements and matter. Examples include pipes, ducts, etc.	
4) IfcElectricalElement: - Generalizes objects related to electrical works and many elements are categorized under subtypes of distribution elements	
5) IfcTransportElement: - Objects that move people and other objects within the building. Examples include elevator, escalator, moving walkway, etc.	
6) IfcEquipmentElement: - Generalizes objects related to equipment to be installed; does not include equipment that has distribution functions.	
7) IfcFeatureElement: - Existence dependent elements that modify the shape and appearance of another object.	
IfcFeatureElementAddition	This is any sort of projection to a bigger element
IfcFeatureElementSubtraction	Related to subtraction such as openings in a component
8) *IfcElementAssembly**:*** - Aggregation of several elements into one entity. e.g. a prefab slab made from different building elements	

The attributes outlined in Table 5 were extracted from the BIM model and stored for all components referenced in the activity model, and used by the system and the end user to complete the scheduling as well as 4D linking process.

Table 5- Attributes of each component extracted from the BIM model

Attribute	Description
Zone	Division of the construction floors into different work areas. This can be defined after the design is complete, as preparing the model for extraction.
Floor	In this study, floor refers to the main spatial division between horizontal platforms ordinarily known as "floors." It helps to group each element based on a shared spatial location.
Building Element Class	Each component in the model belongs to one of the various element categories such as walls, columns, floors and slabs as defined below.
Hierarchy	Hierarchy refers to the parent-child relationship between components and their sub-elements. Example the building story each element belongs to.
Material	Refers to the material each element is made from.
GUIDs	These unique identifiers of each component of the model are used to maintain the relationship between the schedule and the 3D model product model.
Element Display name	This displayed name of each element in the native authoring tool. This assists in reclassifying components if they are described as generic names *such IfcBuildingElementProxy*.
BoundingBox	An orthogonal box around any geometric object that shows the extent of an object or a set of objects.

3.3 Model Preparation and Information Extraction

The input product model to this system is an IFC export file in 3D format. This model is read and interpreted by the system and only the relevant data is stored in a local database. For this to be effective, the model has to go through a preliminary preparation process in its authoring tools by the user. The required major preparation works involve labeling floor and zones in the model using the existing capability of authoring tools (Autodesk, 2015b; Graphisoft, 2015). Each step is discussed below in more details.

Definition of Work Zones or Areas

As part of the work planning process, it is usually necessary to subdivide the project at hand into work areas (Kim et al., 2013) depending on the size of the project. These are mainly meant to assist the project execution team to coordinate different discipline crews and subcontractors, to use the available space and other resources effectively. The sequencing logic built into the system checks if the project has been divided into work zones and groups the content of the design accordingly. Therefore, after the design is completed the building elements in the 3D model are assigned zone values. This division of the project into various work areas or zones considers

two scenarios. The first and the default case is for structurally connected zones, where a building is divided into multiple areas because it is too large an area to consider all the work within each level, as a single activity or work package. One possible scenario is when a long high-rise building is horizontally allocated into various work areas. In this case, work has to progress from one zone to the next within the same floor before the crew of that specific discipline moves up to the next floor level. The structurally connected is the default case considered in this implementation.

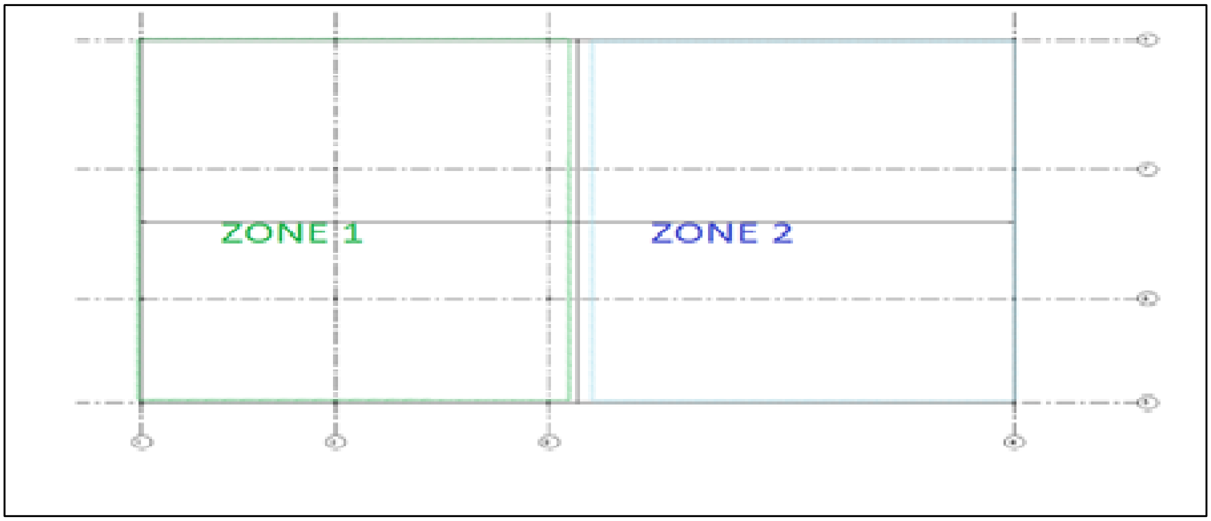


Figure 3 - The default case of zoning for structurally connected buildings

The second case of zoning is when the building zones are structurally independent of each other. In this case, construction can progress vertically within each zone regardless of the progress in other zones.

Assigning Floors

The 3D space between two consecutive floors levels is defined here as a floor or story, and building elements within this range of space are labeled accordingly. This horizontal division of a building is used as a major hierarchy in sequencing construction work. Exporting this information directly from the original authoring tools and the original design files shows inconsistency in the categorization of building elements to their respective floors. Therefore, in this study manually assigning such a label as a simple attribute to the building elements is adopted as a better and more consistent approach to using this information.

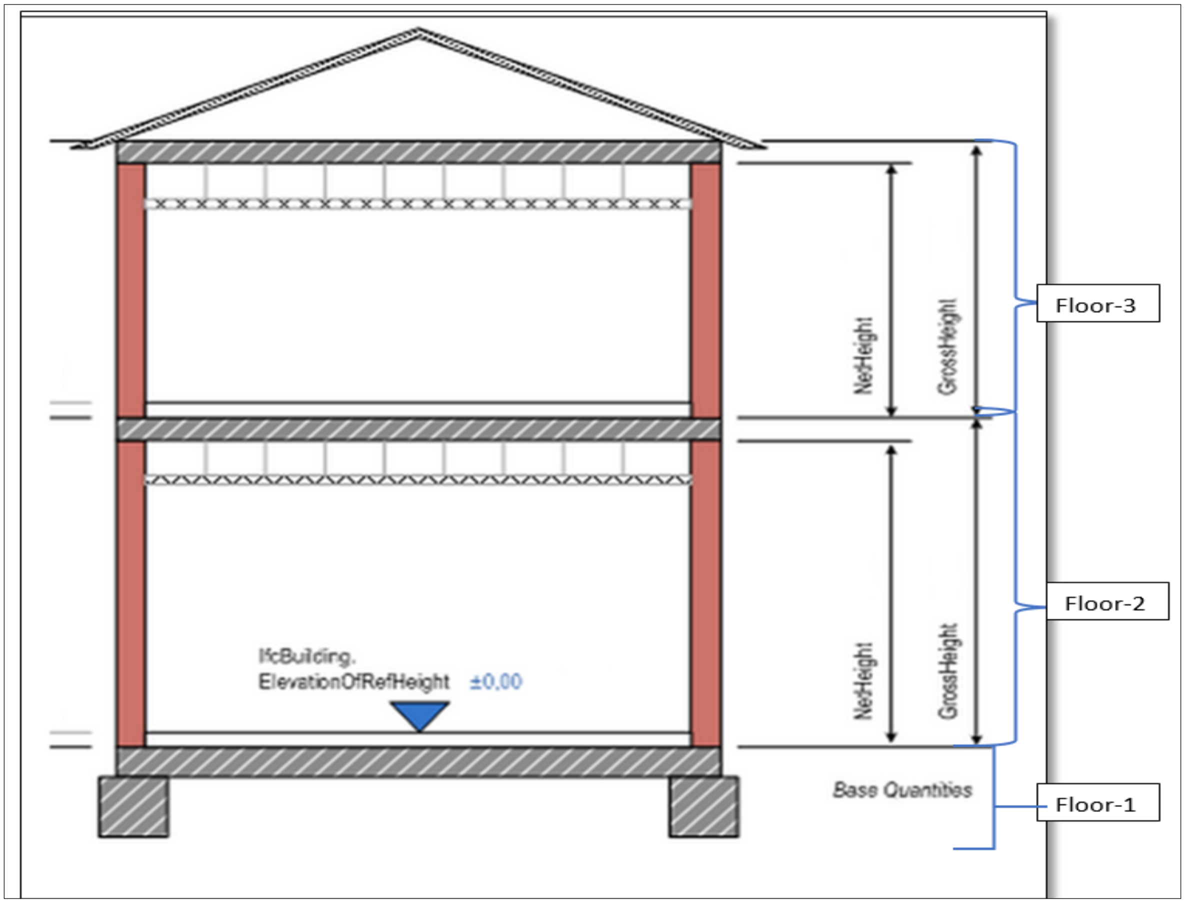


Figure 4- Building floors (story) indicated by the gross height (International, 2015)

Similar to the zone values, floor values are assigned to the various groups of elements in the authoring tool after the actual design is completed. As can be seen in Figure 4, one story aggregates all elements contained between two consecutive horizontal levels in the design.

Material Assignment

The type of material each model item is composed of should be assigned in the authoring tool. Materials and methods of construction determine the types of activities needed to perform the construction of these items. Therefore, the material information is used in matching the different domains to more relevant methods of construction.

Granularity Adjustment of 3D Elements

The final visualization of the design in 4D after linking to the corresponding activities depends on the match in the level of detail of the activities and the 3D models. Usually due to lack of communication and collaboration between the design team and the construction team, the former does not prepare the model to meet the needs

of the latter, which makes the 3D model not fully ready for the 4D work. Therefore, modifying the level of detail in the 3D model to reflect the details in the schedules is necessary. Therefore, the user has to make sure the 3D model has the necessary level of detail before extraction of the information by the system developed in this research.

IFC Export Set Up

Some of the exports from the authoring tools may not be specific enough to represent the item intended in the design. During the experiment with various models, it was observed that so many of elements are by default mapped to generic terms such as *IfcBuildingElementProxy* when more specific terms have already been defined in the IFC schema[IAI], to represent them. Some authoring tools allow the user to customize the export process to meet their needs by exporting more specific standard IFC element names(Autodesk, 2015b). Therefore, for this purpose, a Revit export template was prepared to represent many of the sub elements in more specific IFC containers before export. This step of model preparation reduces the need for the manual matching of numerous building elements exported by the authoring tools as generic names.

3.4 Generation of Sequence Constraints

This research semi-automatically generates the sequence of construction activities by considering factors related to the structural laws of load transfer of components, discipline interaction, workspace access and other implicit factors that could be relevant to individual projects. There are numerous factors unique to each project, which determine the choice of sequence for the developed schedule. Preference and personal judgement usually lead to different schedules for the same project depending on the level of detail sought, variation in sequence and other factors. Because of such subjectivity in schedule development, this research does not attempt to present a blueprint for a universal approach to scheduling commercial projects, but rather a high-level effort to generate a physically plausible sequence of building components and their corresponding activities. The result was used to generate an initial draft of activities and their high-level sequence. Since not all the information needed to sequence the project is readily available in a BIM model, this research takes into account the following interrelated constraints for the component level and activity level sequencing.
Support**:** The target of this logic is sequencing the structural portion of a building. It has been ascertained that structural construction lies in the critical path of the project and dominate the early phase of the process (Chin et al., 2005; Echeverry et al., 1991; Horman, Orosz, & Riley, 2006). Since this is the frame of the building that supports all loads from self-weight as well as live loads, the sequence of the components is based on support. Information about this is not explicitly incorporated in the IFC schema and, therefore, it has to be inferred (Borrmann & Rank, 2010). After extracting and grouping these components by floor level, sequencing them in the reverse direction of the gravitational load transfer (Arya, 2009) can lead to a reasonable sequence of their construction. A general overview of load transfer mechanism is depicted in Figure 5.

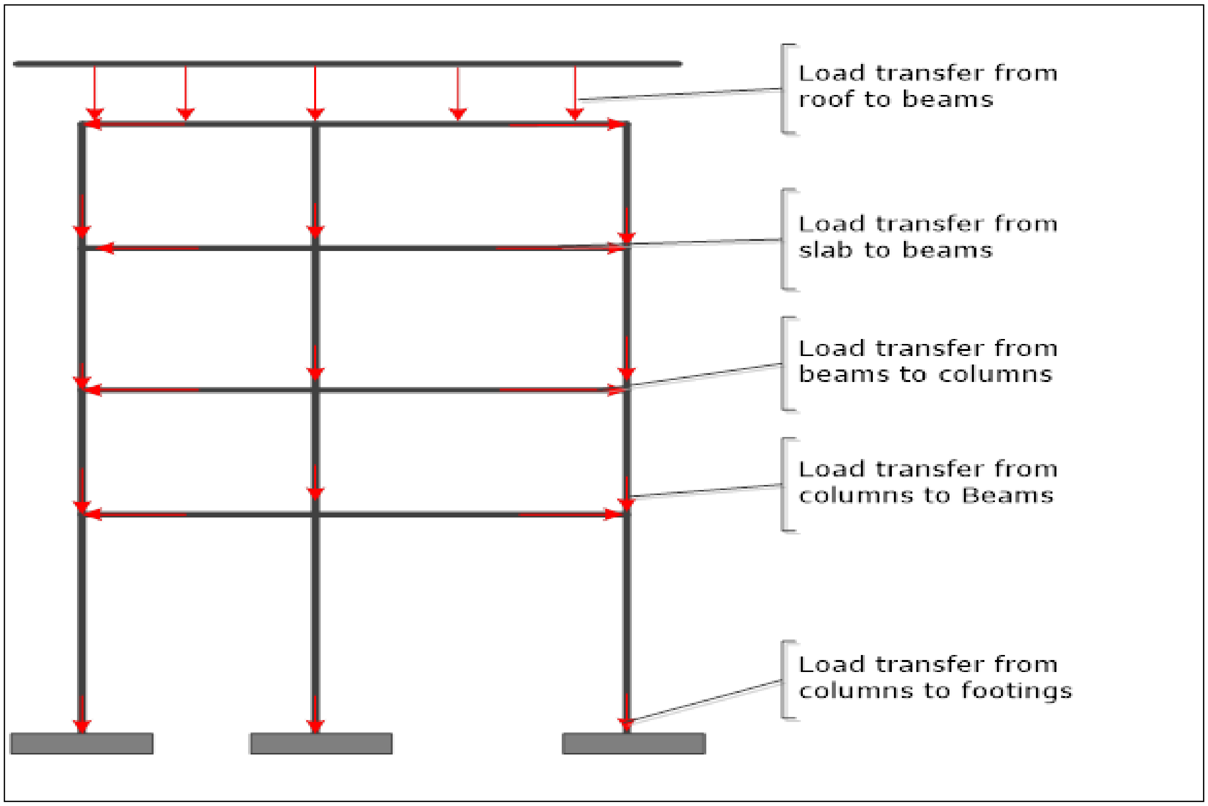


Figure 5- Load transfer mechanism in structural members(Arya, 2009)

Spatial-Aggregation and Enclosed-In: Spatial aggregation in this context refers to floor level grouping and sequencing of the building components therein. Construction of high-rise buildings generally progresses in a bottom-up fashion, from the lowest to the upmost floor. Enclosed-in, on the other hand, refers to building components that are covered by other building components. To gain access for the installation of these objects, it is logical that they should be installed before the covering component. Examples are plumbing and electrical pipes that should be inserted inside walls. This relationship can be deduced from *Boundingbox* property of each element. So, if the boundingbox of one element contains that of another element, the latter is enclosed in the former. This logic is also implicitly applied in various activity sequences. For example, installation of reinforcement bars before casting concrete.

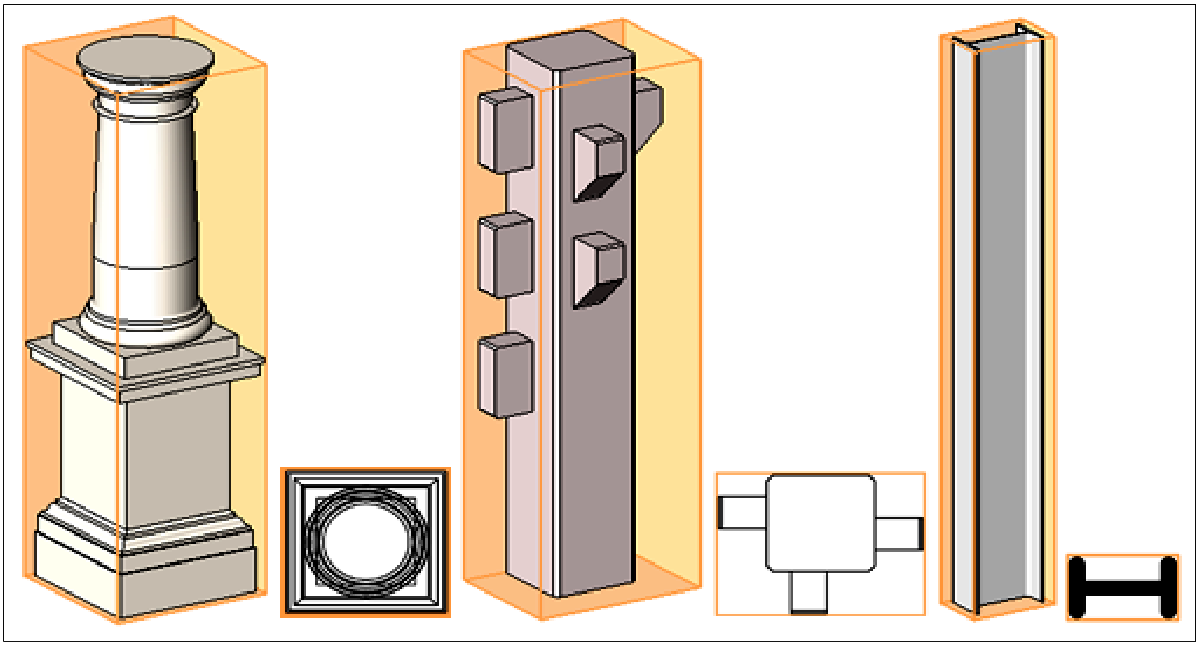


Figure 6- Bounding Box of various column types, represented by the orange lines (Autodesk, 2015b).

Part-of: This relationship can be directly extracted from the BIM model in a parent-child query. Completion of the child element is needed for the completion of the parent element. For example, landing of a staircase unit should be completed before the whole staircase can be considered complete.

Work Continuity: Mobilization and demobilization of different trades of work cost time and money. Because of this, unless it is required to meet physical constraints, uninterrupted workflow in each trade is generally preferred.

Top-Down-Finishing: To protect completed works, especially for finishes, work needs to advance in a top-down mode, in the whole building and individual units such as floors and rooms. The sequence of finishing works such as wall painting and floor ceramic covers should enable free movement of workers without damaging the completed parts. Therefore, installing such layers of objects generally goes in top-down and inside out order. This logic is included as part of the spatial reasoning of scheduling the work.

Miscellaneous*:* Other sequencing factors such as contractual requirements, safety considerations, project technical and client specifications are implicitly considered when predefining sequence in the activity model.

The sequencing factors discussed in section 3.4 are combined into the following main numerical values to find the overall sequence for the whole project.

Relative Domain Priority: This means that each domain or construction discipline follows a certain order of preference, wherever physical factors allow. Accordingly, on each floor, after the identified components are grouped into the predefined domains, they inherit the contractor-assigned relative order number from their domains. This sequence is mainly due to work continuity of different disciplines and is more relevant to the non-structural work since these parts of a building such as

electrical work, doors, and windows are considered as a group instead of as individual components like their structural counterparts.

Structural Sequencing: This factor combines physical factors based on structural load transfer sequence to the ground, to find a sequence of the individual physical building components.

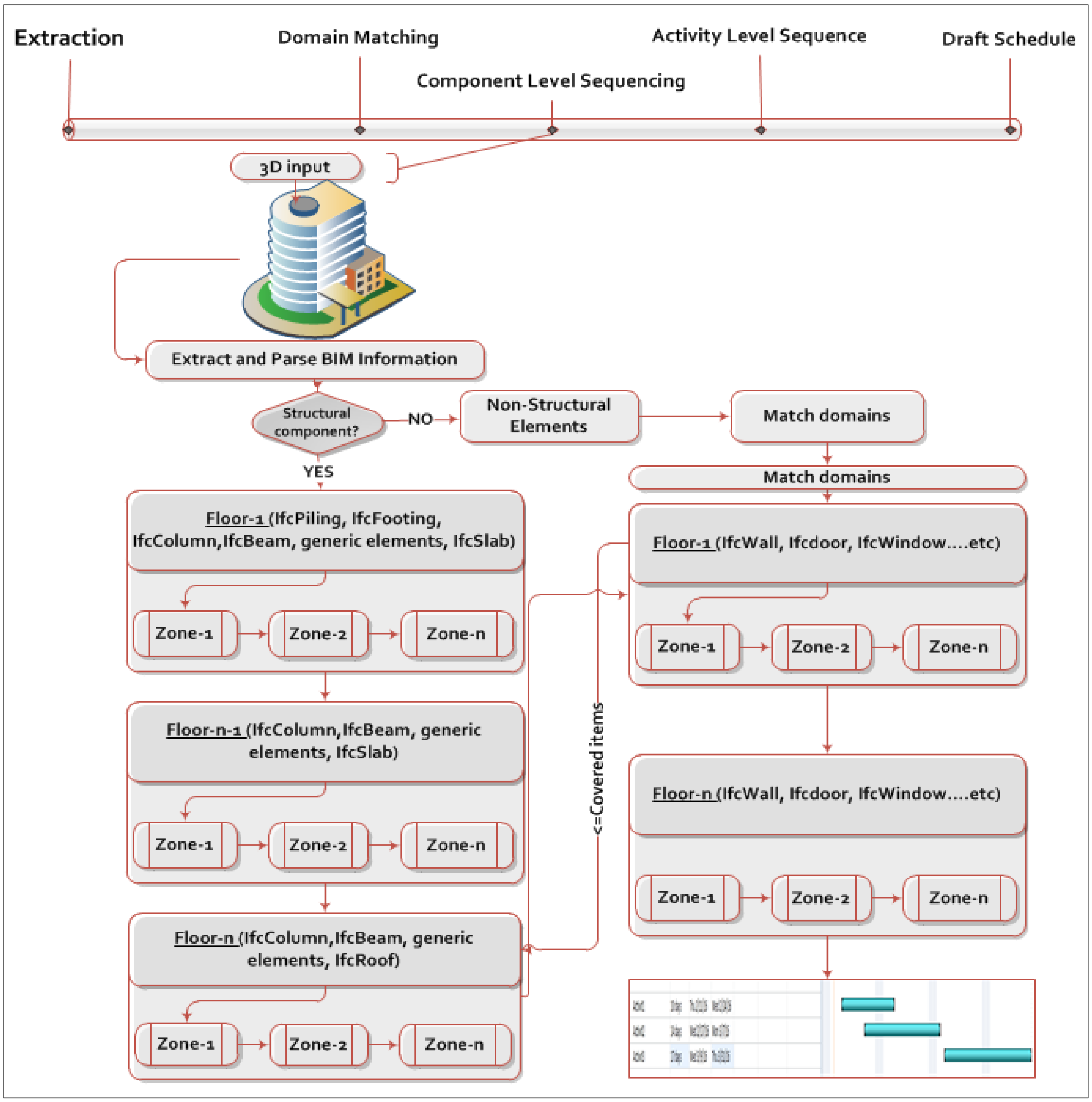


Figure 7- Algorithm for component level sequencing

From the assigned priority numbers with the relative level of order, elements with higher priority number values are installed first, followed by those with smaller priority values. Work progresses ground up, considering the floor values and from the minimum to the maximum zone values, assuming the zone values are assigned in the order of importance or sequence in construction.

As shown in Figure 4, floor-1 refers to the substructure elements, which is different from the other floors as it uniquely includes elements such as piles and foundations, which transfer the load coming from the superstructure to the ground. Intermediate floors between the first and the topmost are similar in their load transfer mechanism, and hence, their element compositions are repeated. The topmost floor is typically, but necessarily unique in that it includes roof and related structures in its composition and hence its load transfer mechanism. This is summarized in Figure 7.

Predefined Sequence of Activities: The predefined activities in the project independent model are placed in some relative sequence within their domains using the priority numbers assigned. The reasons behind the sequence can be any of the above, especially those under miscellaneous considerations. Sequence reasoning at the level of individual activities is beyond the scope of this research.

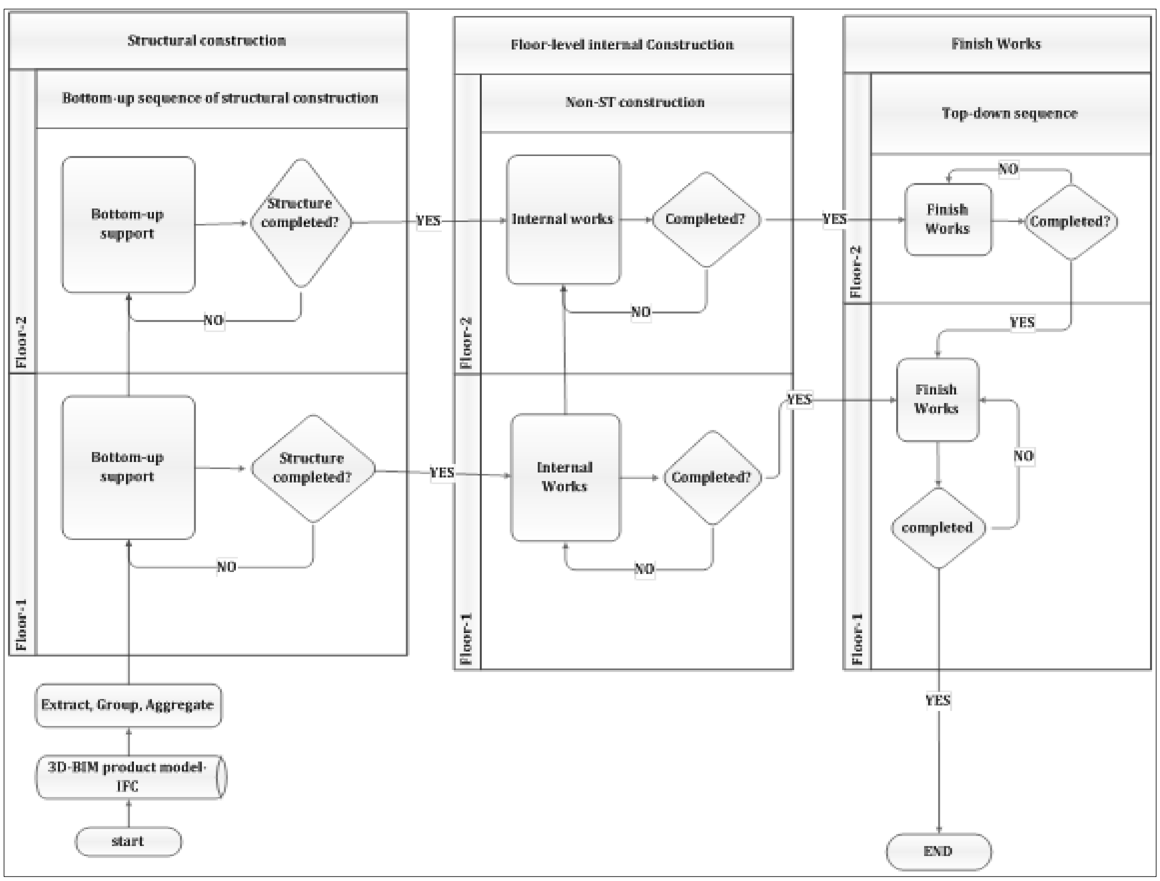


Figure 8-Spatial and temporal progression of the construction process

As illustrated in Figure 8, the sequence of construction starting with the structural portion of the work divides the whole process into different floors (Weldu & Knapp, 2012). Within each floor, all the component level factors are applied to generate the sequence.

Taking into account all the various factors discussed above, the component level priority, floor level priority, the zone and individual activity priority requires a formal approach to combine these priority values and decide the precedence of work. The problem of combining the multiple factors in order to find the single relative importance or priority of each building element essentially defines the well-researched question of multi-attribute decision-making (MADM) technique. To use a similar approach and arrive at a methodological conclusion of the sequence of the components, and hence the activities, the MADM technique is briefly introduced and then customized to fit the problem structure in this research.

3.5 Applying the MADM Method to Compute Sequence

Multi-Attribute Decision Making (MADM) are a class of operational research methods that can be used to prioritize and sequence various alternatives with multiple factors (Triantaphyllou, 2013). In this research, the problem of sequencing building components can be modelled using this technique to objectively combine the various factors and determine the overall sequence priority value. Since the factors considered during the sequencing process are numerous, the MADM method is selected to quantify and combine all these factors to generate the overall draft sequence. The following section discusses how the problem can be formulated to fit the MADM structure.

Problem Modeling

In the context of sequencing of building elements, formulating the problem to match the structure of MADM procedures and format can be carried out as follows. To start with, in major projects, building components as part of a work package are referred to as a group, instead of individually. For example, we refer to walls in a certain area rather than wall 1, wall 2….wall n, and erecting columns in zone 1, zone 2…etc., instead of listing each column individually. The MADM technique involves setting up a decision matrix to combine the relevant factors. Such a matrix looks like Table 6:

Table 6- Formulation of MADM problems

	F_1	**F_2**	**F_3**	**……**	**F_n**
	W_1	W_2	W_3	…….	W_n
E_1	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}
E_2	a_{21}	a_{22}	a_{23}	a_{24}	a_{2n}
E_3	a_{31}	a_{32}	a_{33}	a_{34}	a_{3n}
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
E_m	.	.	.	.	a_{mn}

$E_{m=}$ represents the building elements grouped by Zone of construction and floors

$F_{1, 2 \ldots n}$ represent the factors used to determine the priority in sequencing the building elements. These include zone priority, floor priority, domain priority and structural priority.

$a_{mn=}$ represents the relative importance of each criterion or value of element m considering factor n. For example zone number=3

W_i= weight of each decision criteria

Priority $of\ E1 = Max \sum_{k=0}^{n} (\mathrm{w1} * \mathrm{a11} + \mathrm{w2} * a12 + w3 * a13 + \cdots)$

Once the above matrix is set, there are numerous techniques to solve the problem including the weighted sum model, the weighted product model, analytic hierarchy process,…etc. (Triantaphyllou, 2013) Solving these problems, after these matrices are set is relatively easy. Setting up the weights and their relative importance values, however, are long and complicated processes, which require expert judgement, among other things.

In the case of this research, however, the priority of each factor, and hence its sequence, is mainly predetermined as described in the previous algorithm while the weights are simply relative values and their accuracy is not needed to be more than the minimum required to maintain certain order between them. In other words, assigning values such as 100,200, 300 to indicate their construction order work equally well as values such as 0.1, 0.2, and 0.3 as long as the minimum difference between the values are maintained to reasonably accommodate all entries within each category. This assumption holds for all the factors considered: floors, zones, structural vs non-structural elements and domains of construction. However, in an objective numerical approach, the decision process is represented with MADM method. Therefore, this research uses a simplified version of the Weighted Sum Method without the long approaches to determine the relative importance values and the weights. Multiples of the floor and zone numbers are used as a_{mn} values. The relationships between these values are intuitively established as follows.

The overall component or element level priority is the sum of its structural priority, floor priority, zone priority, and domain priority. As shown in the example of elements in Table 7, the priority values for each factor are written in different scales to make up for the weights assigned and used in the original formula. The difference in the scales is necessary since the factors considered for sequencing in this study are distinct, with clearly predetermined impact on the overall priority of the components. In other words, floor level priority has higher precedence over zone level priority as well as structural priority. With this backdrop, the summation must result in a higher overall priority for any floor 1 structural work than any floor 2 structural work, regardless of their zone priority values. Similarly, for any two structural elements (E1 and E2) on the same floor level, the structural priority values should supersede the effect of the zone priority values for the same elements so that the overall sequence is determined by the structural priority. Therefore, the minimum difference in the structural priority, which is the difference in the priority values between two consecutive elements, must be greater than the range in

zone priorities, which is the difference between the priority values of the lowest and highest zone priority values expected in the whole floor.

In practice, a building project is generally divided into several zones or areas if at all. With that assumption, the following minimum differences (Δ's) between consecutive values and the expected relationships between them have been empirically decided to establish the scales for each factor and then used to compute the overall priority of the elements. The parameters involved here are defined as follows:

$Z_{range=}$Zone priority range is the difference between the highest zone priority (zone-1) and the lowest (zone-n) priority.

S_{range} =Structural priority range is the maximum difference in priority between any two structural elements.

ΔF=20= The Minimum difference between floor priority values (100, 80, 60, 40…).

With this in mind, the actual floor priority is determined as:

Floor Priority= ((FloorCount-Floor #)*20)+20, which results in a minimum value of 20. FloorCount is the total number of floors, while Floor # is the individual floor value.

ΔS=1= The minimum difference between structural priority values (10, 9, 8…). These values are shown in the algorithm for structural sequencing.

Δd= 0.1=The minimum difference between domain priority values

As explained in the previous section, domain priority could usually be determined for non-physical reasons such as material delivery, safety and crew management. Therefore, even though a basic priority was predefined, the system should generally prompt the user for possible preferential sequence.

ΔZ=0.01= minimum difference between zone priority values

To maintain this minimum difference between each zone, zone priority is calculated as follows:

ZonePriority= (ZoneCount-Zone)*0.01 +0.01.

So, if there are 4 zones assigned in the model, zone 1 will have a priority of 0.01+ (4-1)*01=0.04, and the priority for zone 3= 0.01+ (4-3)*0.01=0.02. Hence, zone 1 has greater priority than zone 3.

Therefore, the discussion above about the relationship between the different priorities and the scales used for each factor can be represented using the following algebraic expressions:

$\Delta S > Z_{range}$ …………………………………………………………………… (1)

This indicates that within the same floor, structural priority should supersede any zone priority.

$\Delta F > Z_{range} + S_{range}$ ………………………………………………………………… (2)

So, the scales and the Δ's for each factor were established keeping in mind these relationships and the expected number of assignments under each factor. These values are then summed up to decide which building element should be installed first. According to the table the pile component, with the highest score becomes the first component to be built.

Table 7- Example of BIM Model components restructured in MADM format

Element	Floor	Zone	FloorPriority	ZonePriority	Structural	Priortiy Sum
Pile	1	1	40	0.02	10	50.02
Footing	1	2	40	0.01	9	49.01
Column	1	1	40	0.02	7	47.02
Column	1	2	40	0.01	7	47.01
Beam	1	1	40	0.02	6	46.02
slab	1	1	40	0.02	5	45.02
Column	2	2	20	0.01	7	27.01
Beam	2	1	20	0.02	6	26.02
Beam	2	2	20	0.01	6	26.01
slab	2	1	20	0.02	5	25.02
slab	2	2	20	0.01	5	25.01
staircase	2	2	20	0.01	4	24.01

This example table is a partial view of components of a model and demonstrates the fitness of the established scale to prioritize components as presumed, and the different scales used and their agreement with previous algorithm. It was already stated that construction of structural components should progress from one floor to the next, after finishing each zone, in the order of the structural priorities. The priorities generated in the above table support that claim.

3.6 Automating 4D Visualization

One of the most significant downsides of adopting 4D as a means of visualization, verification and communication of construction schedules is the tedious process of linking the activities to their corresponding 3D objects in the model. As outlined in Chapter 2, the integrated schedule generation and visualization model developed in this study identifies addressing this issue as one of its major targets. The basic approach set out to implement the 4D generation is by using the GUID values inherently available and hence extracted from the BIM models.

The intermediate product model, which extracts, restructures and stores the IFC-based BIM model, is at the heart of this methodology. The extracted information of individual components includes the globally unique identifiers of each entity. These IDs are associated with their respective activities during the matching of components to their

domain specific activities. By using the intermediate groupIDs generated during the whole integration process.

Therefore, as soon as the activities are generated, they already have shared keys with the 3D objects in the model. Consequently, database rules that link all 3D entities to the activities, which contain copies of their GUIDs, with the groupIDs as intermediators, enable the automated link between the activities with the 3D model, essentially automating the generation of 4D visualization.

Similar concepts of having matching ID's between different data models as mapping tools have been demonstrated. In connecting activity locations with predefined levels in AutoCAD (Sheryl Staub-French et al., 2008) assigned similar ids in both the 3D CAD styles of objects and the process view in the REPCON structure. Though their approach entailed a significant manual labeling initially, it sets a clear direction towards the a feasible way of the automating the linking of the product and process models. Figure 9 shows the linking mechanism between the activities of the draft schedule and the product model using both the GUIDs and the groupIDs.

GroupID	ObjGUID	ClassName	Floor	Zone
14555	656284ae-d84a-4c5c-ae16-d638fa12ce74	IFCFOOTING	1	1
14555	656284ae-d84a-4c5c-ae16-d638fa12ce72	IFCFOOTING	1	1
14555	656284ae-d84a-4c5c-ae16-d638fa12ce70	IFCFOOTING	1	1
14555	656284ae-d84a-4c5c-ae16-d638fa12ce6e	IFCFOOTING	1	1
14560	1551350c-45e5-41b8-bdf1-bcfa679fd1a4	IFCROOF	3	1
14560	a6aa132d-ccd7-408f-b2f9-ed67350f3a70	IFCROOF	3	1
14565	5e8712a2-e372-44b6-9e73-0aaa430d3d81	IFCSLAB	2	1
14565	1970f67d-62ee-4fc6-9008-0a9f0071fd4b	IFCSLAB	2	1

GroupID	TaskID	ActivityName	ActivityDuration	StartDate	FinishDate
14515	F2.Z1.DRWD-14515-2	F2.Z1-Doors and Windows-Install glasses	2	2015-08-17	2015-08-19
14515	F2.Z1.DRWD-14515-3	F2.Z1-Doors and Windows-Sealing and finish	2	2015-08-26	2015-08-28
14520	F3.Z1.DRWD-14520-1	F3.Z1-Doors and Windows-Install metal frames	1	2015-11-11	2015-11-12
14520	F3.Z1.DRWD-14520-2	F3.Z1-Doors and Windows-Install glasses	1	2015-11-17	2015-11-18
14520	F3.Z1.DRWD-14520-3	F3.Z1-Doors and Windows-Sealing and finish	1	2015-11-19	2015-11-20
14525	F1.Z1.MECH-14525-1	F1.Z1-Mechanical-rough-In Inspection	1	2015-06-27	2015-06-28
14525	F1.Z1.MECH-14525-2	F1.Z1-Mechanical-Rough-In	2	2015-06-29	2015-07-01
14525	F1.Z1.MECH-14525-3	F1.Z1-Mechanical-Mechanical trim out	3	2015-07-02	2015-07-05

Figure 9- Sample GUID and GroupIDs as a link between a product model and the generated draft schedule

Once the activities look up the GUIDs from the intermediate product model with the help of the GroupIDs, the search uses them to find the 3D components in the main model, as these GUIDS were originally copied from the main models and continue to reside there. Once all 3D components are found, all activities with the matching GUIDs are automatically attached to them, thereby accomplishing the automated linking objective.

3.7 Performance Testing and Validation

The computer system developed to implement the objectives of this research was tested by users currently working in the construction industry to verify that it meets, at least, the core objectives set forth in this research. The main objectives for the validation and testing by users include:

a) To verify that the system allows method-specific activity predefinition and generation
b) To practically witness the integration of the process and product models enabling the automation in generating the draft schedule and linking the activities with their corresponding elements in the 3D file. To this end, a typical multistory building with concrete structure and other basic functional components was used as a case study.

The following two steps were conducted for testing and validating the system's functionalities and contributions.

First, the schedule output of the system was visually inspected considering the completeness of the generated activities and the degree of accuracy in their precedence. In the testing and validation process, eight people with extensive industry experience in scheduling and some level of experience with 4D and other BIM processes were involved. After initial set up of the generic activity model for an assumed company, the users evaluated the operability, functionality, and outputs of the system based on the stated metrics. Feedback from the users was collected using questionnaire shown in Appendix 1.

Second, the process and final outputs of the automated 4D generating module of the system was compared against earlier research systems developed with similar objectives. Specifically, methods and systems used in (Chau et al., 2005), (Alan Russell et al., 2009), (Tauscher et al., 2009), (Kim et al., 2013), (Chen et al., 2013) and (Liu et al., 2015) were compared to the approach and results in this research. Depending solely on the documentation of these previous systems from literature, a comparative analysis was conducted considering factors such as the need for initial or intermediate manual steps; ability of the models to handle object groupings at different level of the work break down structure were to be assessed.

CHAPTER 4- IMPLEMENTATION

The objectives of this research were verified with the development of software, implementing the aforementioned methodology. The purpose of the software is to, at least partially, automate the process of generating draft schedules as well as 4D visualization as a single process. By integrating a generic activity model and data extracted from 3D file of the project in IFC format, a seamless integration has been achieved to generate automatically an initial schedule and its 4D visualization. Here, the author coins modified version of the system's functionalities to name it: 4DADS-System, (automated 4D and draft schedule system), referring to its core capabilities.

4.1 Architecture of the 4DADS-System

The 4DADS-system is built as a plugin to Autodesk Navisworks, one of the most popular commercial tools to build 4D of construction schedules and model review. In an effort to avoid recreating existing solutions, the system utilizes current components and capabilities of the software as related to 4D visualization, but it goes beyond current capabilities of existing tools, as outlined in the objectives of this research. To this end, the application program interface (API) of Navisworks 2015 and 2016 were used to build the back-end logic and additional features needed to run the software. Authoring tools such as Revit 2015 ArchiCAD 16 were used to create different 3D test models and generate neutral IFC file based on the 2x3 release of the IFC data schema. SQL Server 2008 or higher is also required as a critical component of the system's integrated relational database system to support the intended functions. Integrating all the above components, the plugin was built in .NET 4.5 framework and environment. Figure 10 summarizes the basic components of the 4DADS-System.

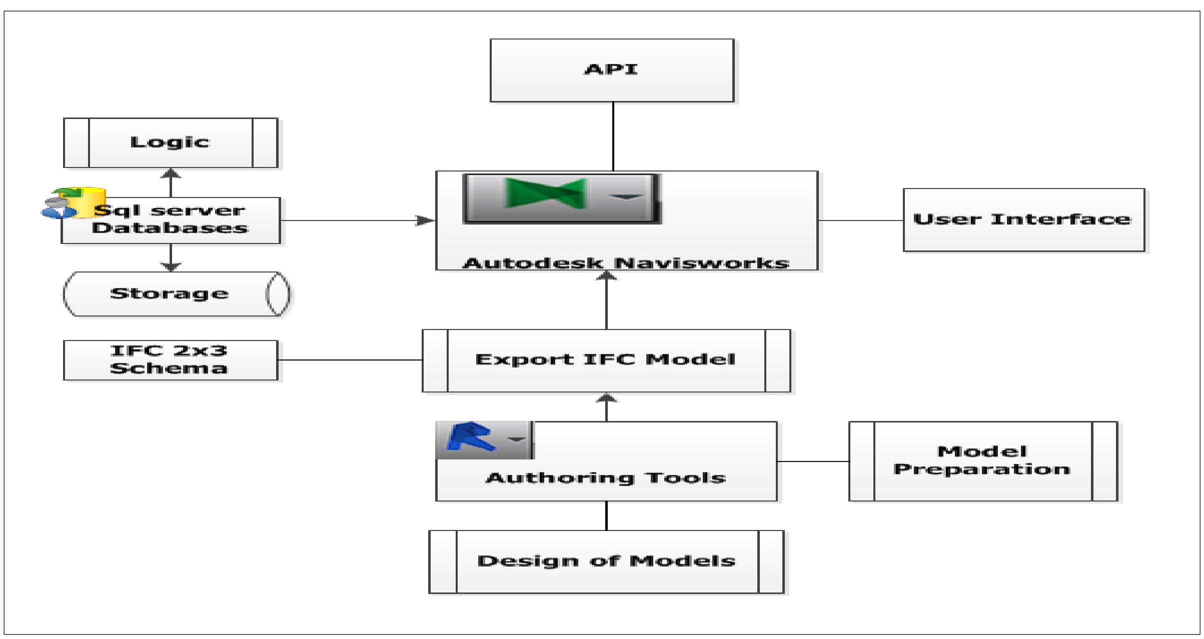


Figure 10- System Architecture

4.2 Initial User Input to the 4DADS-System

The practice of scheduling a project is a concerted effort that requires the technical expertise and experience as well as thorough understanding of the project information including (but not limited to) the design, contractual requirements, technical specifications, environmental regulations, safety, cost and so forth, among other things. These and other factors of each project necessitate the development of a uniquely tailored schedule. Therefore, the degree of automation that can be achieved in the scheduling process is limited by such a nature of construction projects. As a result, the 4DADS-System requires initial information input from the user before it can generate the final outputs. This section describes the process and the user interface of the tool needed to perform that task. Figure 11 shows the main entry point to the plugin.

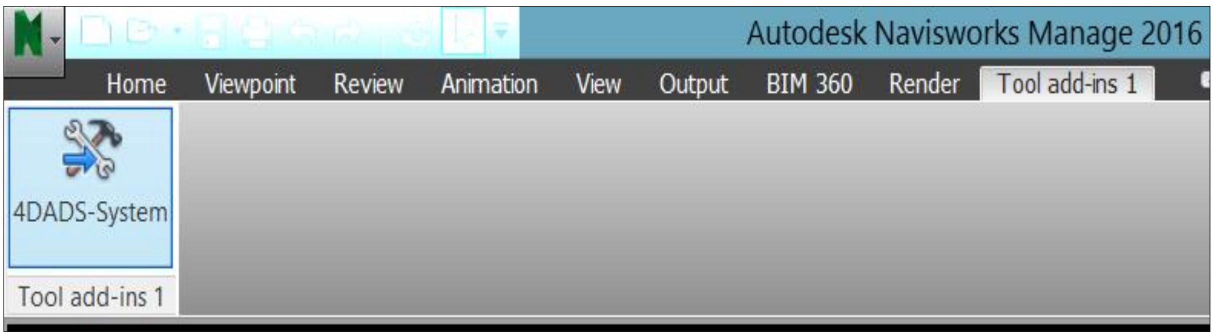


Figure 11- Accessing the Plugin in the main application

The user launches the 4DADS-System from the "add-ins" list of the main application as shown in Figure 11.

The form shown in Figure 12 allows the user to enter the basic domains and methods of construction or edit existing values depending on the needs of a project under consideration. This information would be required to set up a new project category initially or update an existing one.

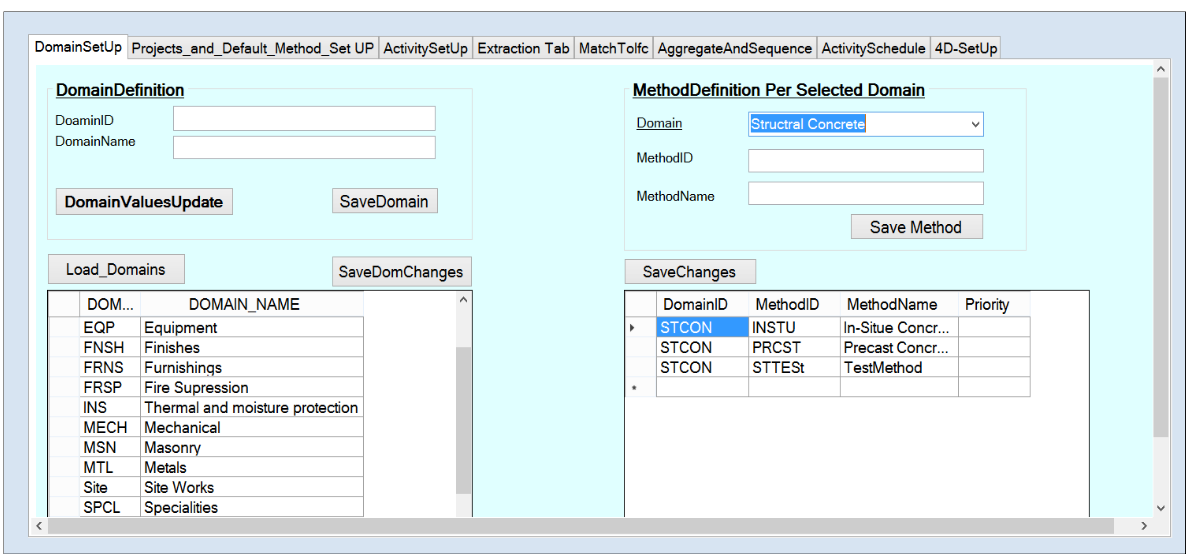


Figure 12- Domain and methods set up in the 4DADS-System

The left section of the form is for defining and editing domains, while the right section of “DomainSetup” form is used to enter methods of construction for each domain selected from the dropdown box at the top right corner, which shows all available domains in the database. For example, the “structural Concrete” in this case is shown to have method IDs that include INSTU and PRCST.

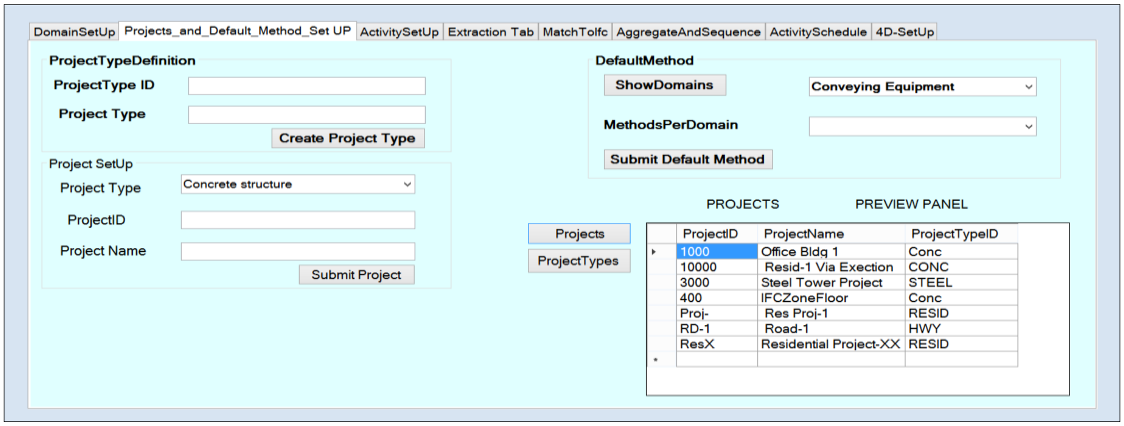


Figure 13- Projects and default methods setup form

Using the form shown in Figure 13, the user can create projects, project types and then assign default methods to each domain of construction based on the type of project specified. Project types are a class of projects that a certain company undertakes and groups them as such based on various factors such as the nature of the work, the clients or business line within the company considered. Once this intra-company classification is made and stored, any upcoming project should fall under any one of these groups. Therefore, when a new project is initiated, the user (such as the project manager or scheduler) assigns the group to which the project belongs. Because of this assignment, the various domains of construction for this particular project inherit the default methods of construction, and hence the predefined activities automatically.

Table 8- Sample mix of project types, their default methods and types of activities

Project Type	Domain	Default Methods	Activities
A	X	1	Activity 1
			Activity 2
			Activity 3
B	X	2	Activity 20
			Activity 30
C	X	1	Activity 1
			Activity 2
			Activity 3

Table 8 shows the possibilities that a single domain of construction can have multiple options of methods, and hence resulting in different sets of activities.

Each domain of construction is associated with one or more methods of construction. These methods might have industry-wide recognized names or they could be simple intra-company conventions, with the main purpose of capturing the process of construction for that segment of work by performing a series of interrelated activities. Figure 14 shows the user-interface of the 4DADS-System through which the end-user enters the series of activities per domain and method of construction.

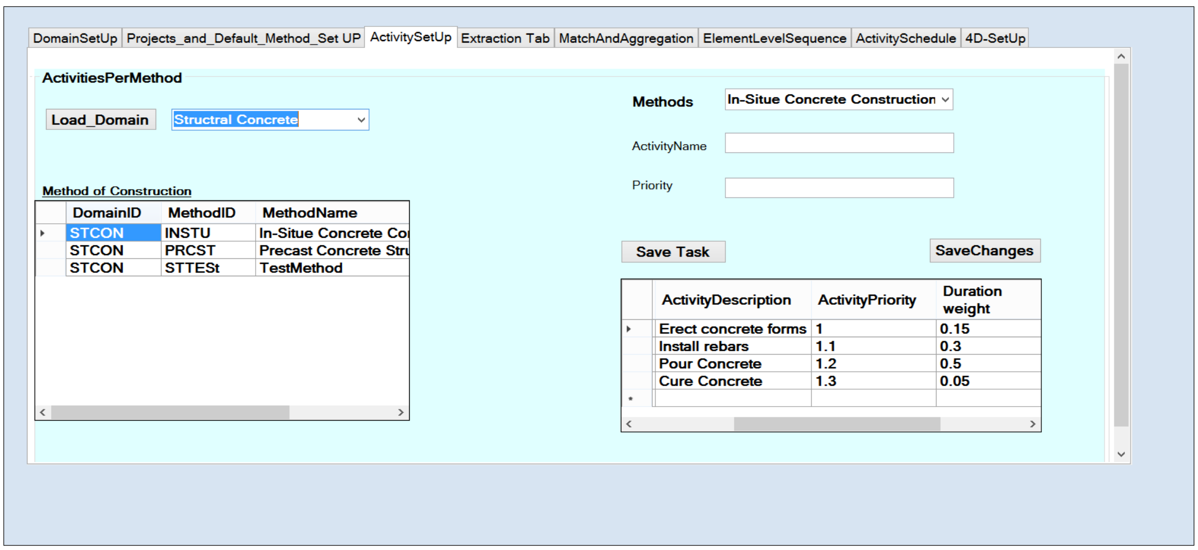
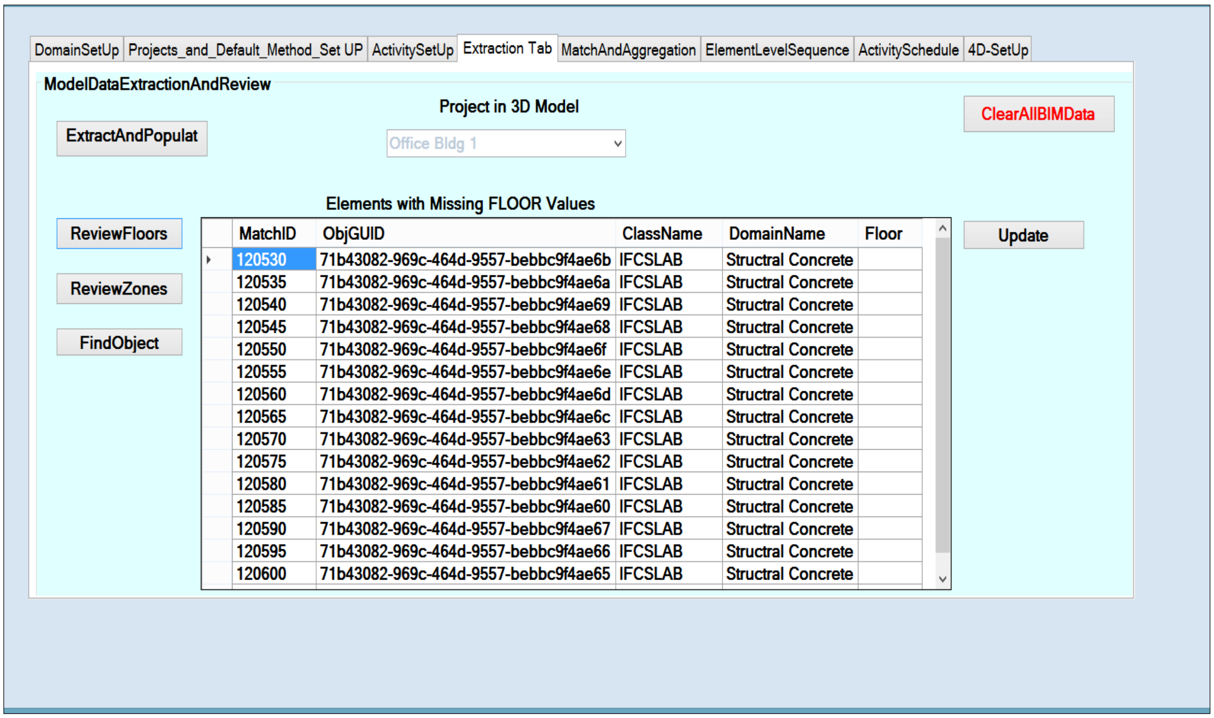


Figure 14-Activity definition and set up form

Using this form, the user is able to navigate through each individual domain by clicking the “Load_Domain” button, which loads the domains to the drop down box at the top left corner and lists all the methods defined for that domain in the table on the left side of the form for an overall view of the methods. At the same time, individual methods and their related activities are shown on the right side of the form. This is where the user pre-defines all the activities that make up each method of construction, as indicated by the “MethodID” column in the table. All information about each activity including its description, relative priority at the method-level and relative duration weight for each activity is entered for the first time or edited using this form. The duration weight is a numerical factor for a quick top-down duration estimation for each activity based on an overall duration estimation by the user at the domain level. Considering the duration weight values shown in the activity table of Figure 14 as example for the in-situe concrete construction method of the structural concrete domain, if user estimates the overall duration for the domain to be 100 days, the durations for the activities listed: erect concrete forms, install re-bars, pour concrete, cure concrete, are calculated as 15, 30, 50 and 5 days respectively.

4.3 User Interaction to Acquire and Manipulate Design Information

One of the fundamental inputs to the scheduling process is the information about the design of the facility and since automating the process of acquiring this essential input is one of the prime objectives of this research, the form in Figure 15 performs one of the critical steps in the operation of the 4DADS-system.



MatchID	ObjGUID	ClassName	DomainName	Floor
120530	71b43082-969c-464d-9557-bebbc9f4ae6b	IFCSLAB	Structral Concrete	
120535	71b43082-969c-464d-9557-bebbc9f4ae6a	IFCSLAB	Structral Concrete	
120540	71b43082-969c-464d-9557-bebbc9f4ae69	IFCSLAB	Structral Concrete	
120545	71b43082-969c-464d-9557-bebbc9f4ae68	IFCSLAB	Structral Concrete	
120550	71b43082-969c-464d-9557-bebbc9f4ae6f	IFCSLAB	Structral Concrete	
120555	71b43082-969c-464d-9557-bebbc9f4ae6e	IFCSLAB	Structral Concrete	
120560	71b43082-969c-464d-9557-bebbc9f4ae6d	IFCSLAB	Structral Concrete	
120565	71b43082-969c-464d-9557-bebbc9f4ae6c	IFCSLAB	Structral Concrete	
120570	71b43082-969c-464d-9557-bebbc9f4ae63	IFCSLAB	Structral Concrete	
120575	71b43082-969c-464d-9557-bebbc9f4ae62	IFCSLAB	Structral Concrete	
120580	71b43082-969c-464d-9557-bebbc9f4ae61	IFCSLAB	Structral Concrete	
120585	71b43082-969c-464d-9557-bebbc9f4ae60	IFCSLAB	Structral Concrete	
120590	71b43082-969c-464d-9557-bebbc9f4ae67	IFCSLAB	Structral Concrete	
120595	71b43082-969c-464d-9557-bebbc9f4ae66	IFCSLAB	Structral Concrete	
120600	71b43082-969c-464d-9557-bebbc9f4ae65	IFCSLAB	Structral Concrete	

Figure 15- Intermediate product data extraction and review form

If there is any old BIM data for the project under consideration in the system, which needs to be cleaned, the user can do so by using the red “ClearAllBIMData” button on the top-right corner of the form. This action deletes any raw product information, the data from the 3D BIM model, which later in the process gets utilized for the expected automation. This cleanup helps to make the database ready to store new BIM data for the “Project in 3D Model” specified at the top center of the form. Entering the project information, including its type and default methods of construction, were discussed and specified under Figure 13.

The next critical step is to extract the necessary BIM data from open 3D model and store it in the databases for later use. The user clicks the “ExtractAndPopulate” button on the top-left corner of the form to perform this step. The system, searches for a 3D model in the current session of the main application and extracts and stores the information about the individual geometric building components such as the names, GUIDs, floors, zones for each component in the model.

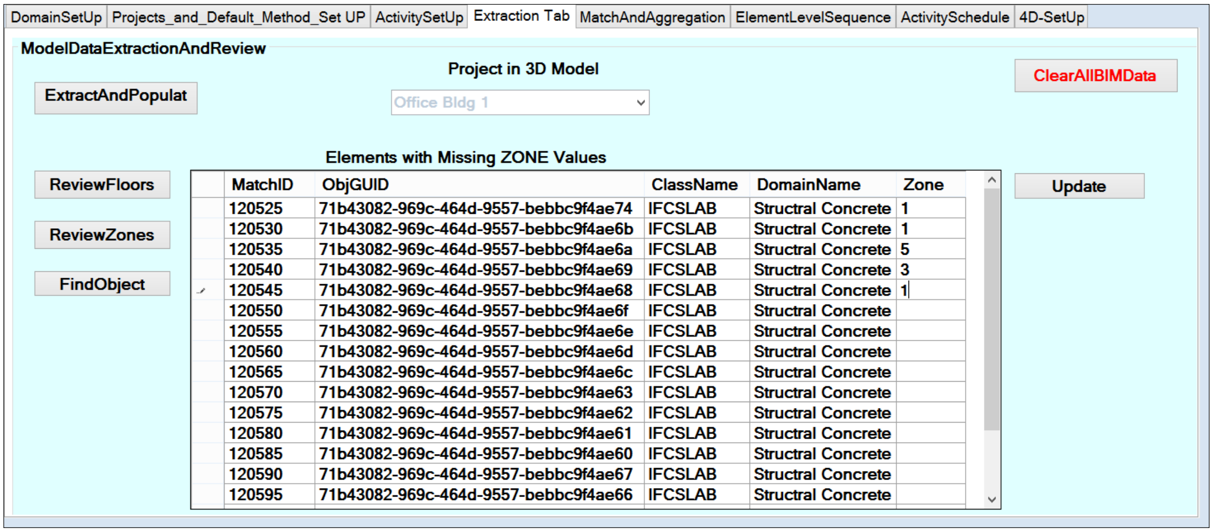


Figure 16- Reviewing extracted BIM data

Before processing the extracted data further and integrating it with the predefined activities, the user needs to verify if the floor and zone values have been assigned to every component in the 3D file as part of the model preparation in the original authoring tool, such as Revit. This step is essential since the floor and zone values are directly applied to calculate the construction sequence of each element. The form in Figure 16 is the same as Figure 15 except that it is used for two different purposes. When the user clicks the button “Review Floors”, it shows data with missing floor values and when the “Review Zones” is clicked, it populates data with missing zone assignment. The user can then search for the component in the 3D model by selecting its GUID value on the form and then clicking the “FindObject” button to find the object and visually determine which zone it belongs to, and enter the value in the blank cells. Updates for both floor and zones are sent to the database by hitting the button “Update”. This functionality is expected to be rarely used, as in the case of forgotten items during the model preparation stage, since it can have a negative impact on the speed of getting to the final outputs.

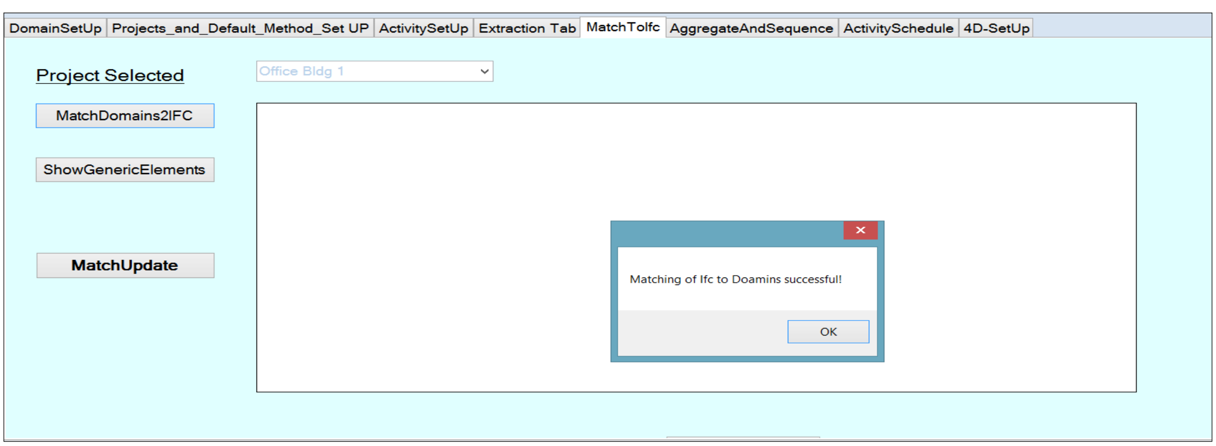


Figure 17- Form to match extracted objects with their respective domains

Once all BIM data is extracted and stored, the user triggers the function of the system that matches each building component into their corresponding domains using the button “MatchDomains2IFC” on the top-left corner. This creates domain based grouping of all the design data, resulting in a matching similar to the output shown in Figure 18. If there are any generic element names in the extracted data, they can be displayed by clicking the button “ShowGenericElements”.

ProjectID	DomainID	ObjGUID	ClassNa...	DomainName
400	DRWD	835c15dd-8c91-49ab-a02e-5f624b6ee4e0	IFCDOOR	Doors and Windows
400	DRWD	835c15dd-8c91-49ab-a02e-5f624b6ee48a	IFCDOOR	Doors and Windows
400	STCON	71b43082-969c-464d-9557-bebbc9f4af94	IFCSLAB	Structral Concrete
400	STCON	71b43082-969c-464d-9557-bebbc9f4af8a	IFCSLAB	Structral Concrete
400	STCON	71b43082-969c-464d-9557-bebbc9f4af88	IFCSLAB	Structral Concrete
400	STCON	71b43082-969c-464d-9557-bebbc9f4af8e	IFCSLAB	Structral Concrete
400	STCON	71b43082-969c-464d-9557-bebbc9f4af8c	IFCSLAB	Structral Concrete
400	STCON	71b43082-969c-464d-9557-bebbc9f4af82	IFCSLAB	Structral Concrete
400	STCON	71b43082-969c-464d-9557-bebbc9f4af80	IFCSLAB	Structral Concrete
400	STCON	71b43082-969c-464d-9557-bebbc9f4af86	IFCSLAB	Structral Concrete
400	STCON	71b43082-969c-464d-9557-bebbc9f4af84	IFCSLAB	Structral Concrete
400	STCON	71b43082-969c-464d-9557-bebbc9f4ae7a	IFCSLAB	Structral Concrete
400	STCON	71b43082-969c-464d-9557-bebbc9f4ae78	IFCSLAB	Structral Concrete
400	STCON	71b43082-969c-464d-9557-bebbc9f4ae7e	IFCSLAB	Structral Concrete
400	STCON	71b43082-969c-464d-9557-bebbc9f4ae7c	IFCSLAB	Structral Concrete
400	STCON	71b43082-969c-464d-9557-bebbc9f4ae72	IFCSLAB	Structral Concrete

Figure 18- Sample output of matching building elements to their domains

If generic elements are found in the extracted project data, the user should open the update-match form shown in Figure 19 using the button “MatchUpdate” and manually match these generic elements to their preferred domains. This is important so that these elements can be part of the remaining processes, which depend on such a match.

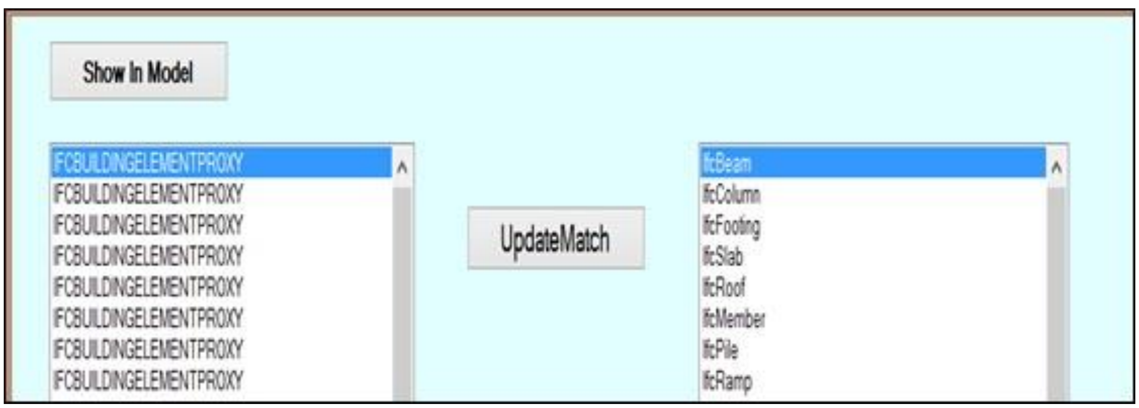


Figure 19-Matching generic elements

With proper preparation of the model and export process, the number of elements that can be exported as generic can be reduced to minimum or none at all.

The “AggregateElements” button on the top left corner of “AggregateAndSequence” form shown in Figure 20 creates groups of objects based on their domain, floor, and zone. This represents an important step in the whole process, the work packages in a schedule refer to a certain grouping in the building based on similarities. An example of such a grouping is the construction of columns in a certain zone of floor 1.

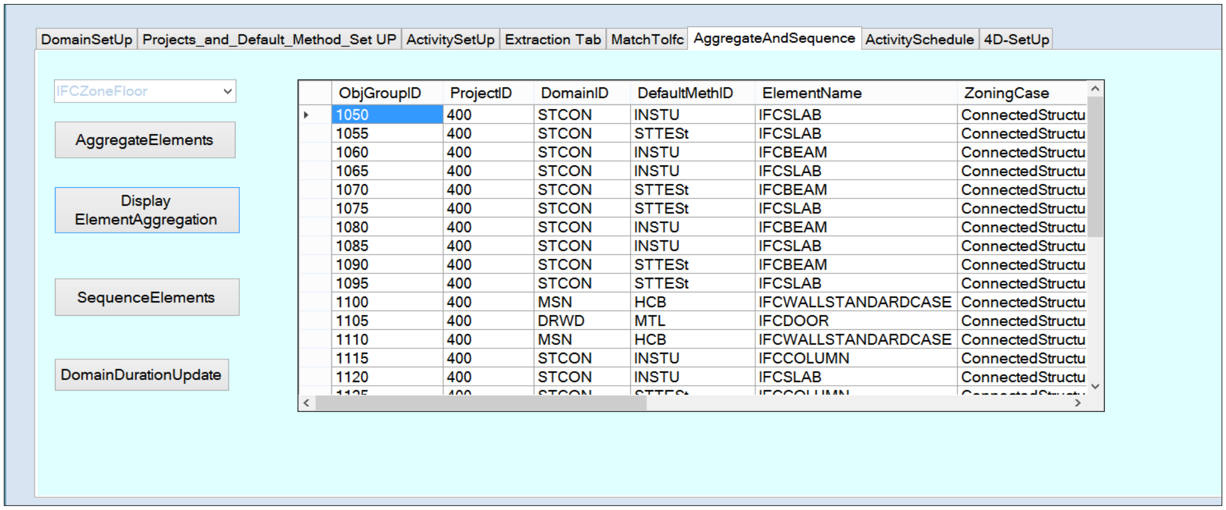


Figure 20- User interface for aggregating and sequencing components

The “SequenceElements” button triggers all the rules applied to sequence the components based on their location in floors and zones, the domain and component priorities they are assigned to, as described in chapter 3.

The “DomainValuesUpdate” button launches the user interface used to manipulate domain level durations, as shown in Figure 21. These “RoughDomainDuration” values are preliminary duration estimates for a quick generation of the schedule. The first button displays current values while the second saves changes made by the user. It is to be noted that the 4DADS-system extracts quantities of material directly from the model. For the activity duration values to be calculated automatically, company and project specific production and productivity information would have to be stored in the database and integrated with the extracted quantities.

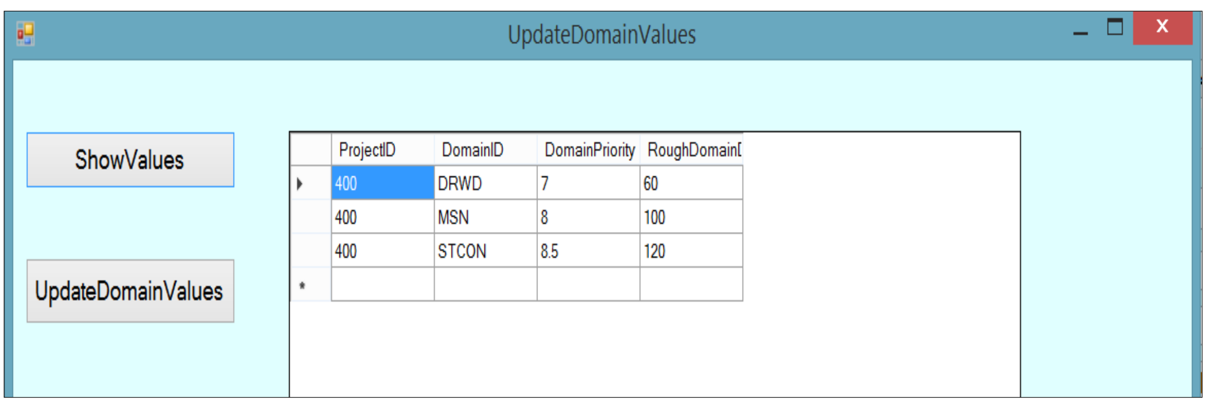


Figure 21- Form for updating domain values

All the effects of the previous processes have to be combined into a single draft schedule at the activity level. Therefore, the form in Figure 22 enables the user to select the project’s start date, which also serves as the start date of the first activity identified

by the algorithm, while the finish date is computed by adding the estimated duration to the start date.

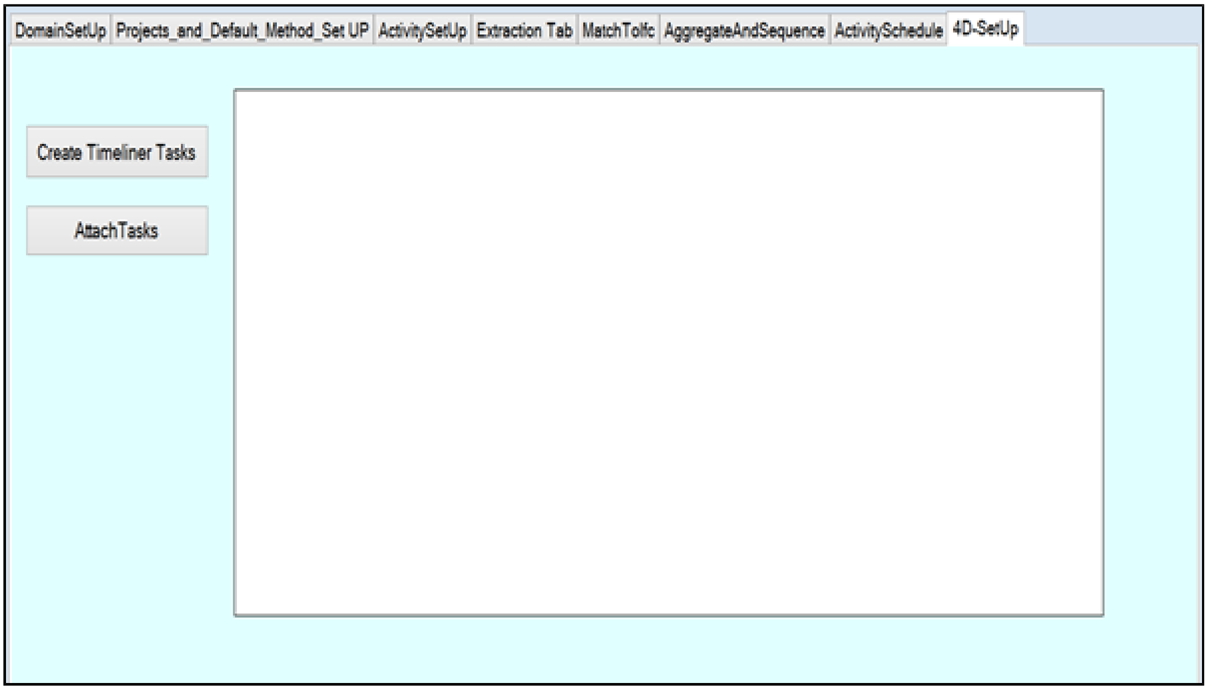


Figure 22- Form to create timelier activities and link them 3D objects

Since only finish-to-start activity relationships are considered in the sequencing scope of this research, the same calculation holds for all activities based on the computed priority values and predecessor and successor values.

Once the draft schedule is generated, it is submitted to the timeliner module of the main application, Navisworks. The form on Figure 22 is used for this purpose. Once the "Create Timeliner Tasks" button is clicked, it submits the generated schedule to the timeliner and the schedule becomes part of the current project in the main application. The second button runs the rule to attach the tasks their corresponding 3D objects. More detail on this is provided in chapter 5.

As pointed out in Section 4.1, the 4DADS-System integrates various tools including SQL Server database systems, to define and store some of the logic and data within. Figure 23 & Figure 24 illustrates overviews of the SQL store procedures and data tables built to implement that.

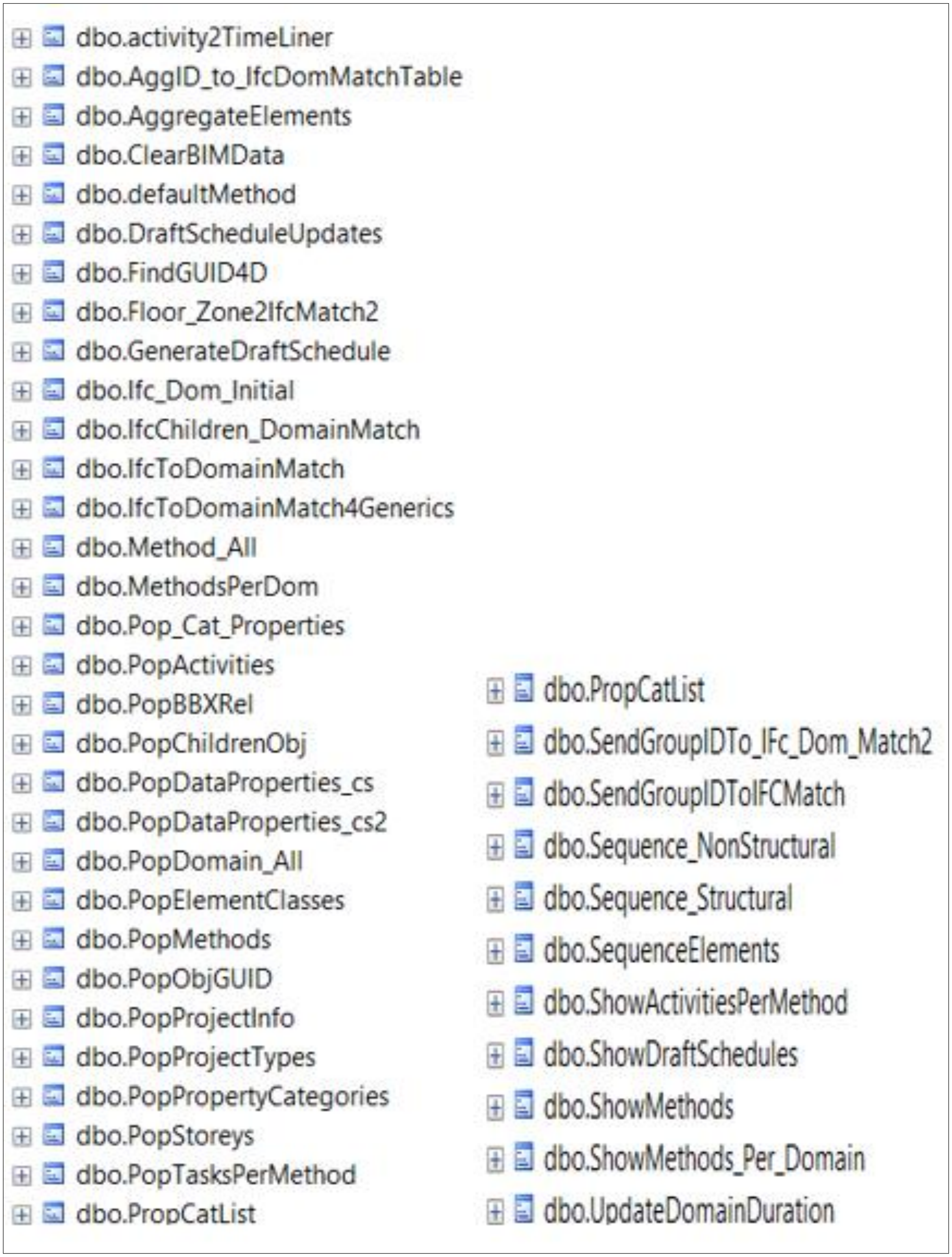


Figure 23-Some of the SQL stored procedures used in the 4DADS-System

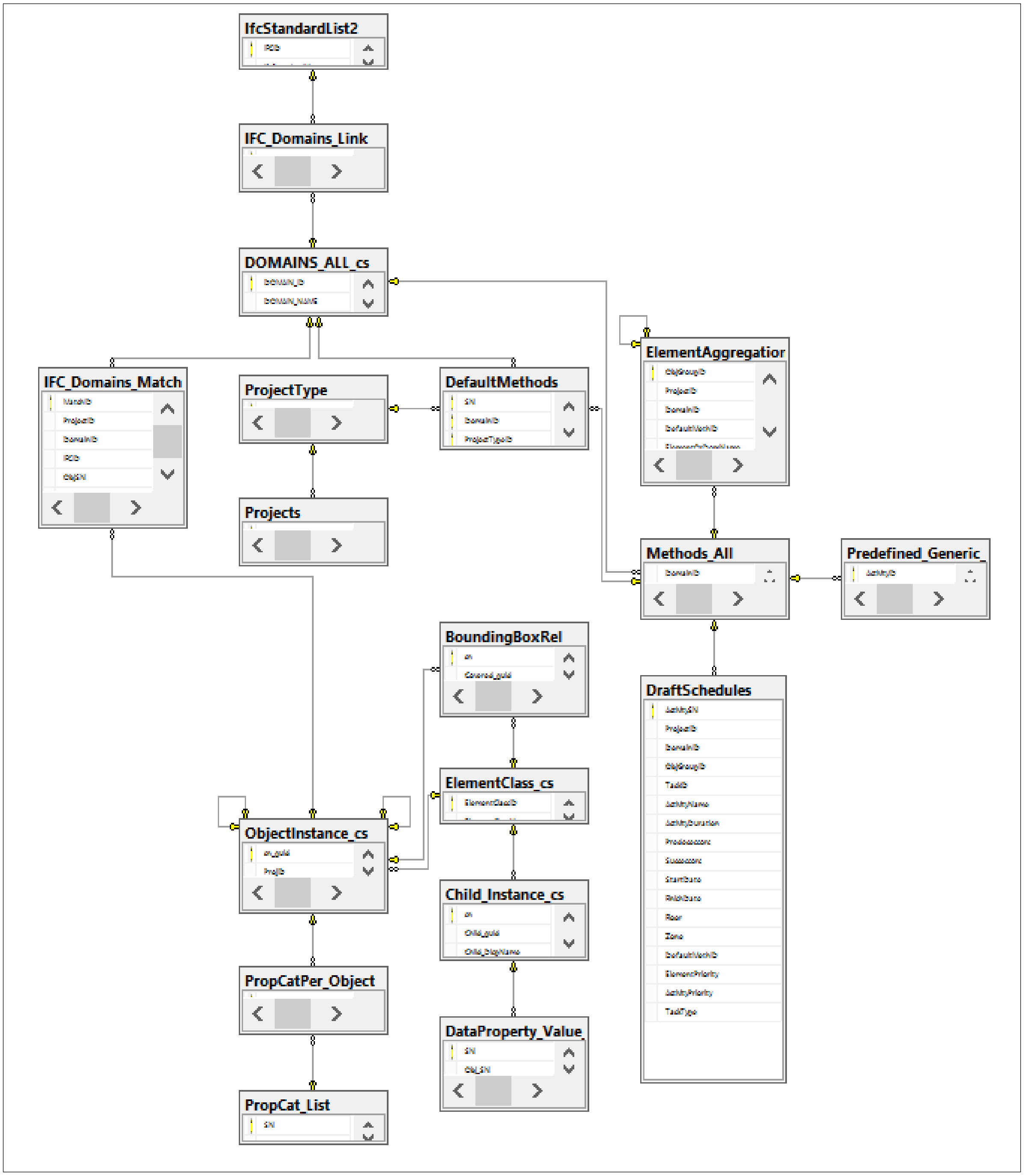


Figure 24- Overview of data tables used in the implementation

In summary, this chapter discusses the basic architecture and user interfaces (UI) developed in the 4DADS-System. Even though, the purpose of the system is to, at least partially, automate the process of scheduling and 4D linking, there is still some basic interaction and information expected from the end user before the system can deliver on its objectives. The UIs are developed to serve that purpose, as discussed in this chapter.

CHAPTER 5- EVALUATING SYSTEM PERFORMANCE

Details of the methodology applied in this research and the computer system developed to substantiate its practicality have been charted out in the previous two units. This chapter discusses the results achieved with the outlined method and the subsequent computer implementation, vis-à-vis the main objectives of the research. To assess the effectiveness and completeness of the various features of the developed system, it was repeatedly tested with various 3D models. To discuss and document the process, results and performance of such tests, two test cases are presented in the following sections. For the first test, the structural 3D model shown in Figure 25, provided by Autodesk as a sample BIM model and publicly available online (Autodesk, 2015a) was utilized. The second case study project is a small architectural model shown in Figure 26, which is also made publicly available by Autodesk.

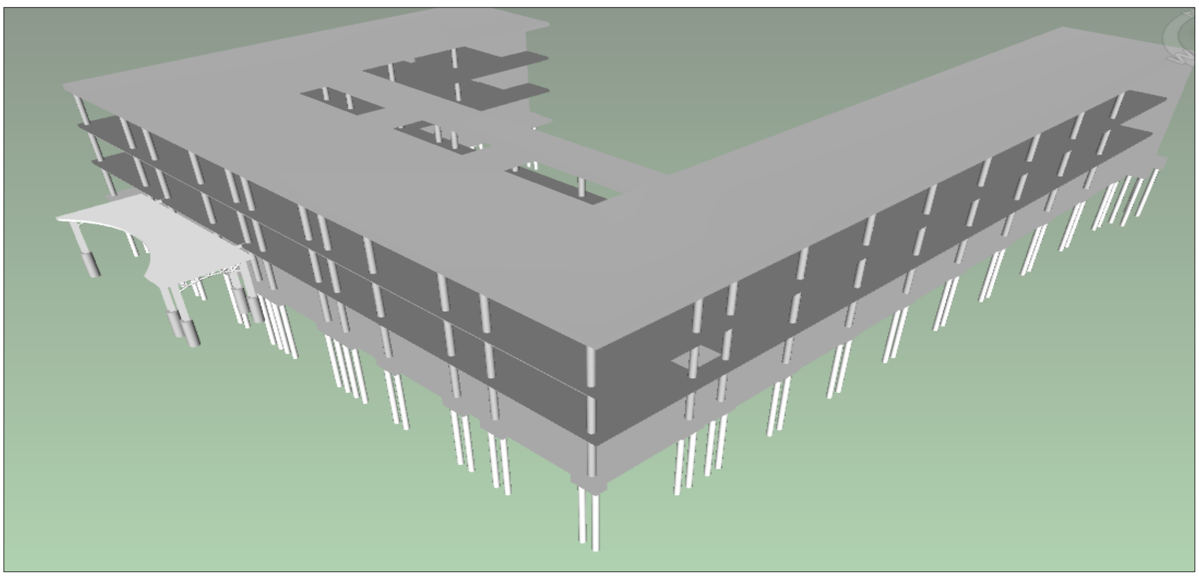


Figure 25- Case Study 1: structural model used to test the 4DADS-system

After assigning floor and zone names or values to the model in Revit, which was performed within 20-25 minutes, it was exported to IFC data format, with a modified export template that ascertains as much specificity as possible in the exported elements. Exporting the model with proper preparation is a required step, since IFC is the standard data format the 4DADS-System can utilize. The term specificity here indicates export to the unique IFC names such as IfcColumn and IfcSlab whenever possible, instead of generic names like IfcBuildingElementProxy, which does not name a single element.

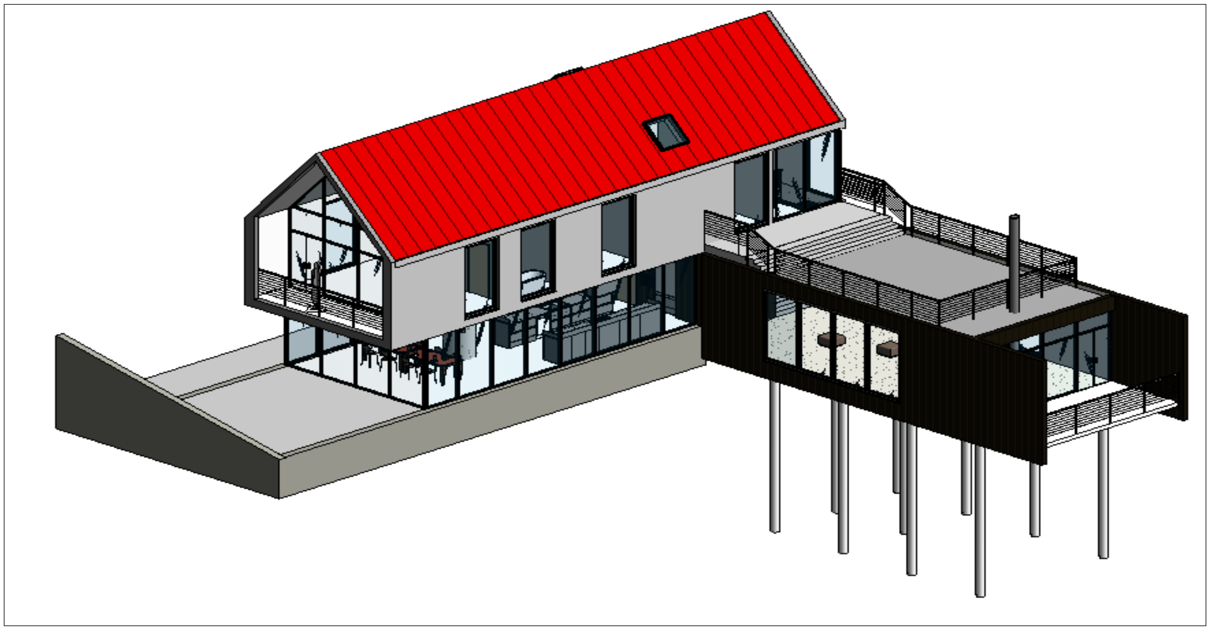


Figure 26-Case study 2: architectural model used to test the 4DADS-system

Figure 27-Floor plan of case study 2

The necessary attributes of the building components in these modes were then extracted, stored , restructured and matched with their respective construction domains, methods and, hence, individual activities. By applying the sequencing rules defined, order of construction between components, followed by the sequence of activities was generated.

5.1 Evaluating the Generic Activity and Intermediate Product Models

With reference to the first objective of this research, which focuses on defining a general activity model for high-rise commercial buildings, the system performs as outlined, albeit with some imperfections. This model stores the general domains of work, defines methods and enables assigning default methods of construction. Since each method of construction corresponds to a specific set of activities, the default methods generate the activities that sufficiently describe the scope of work as well as the preferred level of detail in the schedule. Once this is completed for different categories of projects, the system could read various models and generate the required activities per the scope of work in the model and the level of detail predefined in the general activity model. In the case studies presented, the default method for concrete, for instance, was considered "Cast In-Situ Concrete Construction," with the list of activities shown in Figure 28.

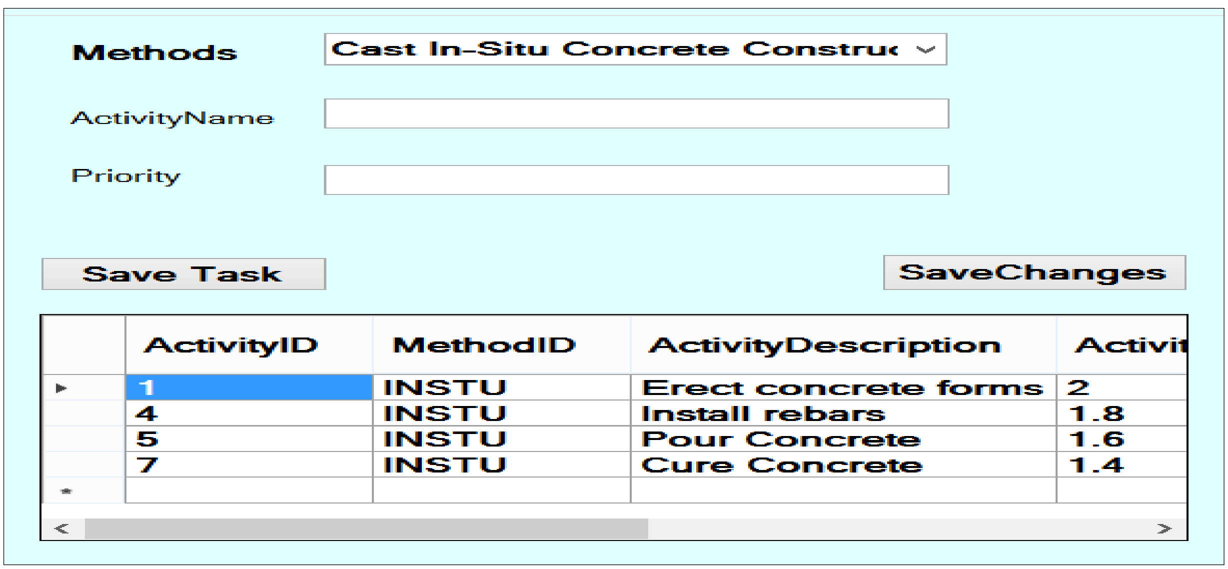


Figure 28-List of activities defined for a method

The system generated the same set of activities for all concrete works in the building as it found them in various floor and zones of the model. In other words, concrete work in the foundations of zone 1, acquires these same set of activities as slab concrete in the fourth floor, zone 1 with the exception that the respective activities were modified to indicate the location of work (floor and zone) as well as the type of component the activities are acting upon. Therefore, the activity for the first group would be "F1.Z1. Foundation-pour concrete," while for the second item it would be "F4.Z1. Slab-pour concrete."

Despite the overall success of the generic activity model, there are still some areas that can be considered for future improvements. One such area is the categories considered as the domains of work. These categories are adapted from MasterFormat, whose purpose does not necessarily align with the scheduling rules implemented here. Because of this, some of the divisions did not include all the items needed for that domain of work. For example, “roof” is in *Thermal and Moisture Protection* division in the master format division. However, roof as a load-bearing element is also part of the structural work. Therefore, in line with the sequencing rules in the 4DADS-System, it is placed under structures and is modeled as such. Because of this, the domains list utilized in this implementation is not considered an industry standard list. Lack of such a standardization could create communication barrier among professionals. Similarly, the methods of construction considered under each domain and explicitly applied, as a link between the domains and the detail activities, is generally an implied concept in the industry practice. Because of that, there are no industry standards to name and categorize them as such. So again, lack of standard description of this concept in the industry means that the method names used in this implementation are non-standard serving only as a bridge between the package of work to be performed and the predefined activities needed to accomplish it.

With reference to the second objective of this research, the development of an intermediate product model, which can be used for seamless and explicit integration of the generic activity model with the design information, the system performs as stipulated in chapter 1, with the exception of some generic elements that could not be readily assigned to a specific domain of work.

The intermediate product model extracts and stores individual 3D elements names and their unique IDs. It also extracts parent-child relationships, bounding box information wherever available, and location information in terms of floor and zone values, material and basic material quantities. This information is then combined with the generic and predefined activity data in order to generate the activities specific to the project at hand and their sequence.

Figure 29 summarizes the overall workflow of the system and the top right portion of this diagram encapsulates the intermediate product model.

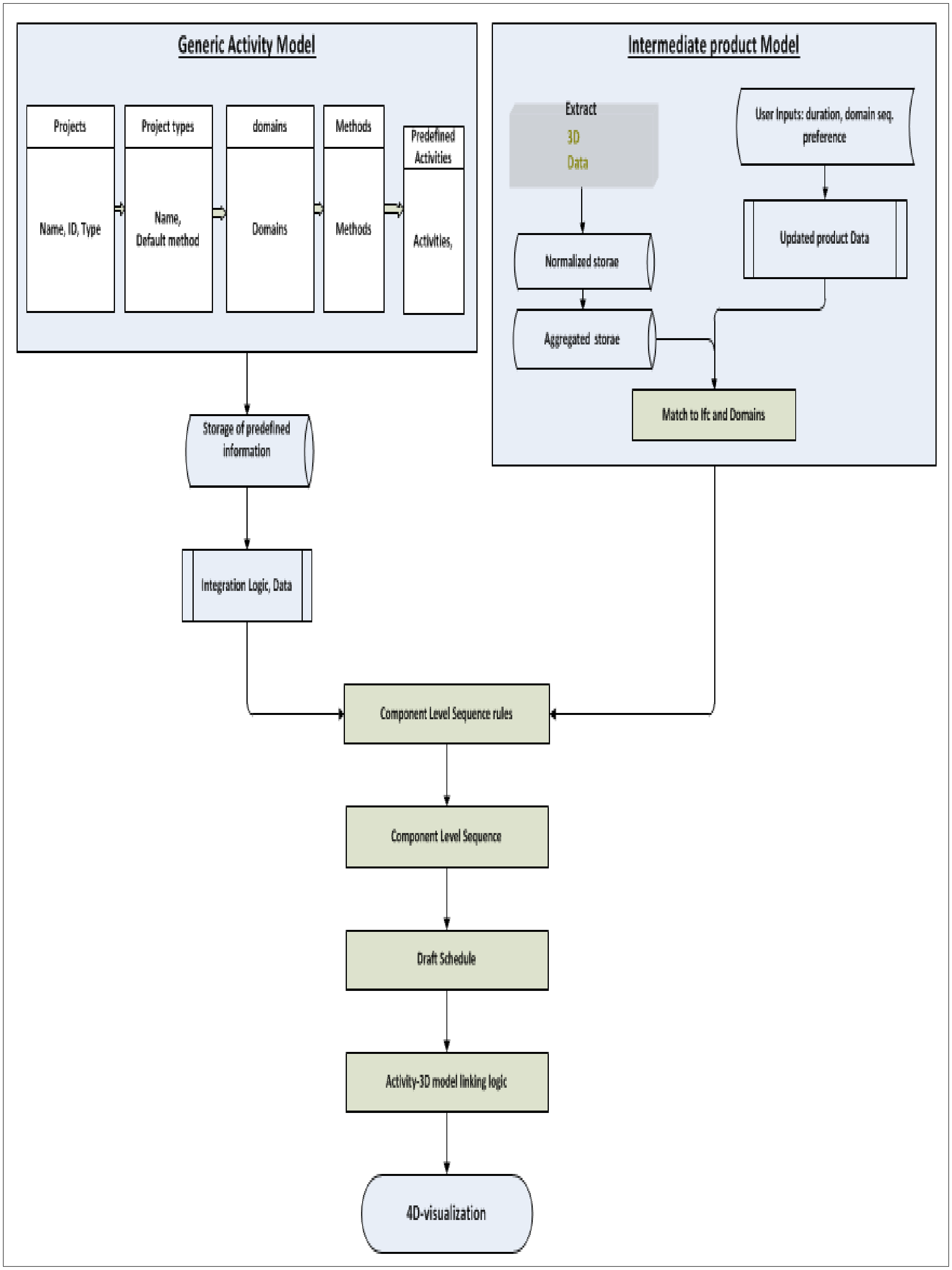


Figure 29- System workflow and components

Dom	objGUID	ClassName	DomainName
	4d910c58-706e-42b...	IFCBUILDINGELEMENTPROXY	
	89b7d9e7-00a9-45d...	IFCBUILDINGELEMENTPROXY	
	89b7d9e7-00a9-45d...	IFCBUILDINGELEMENTPROXY	
	89b7d9e7-00a9-45d...	IFCBUILDINGELEMENTPROXY	
	89b7d9e7-00a9-45d...	IFCBUILDINGELEMENTPROXY	
	89b7d9e7-00a9-45d...	IFCBUILDINGELEMENTPROXY	
	89b7d9e7-00a9-45d...	IFCBUILDINGELEMENTPROXY	

Figure 30-Sample of not matched generic elements

One of the areas of improvement in the intermediate product model is the generic IFC element names extracted from the 3D model, such as IfcBuildingElementProxy and IfcMember, which cannot be automatically placed in a specific domain within the predefined list. Figure 31 shows examples of such generic elements, IfcMember which refers to any cylindrical members such as studs within a wall.

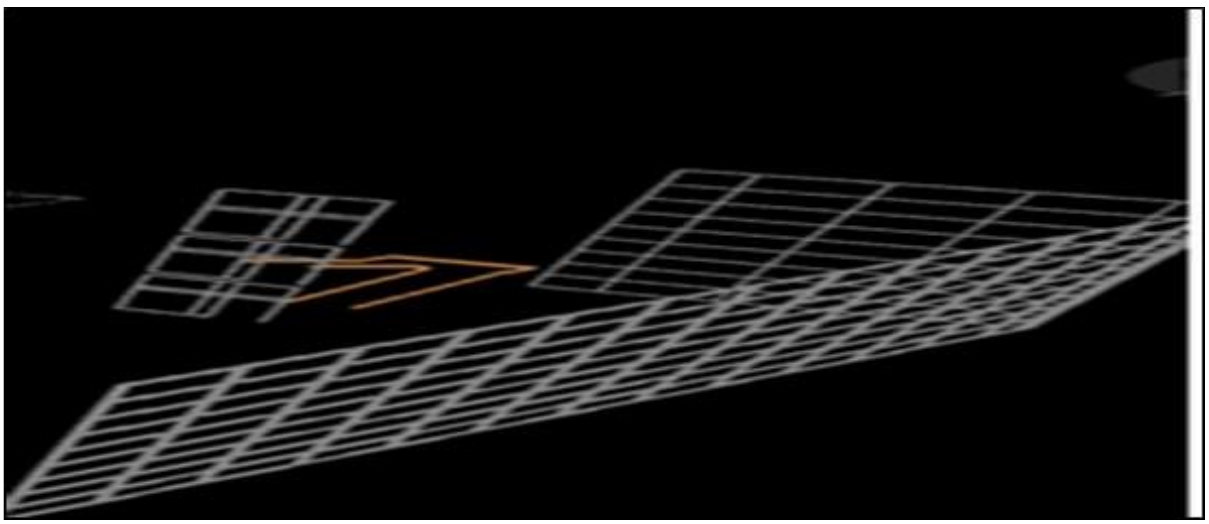


Figure 31-Sample generic element within a 3D model

In such cases where association can be made between the generic element and a standard parent element, in this case, IfcWall, the generic element is recognized as part of the parent and its associated domain. However, such inference is not always possible as many parent elements with generic names are also extracted, thereby making the labelling of the children by association impossible. In such a scenario, the user is presented with the list of the generic elements to make the necessary association manually. Therefore, the intermediate product model successfully extracts, stores and manipulates the 3D information as needed for the ultimate outputs of the system: automated draft schedule generation and 4D visualization.

To document ballpark estimates on the speed at which the 4DADS-system executes the data extraction process from the 3D model, time of extraction has been recorded as shown in Figure 32. Here, the line chart and the values on right

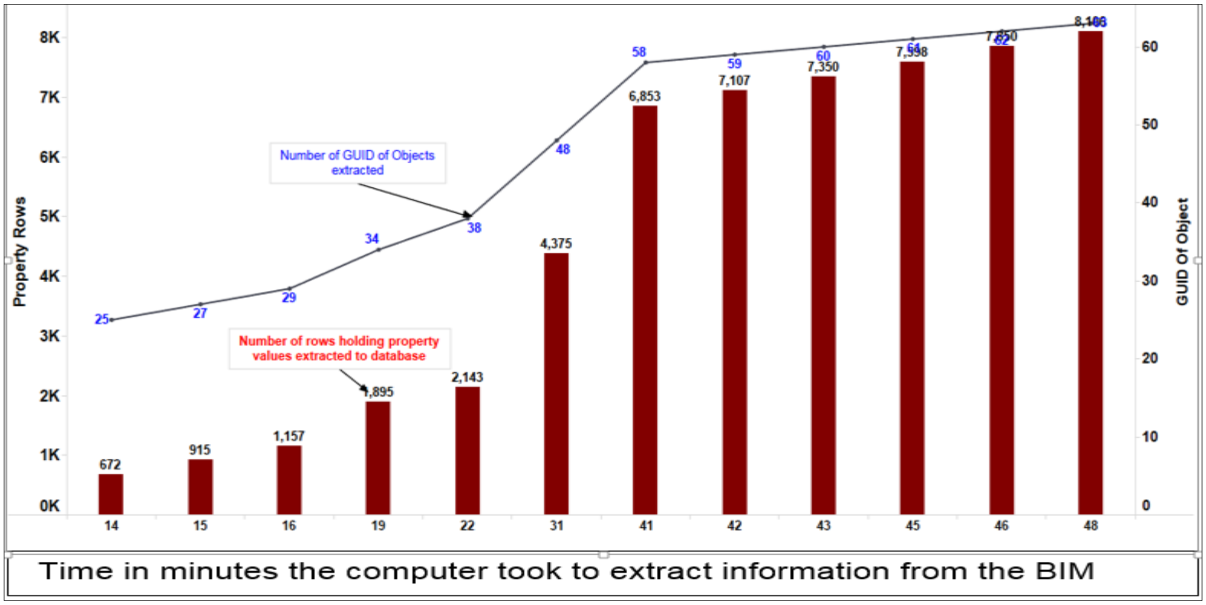


Figure 32-Time in minutes vs 3D model data extraction into database

axis show the number of individual object GUIDs extracted, as the 3D objects and the GUID values stored in the database are one-to-one. Each 3D object has many properties extracted and stored. Hence, the bar chart and the values on the left axis display the number of data properties extracted and stored as a function of time shown in the horizontal axis in minutes. Accordingly, in 31 minutes, 4375 property values were extracted and stored.

Although the focus of the methodology and the system developed in this study is to automate the process of scheduling and 4D, the computational speed in which this can be accomplished can also contribute to its ovearll efficiency. In other words, even if no human intervention is needed, if the computer takes a significantly long time to execute the algorith developed and coded, it can negatively affect the usefulness of the automation sought. However, this factor is mainly dependent upon the processing power of the individual computer hardware utilized, rather than the novelty of the developed methodology. Therefore, this factor is considered useful but not significant for this research as it depends more on the computer architecture and its in-built technologies rather than on the achieved improvement in the scheduling and 4D processes.

5.2 Automated Draft Schedule and 4D Outputs of the 4DADS-System

The ultimate and most important objectives of this research are to semi-automatically generate initial construction activities and their sequences by assimilating information from the general activity model and the specific BIM model of the project under consideration, and then automate the process of visualizing this sequence in 4D. As shown in Table 9, the system generated such a draft schedule with activity names, predecessors, successors, duration, start and finish dates.

The draft schedule begins with a project-start milestone activity whose start date is the start date of the whole project, and ends with a project-finish milestone, which is also the finish date of the last activity in the overall sequence of activities generated.

Table 9-Partial view of the automatically generated draft schedule for case study 1

GroupID	TaskID	ActivityName	Dur.	Pred.	Succ.	Start	Finish
1	MLST-START	Project Start Milestone	0		13360-1	2/7/2012	2/7/2012
13360	13360-1	F1.Z1-FOOTING-Erect concrete forms	1	MLST-START	13360-2	2/8/2012	2/9/2012
13395	13395-2	F1.Z3-FOOTING-Install rebars	6	13395-1	13395-3	4/7/2012	4/13/2012
13395	13395-3	F1.Z3-FOOTING-Pour Concrete	10	13395-2	13395-4	4/14/2012	4/24/2012
13395	13395-4	F1.Z3-FOOTING-Cure Concrete	1	13395-3	13385-1	4/25/2012	4/26/2012
13385	13385-1	Erect concrete forms	5	13395-4	13385-2	4/27/2012	5/2/2012
13385	13385-2	F1.Z2-COLUMN-Install rebars	9	13385-1	13385-3	5/3/2012	5/12/2012
13385	13385-3	F1.Z2-COLUMN-Pour Concrete	15	13385-2	13385-4	5/13/2012	5/28/2012
13385	13385-4	F1.Z2-COLUMN-Cure Concrete	2	13385-3	13380-1	5/29/2012	5/31/2012
13490	13490-2	F4.Z1-Masonry-Build HCB wall	18	13490-1	13490-3	8/29/2014	9/16/2014
13520	13520-1	F4.Z3-Masonry-Produce Blocks	12	13490-3	13520-2	9/21/2014	10/3/2014
13520	13520-2	F4.Z3-Masonry-Build HCB wall	18	13520-1	13520-3	10/4/2014	10/22/2014
13520	13520-3	F4.Z3-Masonry-cure HCB wall	3	13520-2	MLST-Finish	10/23/2014	10/26/2014
2	MLST-Finish	Project Finish Milestone	0	13520-3		10/27/2014	10/27/2014

The activity names describe not only the action executed to accomplish the work, but also the component that particular activity acts upon. The successors and predecessors indicate sequence at the activity level, which was obtained from the component level sequence. The component level sequence would show columns in floor 1 precede, beam installation on the same floor, following the definitions in chapter 3. The activity-level sequence, on the other hand, would indicate that erecting forms for columns in floor 1 precedes installing reinforcement bars (or re-bars) for the same work. In the generated draft schedule, the latter type of relationship is generated as indicated by the task IDs of predecessor and successor activities.

For ease of reading and quick identification by the user, taskIDs are also generated in such a way that they give a basic highlight of the activity they represent, such as the location of the work, domain and basic sequence hint as indicated by the ordinal numbers. For simplicity, only the ordinal numbers of the taskIDs are displayed in Table 9, rather than the actual long description. For instance, taskID 13360-1 has an actual value of F1.Z1-Footing-13360-1, indicating it refers to a group of columns in zone 1 of the first floor.

The durations of individual activities were calculated based on top-down duration estimate approach where duration for work packages at zone level was provided by the user and distributed to individual activities based on weights assigned to the predefined activities. For example, cast-in- place concrete work may have activities such as erect concrete forms, install re-bars, pour concrete and cure concrete. In addition, the duration weights of each of these atomic activities could be distributed as 15%, 30%, 50% & 5% respectively. Therefore, if some concrete work package is roughly estimated to take 100 days, each of these individual activities takes 15, 30, 50, & 5 days respectively, and hence their durations.

One of the most significant downsides of adopting 4D as a means of visualization, verification and communication of construction schedules is the tedious process of linking the activities to their corresponding 3D objects in the model. As outlined in Chapter 2, the integrated schedule generation and visualization model developed in this study identifies addressing this issue as one of its major targets. The basic approach set out to implement the 4D generation is by using the GUID values inherently available and hence extracted from the BIM models. The column “GroupID” forms a crucial bridge between the original 3D model and generated draft schedule. This column refers to a group of elements in the 3D model that are considered as a single work package, and hence acted upon by one set of activities. One example of such grouping could be groups of beams in a similar zone, as shown in Table 10.

Table 10-Sample group IDs used for automating the 4D linking process

GUIDs	ClassName	Floor	Zone	GroupID
60d7d430-05c3-42a3-9105-2fe62068321c	IFCBEAM	2	2	13420
60d7d430-05c3-42a3-9105-2fe62068321e	IFCBEAM	2	1	13405
60d7d430-05c3-42a3-9105-2fe620683218	IFCBEAM	2	1	13405
60d7d430-05c3-42a3-9105-2fe62068321a	IFCBEAM	2	3	13435
60d7d430-05c3-42a3-9105-2fe620683223	IFCBEAM	2	3	13435

Here, in accordance with the methodology discussed in chapter 3, it can be seen that beam objects with GroupID of "13405" refer to those in zone 1 of floor 2. Thus, they belong to the same work package, and hence the same set of concrete activities. As a result, the same groupID represents all their activities in the generated draft schedule. The system uses this ID in the draft schedule to refer back to the intermediate product model to find the native GUID values extracted from the 3D mode. Once the GUIDs are found, they are used to locate the 3D components in the main model. Once found, these 3D components are attached to the activities with groupID that initiated the search. The "TaskType" column is used to identify the activities that actually install physical components visible in the 3D model and those are the only activities, which the 3D models are linked to, from the set of activities for that work package. Figure 33 summarizes this process diagrammatically.

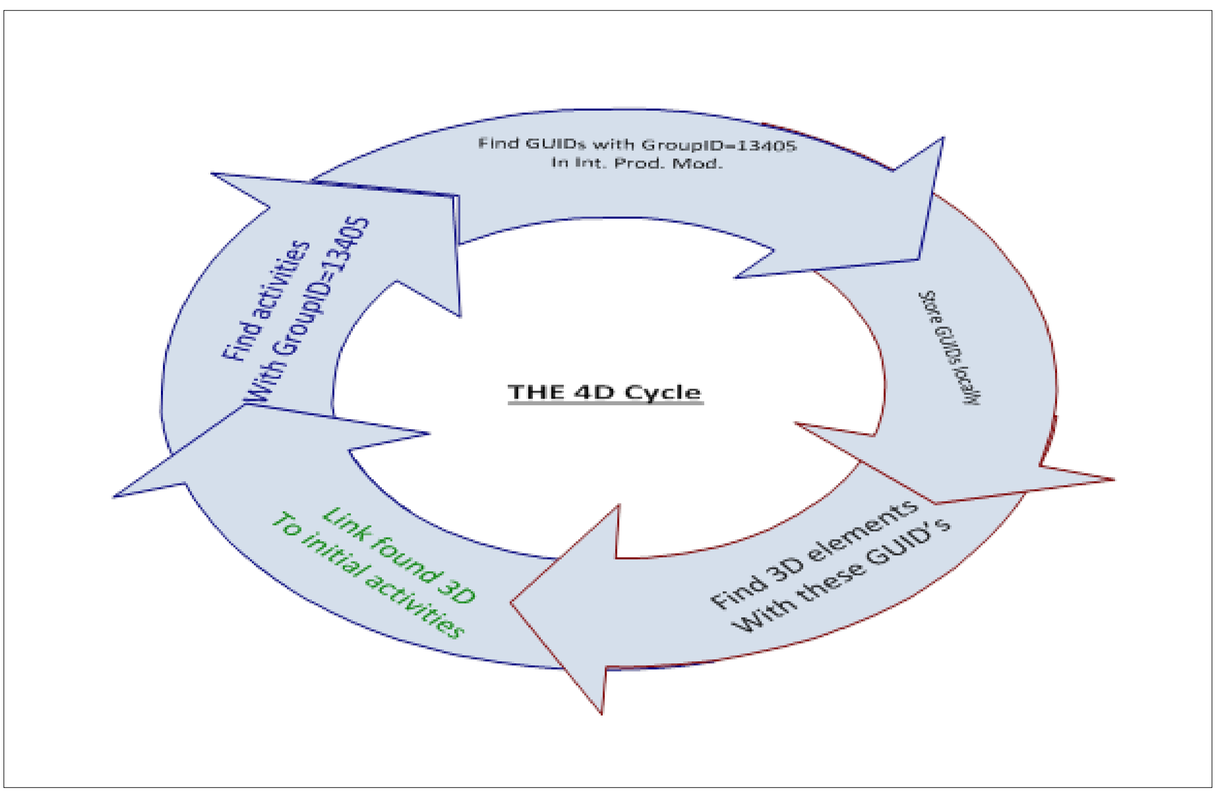


Figure 33-The process of linking the activities to the 3D elements

The 4D linking is performed from the timeliner of the main application. Therefore, the generated draft schedule has to be written onto its timeliner before the linking process can begin. The other advantage of utilizing the main application is that it helps access the in-built simulation engine for the 4D visualization. Figure 37 displays the schedule automatically generated by the system and posted onto the timeliner.

The “Attached” column indicates that some of the activities such as “column-pour concrete” which perform actual installation of permanent parts of the building work are attached to the 3D model. This was again achieved automatically. Depending on the processing power of the computer running the system, the process to generate the schedule and the 4D takes only a few minutes, even though there could be some generic elements in the model that need manual labeling, and hence, causing some delay in the automation process.

After the system automatically linked the schedule to the 3D model, the visualization played shows the sequence of work progressing as expected.

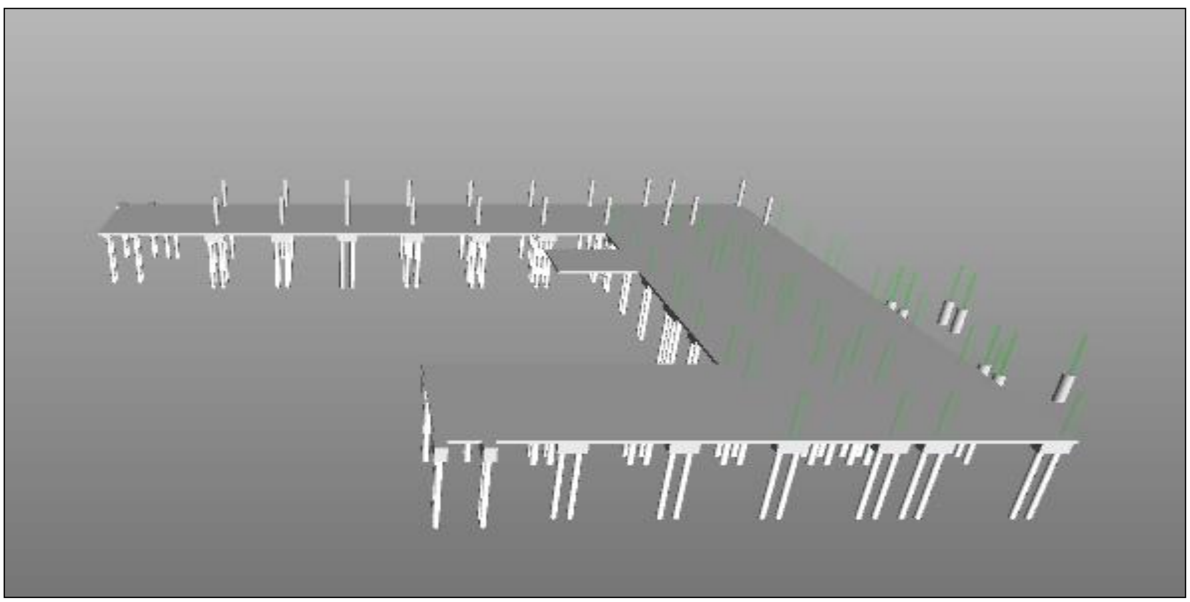


Figure 34-Snapshot of the 4D visualization in case study 1- Floor 2 Zone 2 Columns in progress

As shown in Figure 34 through Figure 36, the building process is proceeding from one zone to the next horizontally and then between floors vertically.

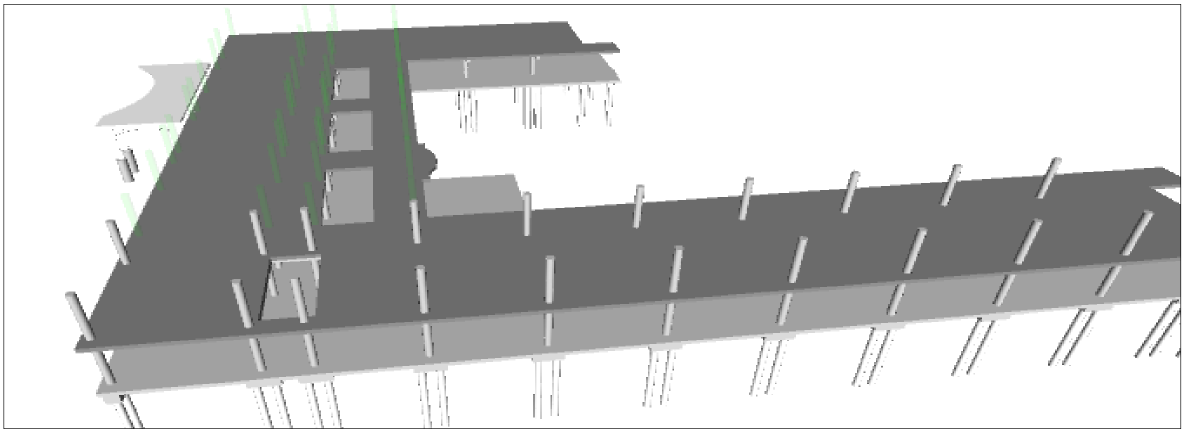


Figure 35-Snapshot of the 4D visualization in case study 1- Floor 3 Zone 2 Columns in progress

According to the stage of progress displayed by the snapshot in Figure 35, Zone 1 columns of floor 3 have been fully installed while zone 2 columns are in progress as indicated by the translucent green colors. The color scheme shown is according to the preference defined in the main applications simulation set up. The far end of the model is zone 3 and the erection of its columns is yet to begin as it can be inferred from the hidden elements in the snapshot.

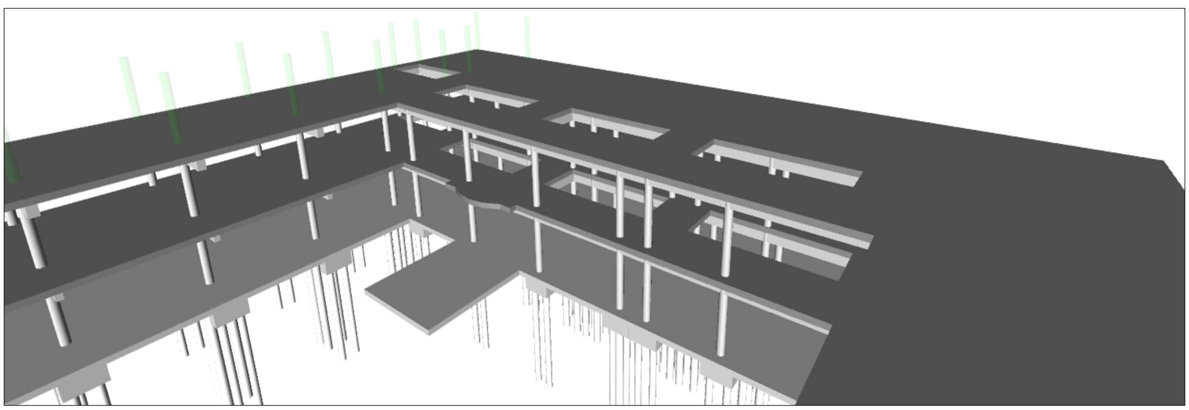
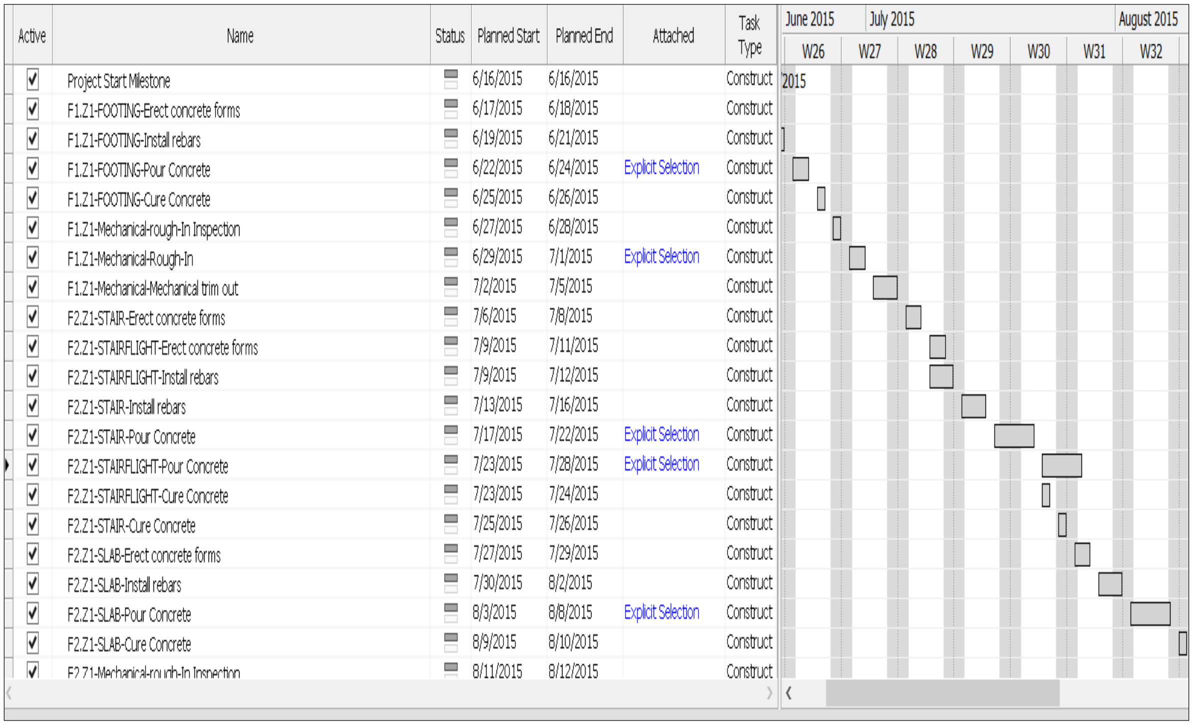


Figure 36- Snapshot of the 4D visualization in case study 1- Floor 4 Zone 1 Columns in progress

Similarly, Figure 36 displays the simulation when the first work-package in the fourth floor, namely the columns in zone 1, are in progress while the rest of work items on that floor have not started yet.

A second case study, the architectural model, demonstrated that the developed scheduling and 4D system performs as described in the methodology section. The schedule snapshot in Figure 37 was captured after it was generated by the system and posted into the timeliner of the main application. The Gantt chart clearly shows the sequence of individual activities graphically, which is a very helpful aid in general scheduling practice.



Active	Name	Status	Planned Start	Planned End	Attached	Task Type
✓	Project Start Milestone		6/16/2015	6/16/2015		Construct
✓	F1.Z1-FOOTING-Erect concrete forms		6/17/2015	6/18/2015		Construct
✓	F1.Z1-FOOTING-Install rebars		6/19/2015	6/21/2015		Construct
✓	F1.Z1-FOOTING-Pour Concrete		6/22/2015	6/24/2015	Explicit Selection	Construct
✓	F1.Z1-FOOTING-Cure Concrete		6/25/2015	6/26/2015		Construct
✓	F1.Z1-Mechanical-rough-In Inspection		6/27/2015	6/28/2015		Construct
✓	F1.Z1-Mechanical-Rough-In		6/29/2015	7/1/2015	Explicit Selection	Construct
✓	F1.Z1-Mechanical-Mechanical trim out		7/2/2015	7/5/2015		Construct
✓	F2.Z1-STAIR-Erect concrete forms		7/6/2015	7/8/2015		Construct
✓	F2.Z1-STAIRFLIGHT-Erect concrete forms		7/9/2015	7/11/2015		Construct
✓	F2.Z1-STAIRFLIGHT-Install rebars		7/9/2015	7/12/2015		Construct
✓	F2.Z1-STAIR-Install rebars		7/13/2015	7/16/2015		Construct
✓	F2.Z1-STAIR-Pour Concrete		7/17/2015	7/22/2015	Explicit Selection	Construct
✓	F2.Z1-STAIRFLIGHT-Pour Concrete		7/23/2015	7/28/2015	Explicit Selection	Construct
✓	F2.Z1-STAIRFLIGHT-Cure Concrete		7/23/2015	7/24/2015		Construct
✓	F2.Z1-STAIR-Cure Concrete		7/25/2015	7/26/2015		Construct
✓	F2.Z1-SLAB-Erect concrete forms		7/27/2015	7/29/2015		Construct
✓	F2.Z1-SLAB-Install rebars		7/30/2015	8/2/2015		Construct
✓	F2.Z1-SLAB-Pour Concrete		8/3/2015	8/8/2015	Explicit Selection	Construct
✓	F2.Z1-SLAB-Cure Concrete		8/9/2015	8/10/2015		Construct
✓	F2.Z1-Mechanical-rough-In Inspection		8/11/2015	8/12/2015		Construct

Figure 37-Generated schedule-Case study 2

The 4D visualization snapshots in Figure 38 through Figure 40 demonstrate a logical progress in the generated schedule for this model.

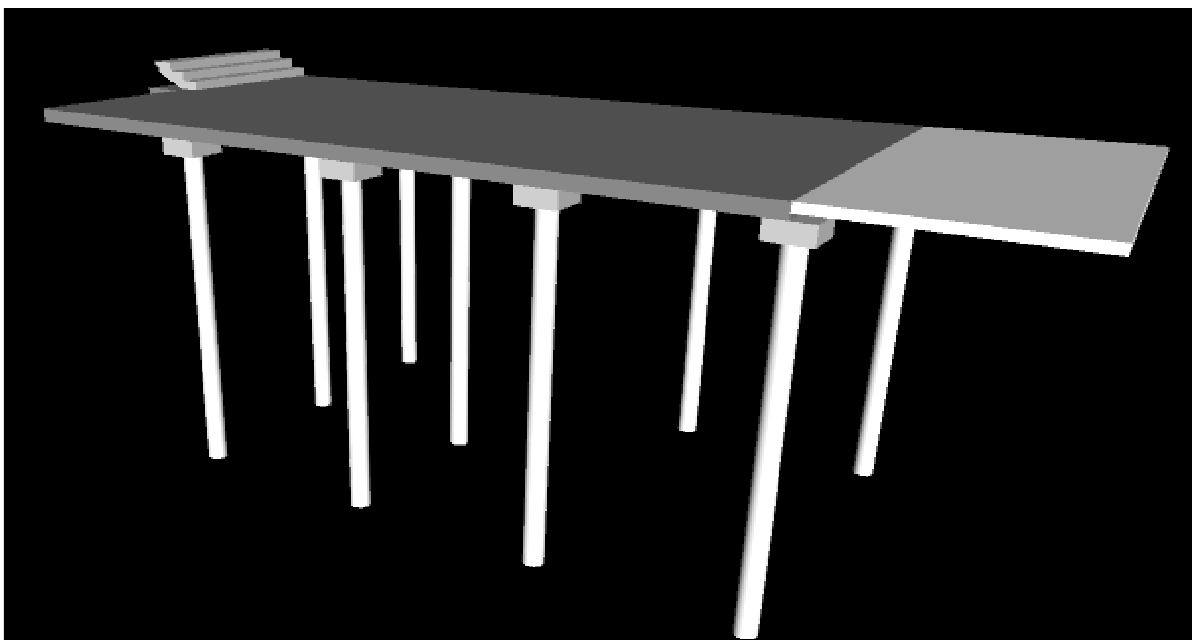


Figure 38-First floor completion-4D snapshot of case study 2

The solid color model items are completed work items while the translucent green walls indicate work in progress at the instant the snapshot was captured.

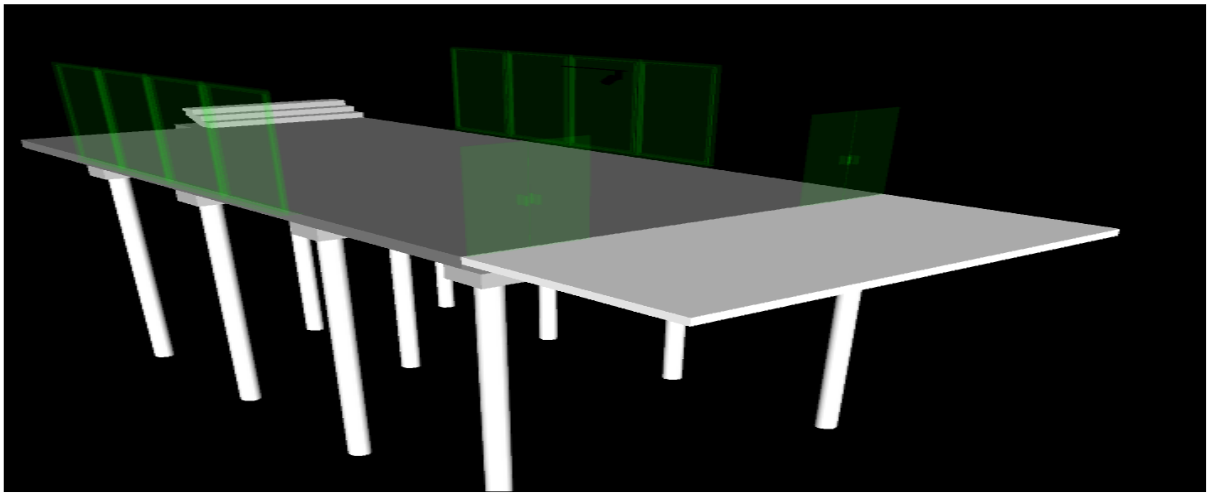


Figure 39-Progress of walls -4D snapshot of case study 2.

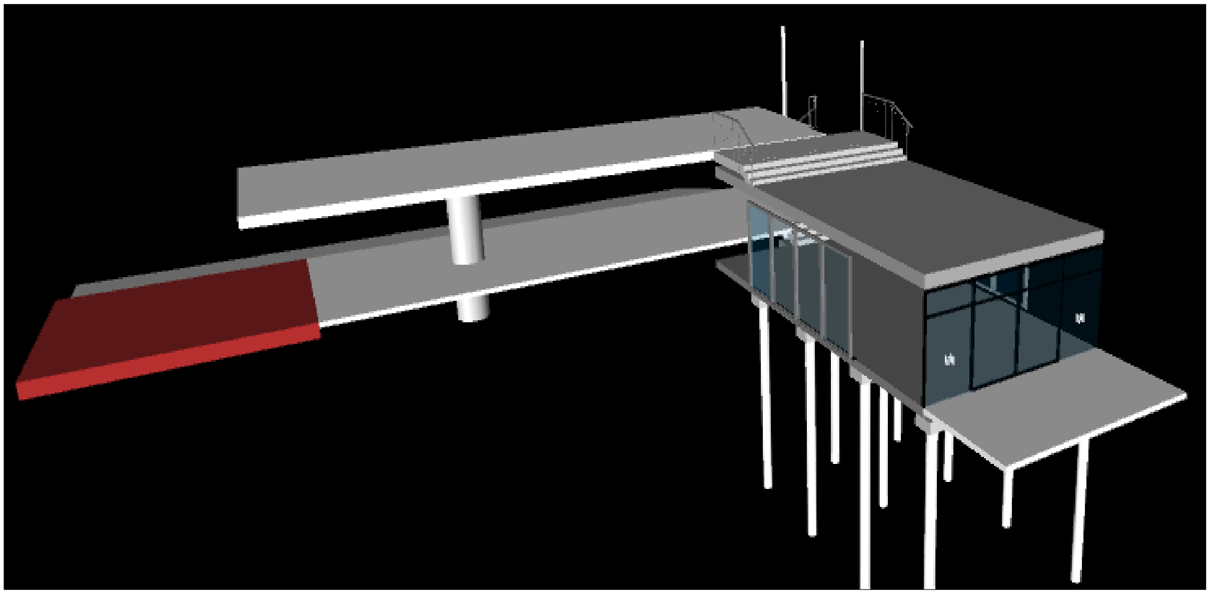


Figure 40-Second floor completion-4D snapshot of case study 2

The power of visualizing the schedule in 4D affords the user not only to easily understand and communicate the intent of the scheduler and the content of the produced schedule but also the completeness of the 3D design itself. An exception caught in Figure 41 demonstrates this fact. This snapshot shows the roof is in progress before the walls are installed.

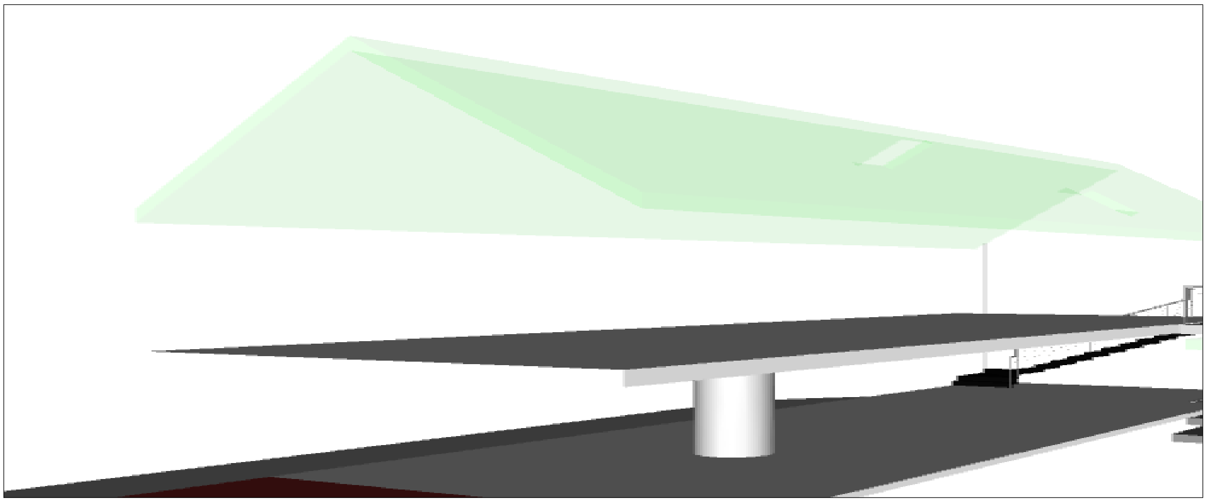


Figure 41-4D snapshot showing incomplete input 3D model in case study 2

The reason for the illogical sequence in this particular case is due to missing columns from the 3D model to support the roof, which in this case is supported by walls. This situation was not expected by the logic built into the 4DADS-system, as it expects a continuous vertical progression of structural work, and hence, columns and beams supporting the roof as in any regular commercial buildings, instead of walls. In consequence, this scenario is a good demostration of how incorrect sequence of work or incomplete design can easily be detected using the 4D visualization.

To sum up, one of the core objectives of this research is to automate the process of visualizing construction schedules in 4D. This automation is mainly achieved by automating the process of linking individual activities to their corresponding 3D elements in the BIM model. The complete cycle starts with the 3D model to extract the necessary information for the draft schedule to be generated, and then returns back to the 3D model and link the schedule to its initial input, the 3D objects. This circular data and process flow finally enables the automated generation of yet another significantly useful output of the system: 4D visualization.

Once the stages of model preparation, pre-planned export, extraction, matching to various domains and sequencing are performed as described in the earlier sections of this chapter, the 4D linking process has been seen to execute satisfactorily displaying the sequence of work exactly as indicated in the generated draft schedule. One major drawback is the case of generic elements, which are not readily placed in a specific domain of work. However, that decision is handled before the 4D process begins. Therefore, as validated by the test models and verified by professionals in the industry, the technique developed and applied in this research to automate the 4D visualization is successful.

5.3 System Testing and User Evaluation Procedure

As part of the validation process, the evaluation of the 4DADS-system aimed at practically verifying its capability to perform the hypothesized purposes of model

extraction, draft schedule generation and automating the linking of activities to their 3D objects in the model, by using a commercial concrete construction project. Accordingly, this was performed with the help of eight voluntary professionals in the industry, who have had an average 10.9 years of scheduling and or BIM related experience. Feedbacks from seven of them were collected on time, and incorporated in this summary, while one of the evaluators was not able to give their feedback even though they participated in the demonstration of the system.

The process involved a one-on-one demonstration of the system's functionalities by this researcher with each participant using the structural model presented at the beginning of this chapter. Each session ranged between 30-60 minutes depending on the level of interest each participant expressed by asking questions and interacting with the system. Following that session, each participant was asked to fill out a questionnaire that included yes or no as well as open-ended questions, in which the participants were asked to give their comments and suggestions on improving various aspects of the system. The questionnaire used for collecting user feedback and suggestions is attached as Appendix 1.

The main points of the feedback questions and face-to-face interactions with the participants attempted to verify about the 4DADS-System are as follows.

1. Whether the system allowed the user to enter the necessary information for the generic activity model
2. Whether the user was able to modify the level of details in the activities, and the sequence of execution both in the generic model and in the actual draft schedule generated
3. If the system generated the relevant activities needed to perform the construction of the building shown in the presented 3D model
4. Whether the users thought the activities and the sequence of execution generated were logical
5. To verify if the system automated the process of linking the activities to their corresponding 3D objects in the design to produce the 4D visualization
6. To confirm if the generated match of the 3D elements to their respective activities was accurate
7. To find out whether the participants thought the automation achieved was an important contribution for the 4D practice in the industry
8. To collect recommendations and additional improvements to the system through open ended questions

The responses from the participants are summarized in the next section.

5.4 Summary of User Feedback on the 4DADS-System

In response to the questions that sought user confirmation with "yes" or "no" choices regarding the basic functionalities of the 4DADS-System, all the participants provided positive answers to all the questions summarized at the end of Section 5.3, with the exception of one in which no response was given. Accordingly, all the participants who

turned in their feedback confirmed that the 4DADS-System effectively performed the following functionalities:

- It allowed the user to pre-define projects, project types, domains, methods of construction and generic activities.
- The system generated the required activities per domain or discipline predefined.
- The system produced activities that sufficiently captured the scope of work defined by the presented 3D model.
- The sequence of work in the output was generally reasonable considering the assumptions provided for this testing, such as the zone and floor definitions.
- The system allowed the user to modify the sequence of activities as needed, after posting the output to the timeliner.
- The process of linking the activities to the corresponding 3D objects was fully automated.

Another feedback item worth noting is the perception of the evaluators on the importance of the improvement to the linking process to automate the 4D visualization was either “very important” or “somewhat important.” Some of the comments provided by the evaluators also indicated that significant timesaving was expected from automating the process. This has been summarized graphically on Figure 42 where 71% of responders indicated that automating the 4D linking process is “very important,” while 29% chose that it is “somewhat important.”

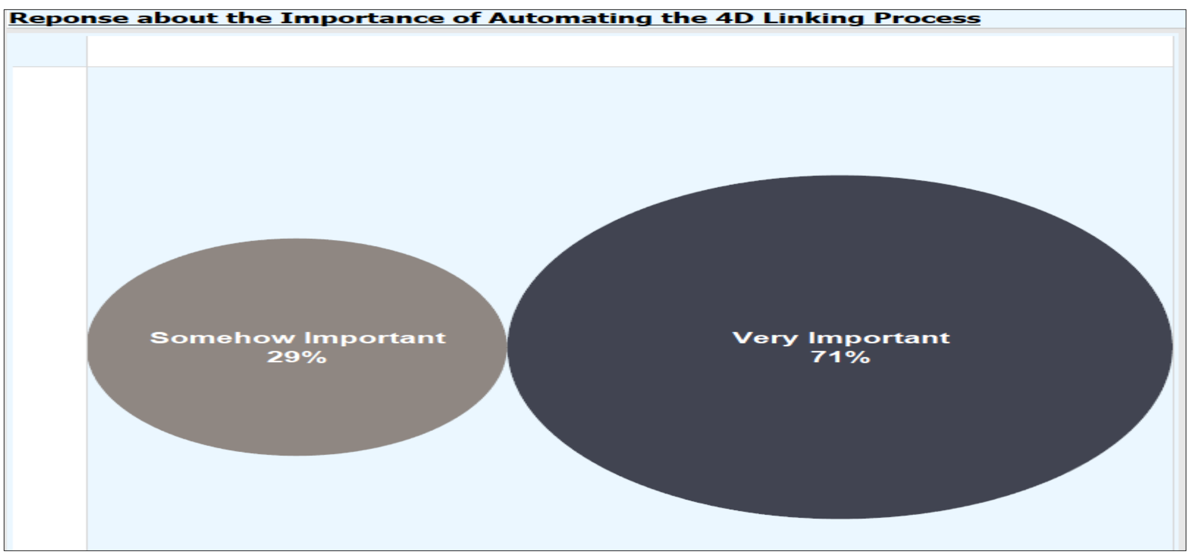


Figure 42-Ratings on the importance of automating the 4D process

Some of the suggestions the participants provided to improve the usability and effectiveness of the system include the following:

1. Generating additional types of sequence relationships between activities in the draft schedule such as start-to-start, finish-to-finish, would be helpful
2. Estimating the durations of activities using quantities from the 3D model and resource information, instead of the top-down rough estimation approach

adopted, where the user enters high level duration at work package level can lead to better accuracies.

3. Creating Gantt chart for the draft schedule generated, before it is posted to the Navisworks timeliner would help understand the schedule better.
4. Having an easier way to detach a 3D element from its attached activity could be a useful feature to have.
5. Having the option to change the successors and predecessors generated would be a useful feature of the software.
6. Ability to resource-load the schedule or ability to export to more capable software tools is recommended.
7. The system was slow to search and attach the 3D elements to their corresponding activities.
8. Automation cannot replace good planning. Thus, teams would need to verify what has been generated by such systems.

It is important to note that one model, the structural in case study 1, was used in all evaluations by the users, which could be one possible reason for the similarity in the answer for the “yes” or “no” questions, since all participants were speaking to the same results. This fact could be considered as a downside of the evaluation process. Most importantly, the fact the evaluators almost unanimously confirmed the accomplishment of the core functionalities outlined in the questionnaire by the system performing the tasks, which are also the main objectives of this research. The participants, additionally, provided few comments about the advantages of the 4DADS-system. These included the following:

- The logic of sequence in the generated schedule could be clearly seen in the 4D visualization, better than traditional Gantt chart or simple activity list.
- The automation saves a significant amount of time, hence money.
- The system works as explained and as expected.

One major observation while conducting this demonstration and getting feedback from the participants was how the reaction of the participants regarding their understanding of outputs of the system and how it progressed during the demonstration session. It was clear that recognizing the correctness of the schedule by looking at the generated draft schedule in tabular format was taking them time. It was clear that as soon as the 4D visualization played, the users could easily see and confirm the sequence of the work, which is also one of the major reasons for the whole concept of 4D.

One recommendation used to modify the system is for the system to generate at least two predecessors and successor activities based on the final element priority values computed. It takes the previous two groups as predecessors and the next two as successor activities. This fact can be seen in Figure 43, where the activities have two predecessors and two successors separated by comma where relevant.

TaskID	TaskName	Start	Finish	Duration	Predecessors	Successors
MLST-START	Project Start Milestone	6/16/2015	6/16/2015	0		F1.Z1.STCON-14555-1,F1.Z1.STCON-14555-2
F1.Z1.STCON-14555-1	F1.Z1-FOOTING-Erect concrete forms	6/17/2015	6/18/2015	1	MLST-START	F1.Z1.STCON-14555-2,F1.Z1.STCON-14555-3
F1.Z1.STCON-14555-2	F1.Z1-FOOTING-Install rebars	6/19/2015	6/21/2015	2	F1.Z1.STCON-14555-1,MLST-START	F1.Z1.STCON-14555-3,F1.Z1.STCON-14555-4
F1.Z1.STCON-14555-3	F1.Z1-FOOTING-Pour Concrete	6/22/2015	6/24/2015	2	F1.Z1.STCON-14555-2,F1.Z1.STCON-14555-1	F1.Z1.STCON-14555-4,F1.Z1.MECH-14525-1
F1.Z1.STCON-14555-4	F1.Z1-FOOTING-Cure Concrete	6/25/2015	6/26/2015	1	F1.Z1.STCON-14555-3,F1.Z1.STCON-14555-2	F1.Z1.MECH-14525-1,F1.Z1.MECH-14525-2
F1.Z1.MECH-14525-1	F1.Z1-Mechanical-rough-In Inspection	6/27/2015	6/28/2015	1	F1.Z1.STCON-14555-4,F1.Z1.STCON-14555-3	F1.Z1.MECH-14525-2,F1.Z1.MECH-14525-3

Figure 43-Partial view of the schedule generated for case study 2

Reviewing the recommendations provided by the participants show that most of the participants are drawing a direct comparison between the scheduling capability of the 4DADS-System and the commercially available and fully developed scheduling software such as Primavera and Microsoft project. Even though all the additional features recommended by the participants are very useful in enhancing the system, and making it more user friendly as well as productive, two fundamental explanations can be given to these recommendations.

First, the purpose of the scheduling capability for the 4DADS-System is to introduce something new to the existing capabilities of scheduling software, which is to generate a draft schedule from 3D BIM models automatically, a capability not available in these existing tools. Because of that, it was not necessary to repeat any of the features available in the existing software. Since the generated schedule is a very quickly obtained initial draft, the final schedule would require much more information about the project in the forms of soft logic, relationships other than finish-to-start, resource loading…etc. For this to happen, the draft schedule could be exported to Microsoft Project. Therefore, the scheduler would be able to take advantage of this commercial software.

Second, the scope of this research, as described in Chapter 1, does not necessarily include many of the suggestions provided by the participants of the evaluation process. Thus, it was not necessary to implement all these enhancements, although some of the recommendations can be added to the 4DADS-System easily. Overall, the user feedback results proved the success of implementing the identified objectives in the 4DADS-system while providing useful suggestions to make the developed software solution more user and industry friendly.

5.5 Comparison of 4DADS-System with Previous Works

As outlined in Section 3.7 of Chapter 3, comparing the 4DADS-system against some of the most recent research works in the area helps to validate its relevance and contributions to the body of knowledge Table 11.

Table 11-Comparison of 4DADS-system against older systems

Features / Systems	BIM Extraction	Activity generation	Sequence automated	4D
4DADS	☑ From IFCs	☑ Generic predefinition plus intermediate product model	± Hybrid of structural and other factors; some user input needed	☑ Fully automated using GUIDs
4DSMM (Chau et al., 2005)	☒ Uses own graphics database to build 3D elements	☒ Manually defined activity template	☒ Manually defined activity template and WBS	☑ Link maintained via shared WBS
(Tauscher et al., 2009)	± Theoretical framework	☑ BIM extraction; Case-Based Reasoning(CBR)	± Theoretical framework; Intensive manual initial attachment	± automation mentioned
(Chen et al., 2013)	± Quantity takeoff extracted automatically	☒ Manually using resource library	☒ Created manually and optimized via simulation	☒ Provides user interface for manual linking
(Kim et al., 2013)	☑ Utilizes IFCs	± Semi-automatically; Component level	± Limited sequencing rules hard-coded into system	☒ n/a
(Liu et al., 2015)	☑ Utilizes IFC BIM	± Optimizes sequence betweinitial network manually	± Resource optimization; limited scope ;manual simulation network; Considers only structural support for sequence	☒ n/a

Considering the core objectives and methods of this research, Table 11 juxtaposes it with some of the most recent works that aimed at automating the processes scheduling

and 4D visualization as separate or interrelated processes. It is important to note that this comparison focusses only on the BIM-driven systems, even though there are numerous other works related to automating the scheduling process based on various techniques, as discussed in the previous chapters.

The symbols used in Table 11 should be read as follows:

☑= Considered as part of the research method and fully attained in the developed system

☒= Not a component of the research method

±= Considered as and achieved partially but not fully

From this comparison of the system developed in this research against some of the closest peers, in terms of the objectives of this research, it can be seen the 4DADS-system is either bigger in scope or has more aspects of the scheduling and 4D process automated. More importantly, although with still some room for improvement, the 4DADS-system bridges the gap between 3D BIM, textual project schedule and 4D visualization. This has been achieved by utilizing an industry standard open-source BIM format (IFCs), a generic activity model, an intermediate product model and a semi-automated sequencing logic, which reflects the need for flexibility in the scheduling process. Additionally, with the exception of some generic items in 3D design, the developed system captures the whole building process to generate both the schedule and 4D visualization, while previous works summarized above are limited in the scope of the BIM design they can utilize or limited in the scope of their final output.

Overall, the 4DADS-system contributes significantly to the progress in this field for it brings the use of BIM in the AEC processes in general and scheduling and 4D visualization in particular, one step closer to achieving the theoretical expectations by the industry and academia.

CHAPTER 6- CONCLUSION AND FUTURE DIRECTIONS

The emergence of building information modeling has been hailed as one of the most significant leaps in the technological advancement of the architecture, engineering and construction industry in the past few decades. The industry and academia have been reporting tremendous gains in productivity of the overall project delivery by using BIM for enhanced information sharing, communication and improved collaboration.

Since BIM is expected to, at least theoretically, serve as the central repository of most information shared between the stakeholders and business processes, it is playing a growing role in enhancing other processes such as facility management, scheduling, estimating, even though to varying degrees of success. One such process at the core of the BIM idea is 4D, which has been acclaimed as a paradigm shift in the way project schedules are visualized, communicated and managed. Despite the benefits validated and accepted by the industry, the manual process involved in generating these 4D simulations by linking schedules and 3D elements, has undercut the advantages gained from its output as it adds to the cost of the project delivery, while delaying the promptly needed visualization. On the other hand, efforts to generate construction activities and their sequence from BIM models have been limited. More importantly, even though quick ways of generating schedules and 4D have a complimentary effect on the project delivery endeavor, the respective progress in these two venues have not necessarily supplemented each other, thereby diminishing the overall value that can be gained from the synergy of these processes.

This research focused on addressing these interrelated challenges by successfully implementing various techniques, thereby advancing the ultimate goal of BIM in this direction to the next level.

6.1 Unique Contribution of this Research

This research introduces unique contributions to the field of 4D BIM simulation and project scheduling. First, it sets a new path by automatically generating both a draft schedule and 4D visualization in a single step, using state-of-the-art technologies and data format in the industry. This was achieved by first bridging the gap in interoperability between the sub-processes of project scheduling and visualization by creating an intermediate product data structure. To this end, the system takes the 3D product model in the Industry Foundation Classes (IFCs) data format and extracts the information needed to generate scheduling activities and execute the high-level precedence rules to generate the sequence of the 3D components, and then individual activities. The other significant use of the intermediate product model is, serving as a permanent bridge between the generated draft schedule and the 3D model of the project, thereby enabling the automatic link to generate the 4D visualization.

By bringing some of the most current tools and technologies in the industry a step forward, feasible and practicable results of the 4DADS-system can be used for actual construction projects, eventually replacing or upgrading the currently available tools and workflows.

Second, it presented an approach to generically model and produce activities for commercial construction projects, as a function of their respective domains and methods. With minimum updates, this project independent predefinition of activities can help construction firms to keep a lean storage of their experience while reflecting the level of detail, they prefer and methods of construction they use at a discipline level, instead of simply storing old schedules for later reference. By doing so, the companies can re-use such well-documented experience to generate similar schedules, such as proposal schedules or actual work schedules, quickly. This generic activity model plays a vital role in the 4DADS-system, as it enables direct linkage with the intermediate product model.

The third contribution of the system is the approach of sequencing the building components, by integrating different physical and non-physical factors into a single decision factor. Such integration has resulted in, at least semi-automated, determination of the construction precedence of individual components, followed by their corresponding activities. At this level, some degree of intervention from the project manager might be needed to refine the precedence at domains level. Similar customization by the user could also be necessary in cases of some generic elements in the model. Therefore, the sequencing process, could in some scenarios, be semi-automated. A fourth but related contribution is the modified version of Multi-Attribute Decision Making (MADM) technique introduced and effectively used to combine the various constraint factors, which determine the sequence of their construction.

The fifth contribution is the successful approach of using GUIDs as a connection between the product and process models. Groups of these unique keys are automatically associated with each activity while matching the object to its domain specific activity, and therefore, the manual process of linking the schedule to the 3D product model has been successfully eliminated. This adds a much-needed value to the technology that has been struggling to prove its financial feasibility.

To sum up, the computer implementation and the results obtained and verified by practicing professionals in the industry substantiate that the developed methodologies have been successful in accomplishing the objectives set forth in this research.

6.2 Future Works and Directions

With its rich content, BIM has a great potential to make project deliveries more transparent, quicker and economical. This research makes use of such content and technologies to implement methods of speeding up the process of generating draft construction schedules and their 4D visualization. However, many aspects of the method developed and implemented in this research can be improved to enhance its effectiveness.

- At its current stage, the schedule generated by the system is expected to serve as an initial draft that can be imported into advanced commercial scheduling software such as primavera and Microsoft project to perform critical path calculations and make use of other features of these tools. To minimize the need for multiple tools in managing schedules and 4D, the system can benefit from having a complete CPM capability that can calculate early and late dates for each activity considering many types of relationships other than finish-to-start. At this

stage, it only considers finish-to-start relationships between activities and generates single start and finish dates.

- The sequencing logic depends on basic structural concepts, spatial aggregation of work packages and domain level prioritization of work that may consider many factors such as work access, safety, resource availability, etc. that are not readily available in the 3D BIM model. Though these are expected to remain important considerations in the future, the technique can be improved by developing and establishing lower level topological inferences to deduce such sequence.
- The generic activity model developed uses domains and methods of construction to generate alternative sets of construction activities. However, the methods considered here are mere links between the domains and their activities. Lack of standardization in definition and description of these methods could limit communication between professionals. Consequently, an approach that eliminates or improves this scenario could add value to the system. Related to this, the domains of work considered could be examined at different levels than the current categories. Higher or lower level of detail could be considered to either simplify it or generate results that are more accurate. In line with this, the level of detail in the 3D model could also be varied. Lower level of details in the model is expected to be richer in information, even though hardware requirements are expected to go steeper than the requirements for the current level.
- At its current stage, methods and the system developed considers only commercial buildings. Its applicability can be expanded to industrial and highway projects.
- The 4DADS-system has employed different technologies including sql server and the API of Autodesk Navisworks 2015. Limit in the API's capabilities to fully recognize the IFC data structure properties is believed to be a limiting factor in the level of detailed information that can be extracted and stored. Therefore, other more matured tools could be tested for better information out of the model.
- Generally, 4D visualization has stringent graphics and computing power requirements, depending on the size and rendering quality of the 3D model. The system developed in this research has been observed to run very slow depending on the size of the model, and could be a limiting factor in its future adoption for use. One reason for this has been the long loops the program had to make between the database, the 3D model and the client. The search loop has to run between the activity list, which in big projects could number in thousands, the intermediate product model stored in an external database and then the objects in the 3D model. Improving these itineraries to make the search quicker could result in faster processing, less computing power and hence less cost and better convenience to the end user.

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APPENDIX 1- FEEDBACK QUESTIONNAIRE

User Feedback to Evaluate the Effectiveness of Developed Computer System

For BIM-Based Scheduling and 4D Visualization

Study Title: ***Automated Generation and Visualization of Initial Construction Activity Schedules from Building Information Models***

Instruction To Evaluators: Please give your feedback using the following questionnaire, after experimenting with the developed computer system. If the alternatives given in the multiple choices are not sufficient, please write your answer in the comments space provided.

Part I: General Activity Model

1. Does the developed computer system (*the system*) allow the user to pre-define projects, project types, domains, methods of construction and generic activities?

a. Yes

b. No

c. Comments____

____

2. Does the system generate the required activities per domain/ discipline predefined?

a. Yes b. No

c. Other (Please write your answer briefly)

____

____

____

3. Does the system allow the user to customize the level of detail in the automatically generated activities?

a. Yes

b. No

c.Comments____

____

____

4. What additional features would you recommend to the system to make the activity predefinition, generation and customization aspect of it more usable?

____

____

____
____

Part II: Product and Process Integration

1. Assuming the 3D model presented as part of the case study to represent the required scope of work, are the activities generated sufficient to represent this scope of in the design?
a. Yes
b. No
c. Comment____
____
____

2. From your experience and expectation of activities for concrete structure of a commercial building, is the presented sequence of activities generally logical?
a. Yes
b. No
c. Comment____
____
____

3. Does the system allow the user to modify the sequence of activities, if they wish to?
a. Yes b. No
b. Comment____
____
____

4. What additional features would you recommend to the system to make the activity sequence and options for modify the generated sequence?

____
____
____
____

Part III: 4D Linking

1. Assuming the generated activities and their sequences are accurate (evaluated separately in previous sections), is the linking of activities to their 3D objects fully automated?
a. Yes
b. No

c. Comment____
____

2. Considering the linked 3D objects with their corresponding activities, c
a. Yes
b. No
c. Comment____
____

3. From your experience and understanding of 4D BIM, how important an improvement is the automation of the linking process for the generation of 4D production?
a. Very import
b. Somehow important
c. Not important
d. Comment____
____

4. What additional features would you recommend to the system to make the activity sequence and options for modify the generated sequence?
____
____
____
____

<u>Part IV: Participant's Basic Information</u>

1. Are you 18 years of age or above?
a. Yes b. No
2. Currently or in the past, do you use or develop or manage construction schedules as part of your job?
a. Yes b. No
3. If "Yes" for No.2, how many years of scheduling related experience do you have? Answer=____________________
4. Do you have basic understanding of 4D BIM and how it is developed ?
a. Yes
b. No
c. Comment____
____

APPENDIX 2- CONSENT FORM

1. Study Title: Automated Generation and Visualization of Initial Construction Activity Schedules from Building Information Models
2. Performance Site**:** In Houston, TX, at locations convenient for evaluators.
3. Investigators: The following investigators are available for questions about this study: M-F 8:00am- 4:30 pm
   A. Dr. Gerald M. Knapp (225-578-5374)
   B. Yibrah Weldu (225-207-0530)
4. Purpose of the study: the purpose of the survey to be filled out by the users is to evaluate the effectiveness of the computer system developed and collect feedback from experts in the industry.
5. Subject Inclusion: construction experts with some experience in scheduling and or virtual construction (also called BIM), who are 18 or above and who do not report psychological and neurological conditions.
6. Number of subjects: 8.
7. Study Procedure: The principal investigator will first explain the purpose of the developed computer system to the individual participants and practically demonstrate for around 10 minutes how it works. The participants will then test the basic functionalities of the system with the 3D model case study project presented and fill out the survey based on their experience.
8. Benefit: Subject participation is voluntary and they will not be paid any money to participate in the study. They study may yield valuable information about model-based scheduling and 4D visualization of schedules.
9. Risks: The investigator does not expect any risk on participants as a result of this study.
10. Right to Refuse: Subjects may choose not to participate or to withdraw from the study at any time without penalty or inconvenience to them.
11. Privacy: Results of the study may be published, but no names or identifying information will be included in the publication. Subject identity will remain confidential unless disclosure is required by law.
12. Signatures:
13. The study has been discussed with me and all my questions have been answered. I may direct additional questions regarding study specifics to the investigators. If I have questions about subjects' rights or other concerns, I can contact Dennis Landin, Institutional Review Board, (225) 578-8692, irb@lsu.edu, www.lsu.edu/irb.) I agree to participate in the study described above and acknowledge the investigator's obligation to provide me with a signed copy of this consent form.

Subject Signature: ___________________________ Date: ______________

APPENDIX 3- INSTITUTIONAL REVIEW BOARD APPROVAL

ACTION ON EXEMPTION APPROVAL REQUEST

LSU

Institutional Review Board
Dr. Dennis Landin, Chair
130 David Boyd Hall
Baton Rouge, LA 70803
P: 225.578.8692
F: 225.578.5983
irb@lsu.edu I lsu.edu/irb

.

TO: Yibrah Weldu
Engineering Science

FROM: Dennis Landin
Chair, Institutional Review Board

DATE: May 14, 2015

RE: IRB# E9349

TITLE: Automated Generation of Construction Activities and 4D Visualization from BIM Models

New Protocol/Modification/Continuation: New Protocol

Review Date: 5/14/2015

Approved X **Disapproved**__________

Approval Date: 5/14/2015 **Approval Expiration Date:** 5/13/2018

Exemption Category/Paragraph: 2a,b

Signed Consent Waived?: No

Re-review frequency: (three years unless otherwise stated)

LSU Proposal Number (if applicable):

Protocol Matches Scope of Work in Grant proposal: (if applicable)

By: Dennis Landin, Chairman DLandin

PRINCIPAL INVESTIGATOR: PLEASE READ THE FOLLOWING –
Continuing approval is CONDITIONAL on:

1. Adherence to the approved protocol, familiarity with, and adherence to the ethical standards of the Belmont Report, and LSU's Assurance of Compliance with DHHS regulations for the protection of human subjects*
2. Prior approval of a change in protocol, including revision of the consent documents or an increase in the number of subjects over that approved.
3. Obtaining renewed approval (or submittal of a termination report), prior to the approval expiration date, upon request by the IRB office (irrespective of when the project actually begins); notification of project termination.
4. Retention of documentation of informed consent and study records for at least 3 years after the study ends.
5. Continuing attention to the physical and psychological well-being and informed consent of the individual participants, including notification of new information that might affect consent.
6. A prompt report to the IRB of any adverse event affecting a participant potentially arising from the study.
7. Notification of the IRB of a serious compliance failure.
8. **SPECIAL NOTE:**

**All investigators and support staff have access to copies of the Belmont Report, LSU's Assurance with DHHS, DHHS (45 CFR 46) and FDA regulations governing use of human subjects, and other relevant documents in print in this office or on our World Wide Web site at http://www.lsu.edu/irb*

VITA

Yibrah W. Weldu, a native of Ethiopia, received his bachelor degree in civil engineering from Jimma University in July 2006. He then worked as project engineer and a senior project engineer for a German company, GIZ, in Ethiopia until December 2008. He started his graduate study in Louisiana State University (LSU), in spring 2009, which later was changed to dual degree, to concurrently pursue his PhD; during which he also worked as graduate assistant for the Department of Parking & Transportation Services of LSU, on their GIS projects. After receiving his master degree in engineering science in May 2013, he worked as BIM specialist & project engineer for MAPP Construction in Baton Rouge until May 2014. Then he accepted his current position to work as Project Controls Engineer at Kiewit Energy Group in Houston, TX, where he works as a subject matter expert in the areas of BIM, analytics and scheduling.