Simulation-Based 4D Modeling for Planning and Scheduling of Elevated Urban Highway Reconstruction Projects

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ABSTRACT

Simulation-Based 4D Modeling for Planning and Scheduling of Elevated Urban Highway Reconstruction Projects

Ahmad Doriani

Highway infrastructures in North America have surpassed their service life, and the transportation developments are shifting from construction of new highways to reconstruction of existing facilities. Elevated urban highway reconstruction projects involve complex geometry and limited space available which lead to spatio-temporal conflicts. Additionally, maintaining acceptable flow of traffic without compromising safety in highway construction zones is another major issue for planners. Overall, the phasing of construction work in such projects is complicated due to the structural complexity, large number of involved contractors, independent resource utilization planning by each contractor, and the vast number of activities that will be taking place at the same time.

This research proposes a new methodology by integrating 4D modeling and simulation in the planning and scheduling phases of elevated urban highway reconstruction projects to detect spatio-temporal conflicts. A sequence assessment approach using a deterministic 4D model is presented to define the order in which the segments should be constructed or demolished. The result of this step is a sequence which will be used as the process chain for simulation techniques. Then, a probabilistic 4D model is introduced by linking the 3D model of the project with generated probabilistic schedules from Monte-Carlo and Discrete Event simulations. The proposed approach is capable of identifying scenarios with the highest potential of conflict and calculating the probability associated with each scenario. The benefits of the proposed approach are highlighted, and the feasibility of the proposed methods is explored through three case studies.

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First and foremost, my greatest gratitude and appreciation goes to my dear supervisor, Dr. Amin Hammad for his support, close supervision, and patience. This dissertation would not have been possible without his guidance and advice. I would seize the opportunity to learn and work with him. I would like to express my appreciation to Mr. Mohamed Mawlana and Mr. David Chedore who helped me for developing the simulation and 3D models. I would like to acknowledge my colleagues Mr. Shayan Setayeshgar, Mr. Mohammad Mostafa Soltani, Mr. Farid VahdatiKhaki, and Mr. Ali Nejati for their intellectual cooperation. Finally, I thank Concordia University and the Ministère des transports du Québec for providing the financial means and required data to complete this project.

DEDICATION

To my parents, Gerami Doriani and Jila Khorshidi who made all of this possible, for their endless encouragement and support.

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List of Abbreviations

Abbreviation	Description
2D	Two-dimensional
3D	Three-dimensional
4D	Four-dimensional
AASHTO	American Association of State Highway and Transportation Officials
AECOO	Architecture, Engineering, Construction, Owners, and Operators
AIA	American Institute of Architects
AMG	Automated Machine Guidance
BIM	Building Information Modeling
BrIM	Bridge Information Modeling
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CII	Construction Industry Institute
CIM	Computer-Integrated Manufacturing
CMMS	Computerized Maintenance Management System
CNC	Computer Numerically Control
COBIE	Construction-Operations Building Information Exchange
CPM	Critical Path Method
DTM	Digital Terrain Model
GIS	Geographic Information System
IAI	International Alliance of Interoperability
IFC	Industry Foundation Classes
ISO	International Standard Organization
JPCCA	Japan Pre-stressed Concrete Contractors Association
LandXML	Land data in eXtensible Markup Language
LSM	Linear Scheduling Method

MTQ	Ministère des Transports du Québec
NBIMS	National Building Information Model Standard
NIBS	National Institute of Building Sciences
NIST	National Institute of the Standard and Technology
PERT	Program Evaluation and Review Technique
PGBT	President George Bush Turnpike
RFID	Radio Frequency Identification Device
SHAs	State Highway Agencies
STEP	STandard for the Exchange of Product model data
TIN	Triangular Irregular Network
TransXML	Transportation data in eXtensible Markup Language
TMP	Traffic Management Plan
WBS	Work Breakdown Structure

CHAPTER 1 INTRODUCTION

1.1 General

Highway infrastructures in North America are approaching, or have surpassed, their service life. As a result, a great amount of reconstruction and rehabilitation work is expected on existing highways. Such activities affect drivers, highway workers, businesses and other community functions (Jeannotte & Chandra, 2005; Mahoney et al., 2007). Reconstruction projects of urban highways are unique projects that differ from other construction projects because of (Saag, 1999): (a) the huge cost involved in urban highways reconstruction, which requires different and innovative financing techniques; (b) the magnitude of the work to be undertaken often requires organizational modifications at the transportation agency level; (c) the partial closure or disruption of travel on these important traffic routes has a daily effect on drivers and the community as a whole; and (d) the need to ensure travel continuity through or around the construction zone. Current practices in the construction industry suggest that urban highway rehabilitation projects often overrun in budget and time due to the high cost of equipment and materials, change orders of work, meteorological and environmental factors, potential conflicts with stakeholders, economical and social activities, and a large number of unpredictable factors (Dawood & Shah, 2007; Hannon, 2007).

Furthermore, urban highway reconstruction projects are very difficult because of the limited space available which leads to spatio-temporal conflicts. In addition, maintaining acceptable flow of traffic in highway construction zones is a major issue for planners. Another major concern is providing enough work space for construction workers and sufficient lane width for road users without compromising safety. Large highway reconstruction projects are usually managed by a consortium and the construction work is usually divided into subprojects among several contractors. The phasing of the construction work in such projects is time consuming and complex process due to: (a) the structural complexity of such projects; (b) the number of contractors involved; (c) the independent resource utilization planning by each contractor; and (d) the vast number of activities that will be taking place concurrently. The construction management firm within the consortium will have to phase the construction work in an effective way in order to avoid any spatio-temporal conflicts. These conflicts will lead to project delays, overrun in cost and disputes between the involved parties. Without the use of simulation and 4D modeling, it is almost impossible to detect those spatio-temporal conflicts. Therefore, a new methodology for minimizing the risk of such problems and facilitating the planning and scheduling processes is needed.

1.2 Research Objectives

Considering the above-mentioned issues in elevated urban highway reconstruction projects, this research aims to develop a new 4D modeling approach for identifying potential conflicts at the planning and scheduling phase considering that both construction and demolition operations are carried out at the same time. The specific objectives are:

(1) Investigating the application of 4D modeling for sequence assessment in the planning stage of elevated urban highway reconstruction projects.

(2) Investigating a simulation-based probabilistic 4D modeling approach for scheduling of elevated urban highway reconstruction projects

(3) Investigating a process for realizing the proposed method using available tools

1.3 Thesis Organization

This research will be presented as follows:

Chapter 2 Literature Review: A literature review is performed to investigate and understand topics related to the proposed methodology. This chapter briefly reviews elevated urban highway reconstruction projects and planning and scheduling techniques including work zone planning and traffic management planning. A short summary of Building Information Modeling (BIM) and Bridge Information Modeling (BrIM) is also provided. Moreover, simulation and 4D modeling techniques are focusing on the applications of 4D modeling for highway projects.

Chapter 3 Proposed Methodology: This chapter gives a description of the proposed sequence assessment method and the probabilistic 4D modeling approach. A new method for identifying the scenarios with the highest probability of potential conflict between construction and demolition processes is proposed. In addition, the development process of the proposed methodology is explained including the new benefits of the proposed methodology.

Chapter 4 Case Studies: In this chapter, the proposed methods for sequence assessments and developing probabilistic 4D models are demonstrated through three case studies. The objective of Case 1 is to demonstrate the proposed sequence assessment approach, while Case 2 and Case 3 aim to demonstrate the applications of the proposed probabilistic 4D model for identifying potential conflicts using Monte-Carlo and Discrete Event simulations, respectively.

Chapter 5 Summary, Conclusions, and Future Work: This chapter summarizes the work performed during this research, highlights the proposed contributions, and suggests some recommendations and limitations as the opportunities for future work.

CHAPTER 2 LITRATURE REVIW

2.1 Introduction

This chapter presents the literature review performed during this research. This review briefly discusses elevated urban highway reconstruction projects and planning and scheduling techniques including work zone and traffic management planning. A short summary of BIM, BrIM, and simulation techniques is also provided. In addition, the previous research related to 4D modeling is reviewed, and the applications of 4D modeling for highway projects are highlighted.

2.2 Elevated Urban Highway Reconstruction Projects

Nowadays, transportation developments are shifting from construction of new highways to reconstruction of existing facilities. Considering the fact that the cost of reconstruction projects will normally go beyond the original construction cost, these types of projects are going to be the most costly of all projects. Reconstruction of urban highways is needed for providing additional capacity to the current traffic flow, improving safety and meeting new design standards, preserving existing pavements and structural conditions, or moderating geometric deficits resulted from poor operational conditions. To achieve success, good project management is considered as a vital element in the reconstruction of urban highway projects (Saag, 1999).

The most important factor in the reconstruction of urban highway projects is the duration needed for construction processes. The scheduled duration not only impacts the users of highways, but it also affects the whole community around the project area. To reduce the project duration while maintaining the same level of quality, it is necessary to use innovative approaches in project delivery system and contracting methods. Public involvement and effective communication are other factors that should be considered from an early planning stage. In transportation agencies, there is a sizeable funding allocated for public involvement and communication programs (Saag, 1999).

2.2.1 Work Zone Planning

A construction work zone is an area of a road or a highway where construction, maintenance, or utility work activities are taking place. Typically, these work zones are marked by signs, channelizing devices, barriers, pavement markings, and/or work vehicles (Department of Transportation, 2003). The appropriate procedures and preparation needed for a work zone are determined by the type of the planned operation, time duration, space requirements, and road characteristics (Minnesota Department of Transportation, 2011). The objectives of work zones are: to ensure an acceptable level of safety for workers and road users; to minimize undesirable impacts on traffic and community; and to facilitate project completion on time and within the desirable quality (Antonucci, 2005). It should be noted that work zone planning is related to traffic phasing, which should be done in parallel to construction phasing.

2.2.2 Traffic Management Plan (TMP)

In urban highway reconstruction projects, maintaining the traffic service in a corridor is essential because of the high traffic level in this area. Aside from the cost for engineering, construction, administration, social and environmental purposes, these projects involve user costs such as increased travel time, vehicle operation, and accident costs. Hence, an effective TMP is needed to be integrated with construction management plan. The followings are three different elements for a highway TMP: (a) a traffic handling strategy; (b) impact mitigation strategies for alternative routes; and (c) a public involvement and communication plan. A traffic handling strategy consists of three general categories: minor capacity reduction with keeping the same number of lanes, lane closure, and full highway closure (Saag, 1999).

TMP development initiates during system planning and preliminary engineering in order to ensure that the implementation costs are considered. The process of developing TMP evolves through the project design, and it is modified during implementation and monitoring stages. Figure 2.1 shows a general process of developing, implementing, and assessing TMP that would be considered by agencies. As Figure 2.1 presents, the process starts in planning/design phase with the involvement of all technical specialists in order to identify potential issues. This process considers three types of TMPs such as "Basic", "Intermediate", and "Major" based on the significance of the project (Jeannotte & Chandra, 2005).

Figure 2.2 shows Phase 1 of the traffic plan developed for Rt. 28 – McLearen Road Interchange located in Fairfox County, Virginia. The 4D model developed by Platt (2007) provides an enhanced visualization of this phase.

2.2.3 Constructability Issues

Constructability is defined as the optimum use of construction knowledge and experience in planning, design, procurement and field operations to achieve overall project objectives (CII, 1986). Due to the complexity of current projects and the ongoing need for more rapidly and less costly deliverables, constructability input and feedback is considered necessary (Fischer & Tatum, 1997).

Fischer and Tatum (1997) mentioned several preliminary design variables that are important to perform constructability analysis, some of those variables are: (a) dimensions of elements (e.g. height, width, and length); (b) distances between elements (e.g., bridge clearance and story heights); (c) changes in dimensions and distances (e.g., from floor to floor or from bay to bay); and (d) repetition of dimensions and distances, and modularity of layout. Zin (2004) found that the constructability concepts for building projects and highway projects are almost alike.

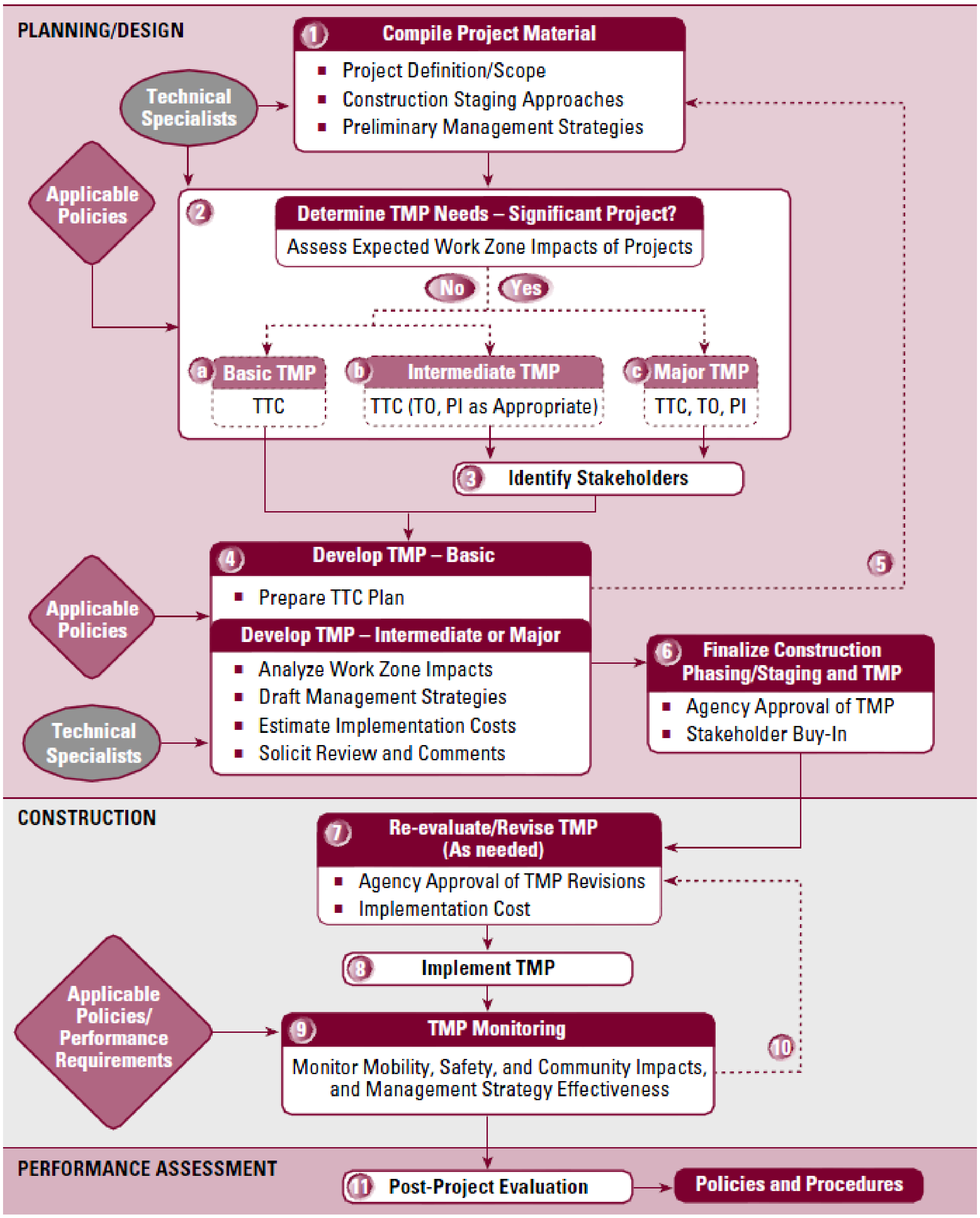


Figure 2.1 A process for TMP (Jeannotte & Chandra, 2005)

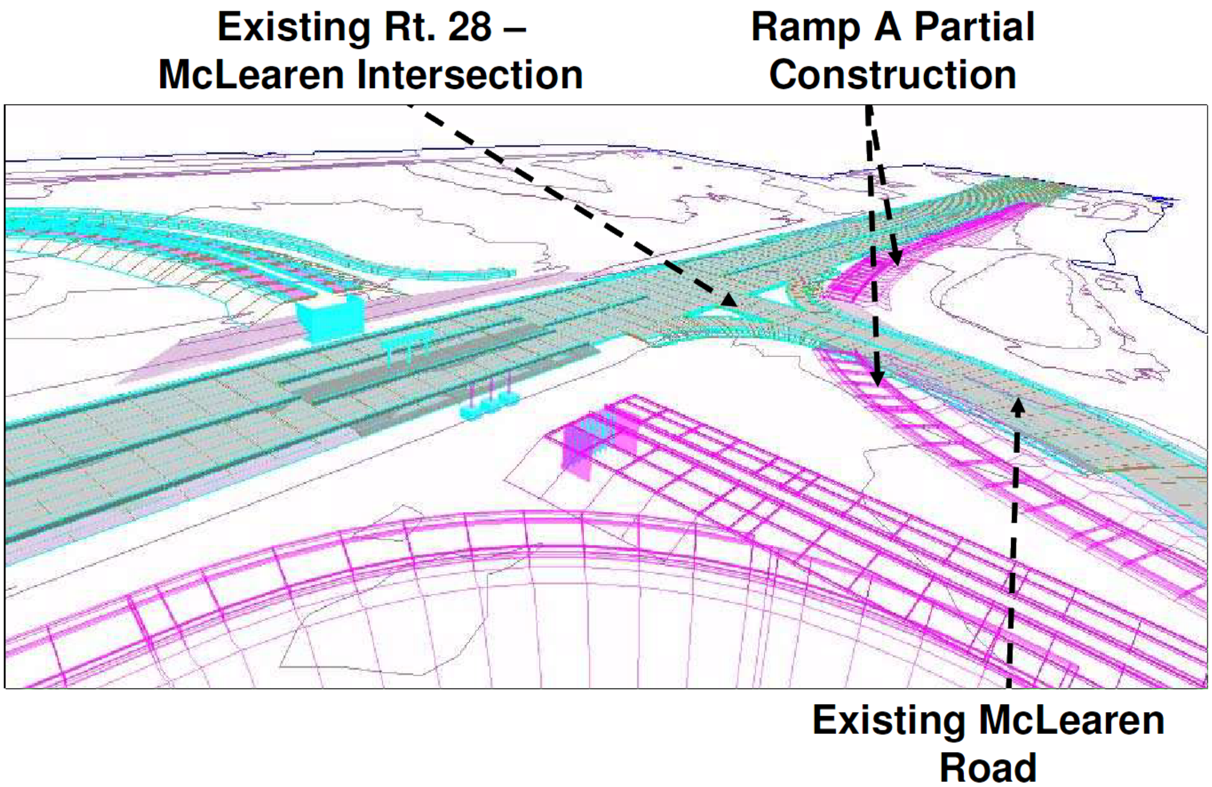


Figure 2.2 Phase 1 of the trafficc control plan for the Rt. 28 - McLearen Road interchange project (Platt, 2007)

2.3 Planning and Scheduling

Project planning and scheduling, as the core of project management, are the most crucial and intensive phase of each project. Construction scheduling provides a tool to coordinate all the available resources, such as workers, machines, and materials, in a timely order within the desired time and costs. Traditional construction schedules have used Gant chart technique and Critical Path Method (CPM). CPM still has a high demand in construction projects because of the aggressive marketing by CPM software developers. However, the highly competitive atmosphere in the construction industry necessitates deploying innovative approaches to accomplish the projects in shorter time and less cost (Moselhi, 2009; Wu et al., 2010).

Regarding the need for automated schedule generation and the inability of the CPM software to assess uncertainty and schedule correctness in terms of process duration for a specific amount of resources, new approaches for construction scheduling have been proposed. Simulation has been applied as a powerful tool to investigate the construction schedules by many researchers. Simulation techniques are more explained in-detail in the Section 2.3.2. Although Program Evaluation and Review Technique (PERT) has also used to assess the uncertainty, this method is unable to guarantee the uninterrupted utilization of resources, and always underestimates the project duration (Halpin & Riggs, 1992).

As an automated approach for bridge construction schedule generation, a new methodology proposed a constraint module to overcome the fixed process chains used in Discrete Event simulation. Most simulation systems work based on a rigid process chain and do not consider the optimization of sequences of the activities (Wu et al., 2010). By applying a constraint-based simulation, instead of modeling an explicit process chain, the constraints involved with each activity is modeled. These constraints include all the requisite preceding activities, machines, manpower, materials, and the needed space. In this manner, the approach provides a high level of flexibility for modeling construction processes (Beißert et al., 2007). As shown in Figure 2.3, two simplified possible sequences of activities are demonstrated in order to show the impact of sequencing configurations on the overall project duration. Based on the proposed network, activity B has to be finished before C can be started, and it is assumed that the resources p and q are available exactly once each. The right-hand side shows the two possible scenarios have a 2 day difference in their total durations (Wu et al., 2010).

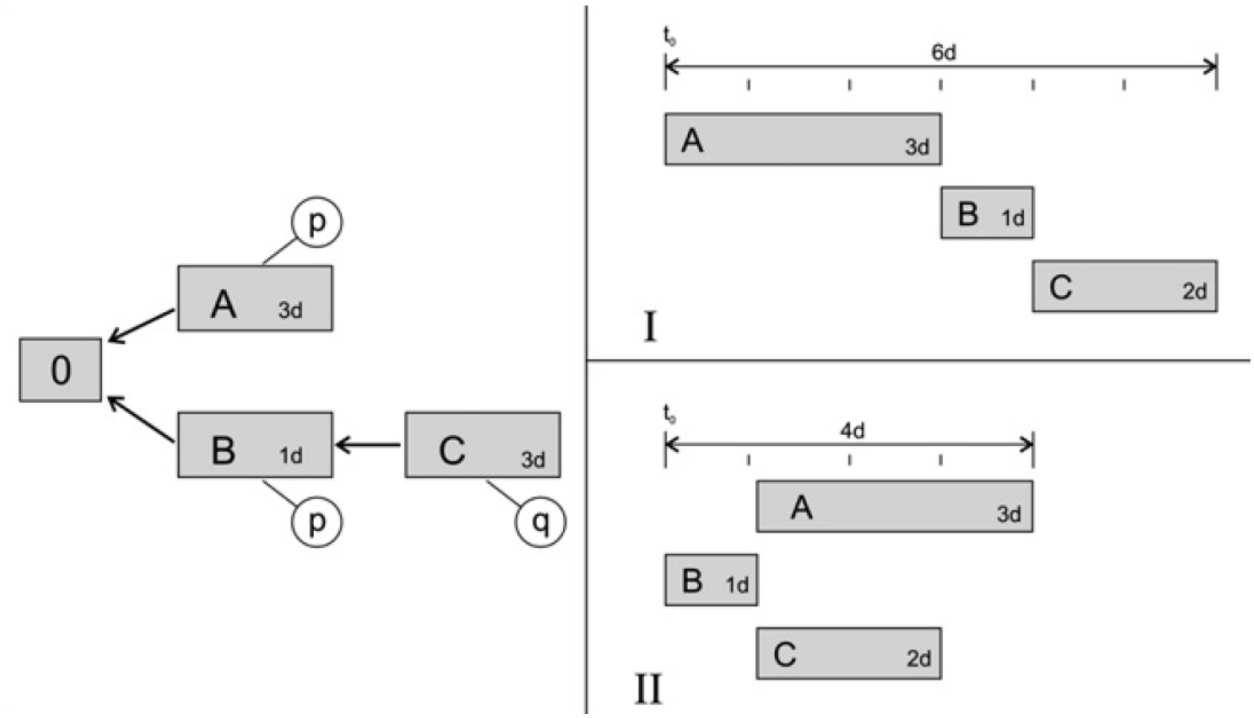


Figure 2.3 Two possible sequencing configurations (Wu et al., 2010)

Although CPM networks have the ability to allocate the resources, the uninterrupted utilization of resources is not assured. The CPM network shown in Figure 2.4 is prepared for three repeating units of work. The solid lines represent the precedence relationship between the activities, while the dashed lines link similar activities from a unit to another. The proposed network results in project duration of 18 days based on the critical path including the activities A1, C1, C2, D2, D3, and E3. The links between the activities in the CPM network ensure the precedence relationship and resource availability requirements. However, the continuity of resource deployment is not directly guaranteed in the CPM network. For example, even though the uninterrupted usage of resources for activity C is provided, the scheduled network does not deliver the continuous usage of resources for activity D. This inability of the CPM network to maintain the continuity of resource usage is the reason to apply Linear Scheduling Methods (LSM) for repetitive projects (Harris & Ioannou, 1998).

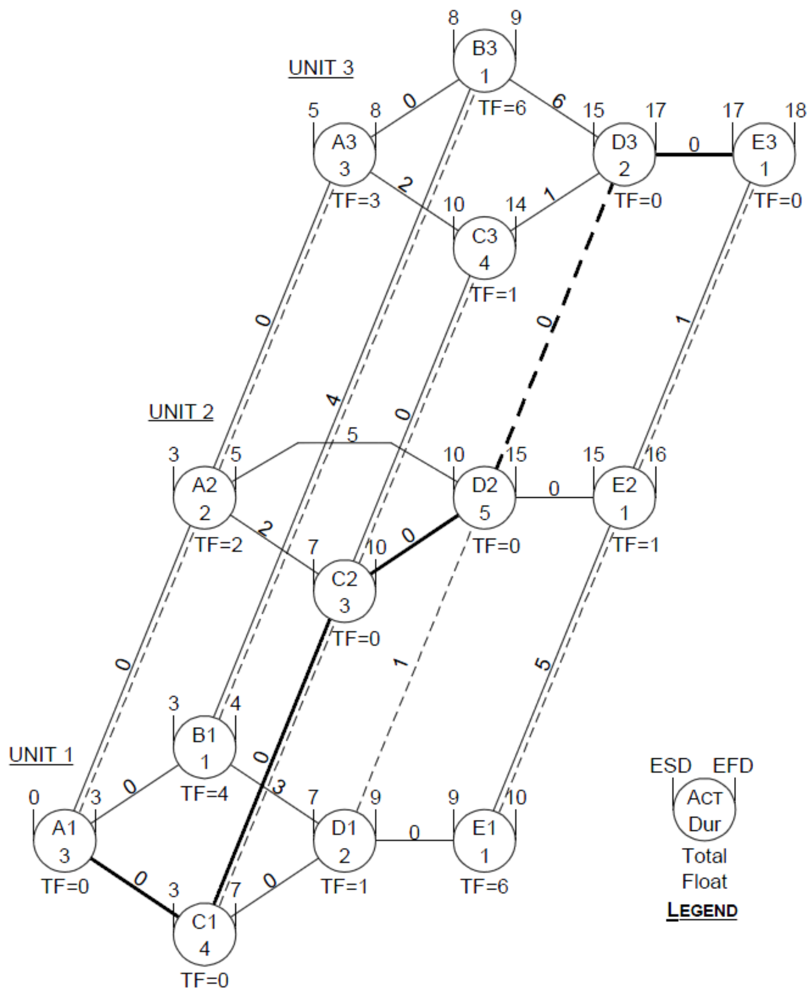


Figure 2.4 CPM network for three repetitive units (Harris & Ioannou, 1998)

2.3.1 Planning and Scheduling of Repetitive Projects

Multiunit projects such as highways, pipelines, housing developments, and multistory buildings are characterized by repeating activities from one unit to another. These identical units include stations in highways, meters in pipelines, houses in housing developments, and floors in multistory buildings (Harris & Ioannou, 1998). Basically, repetitive projects are divided into two categories: (a) linear or location-based projects such as highway and pipeline projects, and (b) nonlinear or point-based projects such as multistory buildings and housing developments. Linear projects progress continuously from one unit to the next along the horizontal alignment, while nonlinear projects involve discrete units. Applying multiple crew strategies in linear projects is done simply by assigning each crew to a section of the project; however, in nonlinear projects crews are assigned to alternating units. Figure 2.5 shows the two different multiple crew strategies adapted in linear and nonlinear projects (Hassanein & Moselhi, 2004).

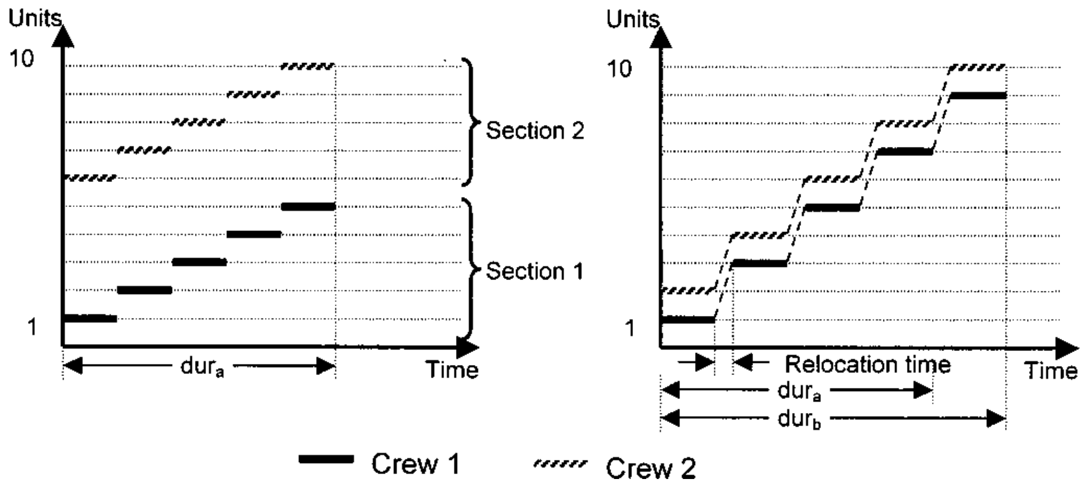


Figure 2.5 Multiple crew assignment strategies: (a) assigned to sections; and (b) assigned to alternating units (Hassanein & Moselhi, 2004)

As mentioned in Section 2.3, although Gant charts and CPM techniques are the most common scheduling methods, these methods do not guarantee the optimum usage of resources and lack details for linear projects. Taking pipeline projects as an example in scheduling linear projects, the main priority is finding the optimum production rate for repeating activities, not the sequence of activities. Therefore, the main focus is on repetitive activities to assure the optimum and uninterrupted deployment of resources is achieved. In fact, a linear schedule is plotting the progress of repeating activities on a chart with location along one axis and time on the other (Duffy et al., 2011).

To overcome the above-mentioned issues, LSM is introduced for highway construction projects. Identifying the locations of each activity and its production rate helps project managers to plan the resources and mobility of equipment. By comparing LSM with CPM, it is noted that LSM results in fairly detailed information with less confusion compared to CPM. However, there might be a time to integrate these two methods in order to have the most effective schedule (Chrzanowski & Johnston, 1986; Johnston, 1981). LSM is developed based on either deterministic or probabilistic data. The probabilistic linear schedule is based on Monte-Carlo simulation and considers the uncertainties involved with construction projects (El-Sayegh, 1998).

2.3.2 Simulation Process

Simulation is a powerful tool that can be used to mimic the behavior of real-world systems over time (Law et al., 1991). Simulation in construction is used for planning and resource allocation, risk analysis, site planning and productivity measurement (AbouRizk et al., 1992; Wainer, 2009). The construction processes that have repetitive and cyclic nature can be planned and analyzed using simulation (Touran, 1990). Simulation is also used to compare the outcome of different scenarios and alternative construction methods (Oloufa, 1993). Many examples of using simulation can be found in the literature such as earthmoving operations (Halpin & Riggs, 1992; McCahill & Bernold, 1993) and selection of an earthmoving operations fleet (Marzouk, 2003).

Monte-Carlo simulation is a technique that performs risk analysis by generating possible results for any factor that involves uncertainty. Monte-Carlo simulation generates random numbers from the duration's distribution of the activities of the project. Each run of this simulation will result in generating one schedule for the complete project (Mubarak, 2010). Beta distribution function can be used to represent the duration of construction activities (AbouRizk & Halpin, 1992). The beta distribution can be approximated using triangular distribution with 3 values: optimistic, most likely, and pessimistic.

Discrete Event simulation also utilizes a mathematical/logical model of a system in order to inspect the interaction between flow units and to estimate the performance and production of the system as established. The simulation model determines the idleness of resources and locates any potential bottlenecks. The desired objective is to avoid or minimize imbalance between resources by suggesting an appropriate selection and balance of resources. To achieve this, the developed simulation model should reflect the real world system. Although the utilization of a model to act as a real world system is an abstraction, a proper level of detail of actual situations should be considered in developing the model. By assigning a probability distribution for each work task, Monte-Carlo simulation can be used to randomly determine when units are moved and the delays. Whether the durations of work tasks are deterministic or probabilistic, the progress of units occurs at discrete points in time. Considering the discrete nature of unit movements in simulation process, this procedure is called discrete event simulation (Halpin & Riggs, 1992).

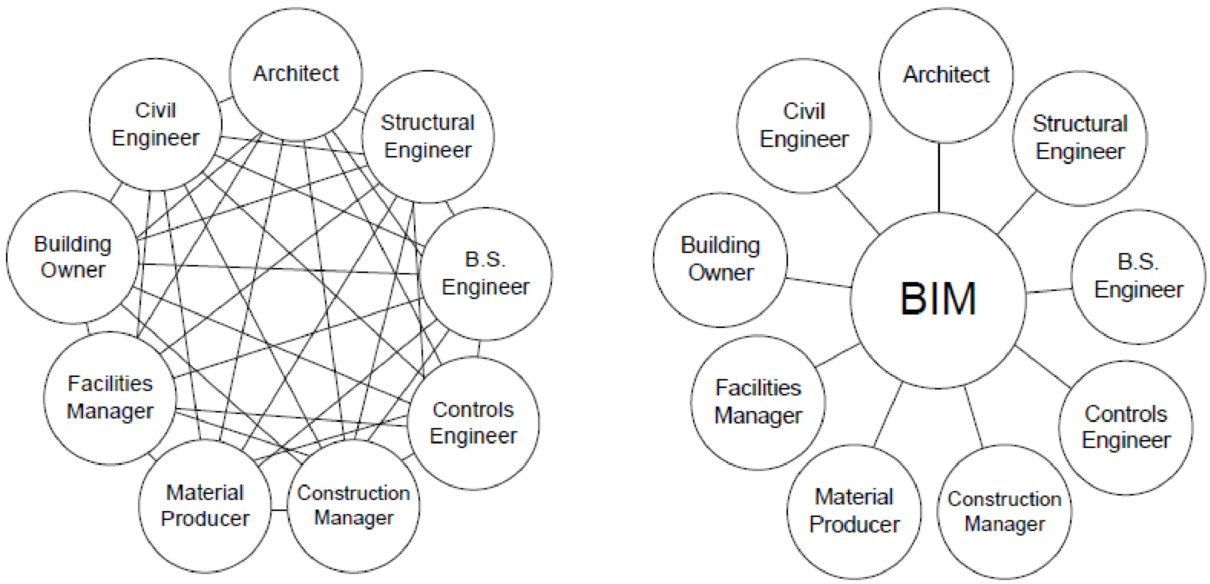
2.4 Building and Bridge Information Modeling

The fragmented nature of the construction industry has resulted in poor efficiency, which is associated with lack of interoperability to exchange information between stakeholders. The desire for standard models to share information has introduced the concepts of Building Information Modeling (BIM) and Bridge Information Modeling (BrIM) as a solution to data exchange challenges.

2.4.1 BIM

The Architecture, Engineering, Construction, Owner, and Operator (AECOO) industry is a dynamic, complex, and fragmented industry. According to a study made by the US Bureau of Labor Statistics, all industries have had an increase in productivity by over 200% since 1964. During this period, the AECOO industry has had a decreasing rate in productivity (AIA, 2012). Traditionally, there is a gap between the design and construction disciplines of this industry because the designers and contractors hardly communicate before the start of the construction phase. The lack of construction information in the design phase results in the decrease of quality, and increase of time and cost of the projects. According to the National Institute of Standards and Technology (NIST), the lack of interoperability in the software in the AECOO industry costs $15.8 Billion annually (Uhlik & Lores, 1998).

BIM is an emerging technology that helps all stakeholders work together, which leads to an increased efficiency. Figure 2.6 (a) shows the document centric approach, which has several challenges for information sharing, and Figure 2.6 (b) shows the information centric approach. According to Sjogren and Kvarsvik (2007) the main issues with the document centric approach are: (1) communication errors and loss of project information within the same domain, and (2) re-entering information on average seven times in different systems before the delivery of the facility to the owner. In the information centric approach, all the stakeholders are able to communicate to each other through a common language by using BIM technology and use a single repository for all the information (Sjogren & Kvarsvik, 2007). BIM helps to create and use coordinated, consistent, and computable information of a building project. In addition, the parametric nature of this information helps in design decision making, production of high-quality construction documents, prediction of building performance, cost estimating, and construction planning (Eastman et al., 2011). BIM can also be used in renovation or demolition work (Becerik-Gerber et al., 2011). Motamedi and Hammad (2009) studied the lifecycle management of facilities components using Radio Frequency Identification Device (RFID) and BIM.



(a) (b)

Figure 2.6 (a) Document centric vs. (b) Information centric data exchange (Sjogren & Kvarsvik, 2007)

The AECOO industry has changed over the last decades, and buildings have become more complex with more integrated systems which are interconnected. Therefore, as buildings are getting much more complex, designer should consider more factors in the analysis of their designs. BIM makes it possible to have one repository to store all the design components' data and each component should be described once. BIM provides both graphical and non-graphical data such as drawings, specifications, and schedule. Changes to each item should be done only once and in one place, so all the team members can monitor the changes instantly. One of the benefits of BIM is that BIM makes it possible for all stakeholders to insert, extract, and modify information of the building during the different phases of the facility lifecycle. By using BIM, a 3D simulation of the building and its components can be realized. This helps to predict collisions and to calculate material quantities (Eastman et al., 2011). According to Khemlani (2004), in earlier Computer Aided Design (CAD) systems, building components such as walls, doors, and windows were represented by using geometric entities such as points, lines, rectangles, planes, etc. (Figure 2.7 (a)). BIM-based CAD systems are object oriented in that basic components of drawings are building elements. Furthermore, in traditional 2D and 3D CAD systems, space is not defined explicitly, but in building data model, space is a fundamental part of the building data model that can define the relationships between walls, ceilings, and floors. Figure 2.7 (b) shows the wall-to-space relationship in a building data model. It is also possible to do several types of analysis relevant to the spaces by using BIM, which is not possible by the use of traditional CAD systems.

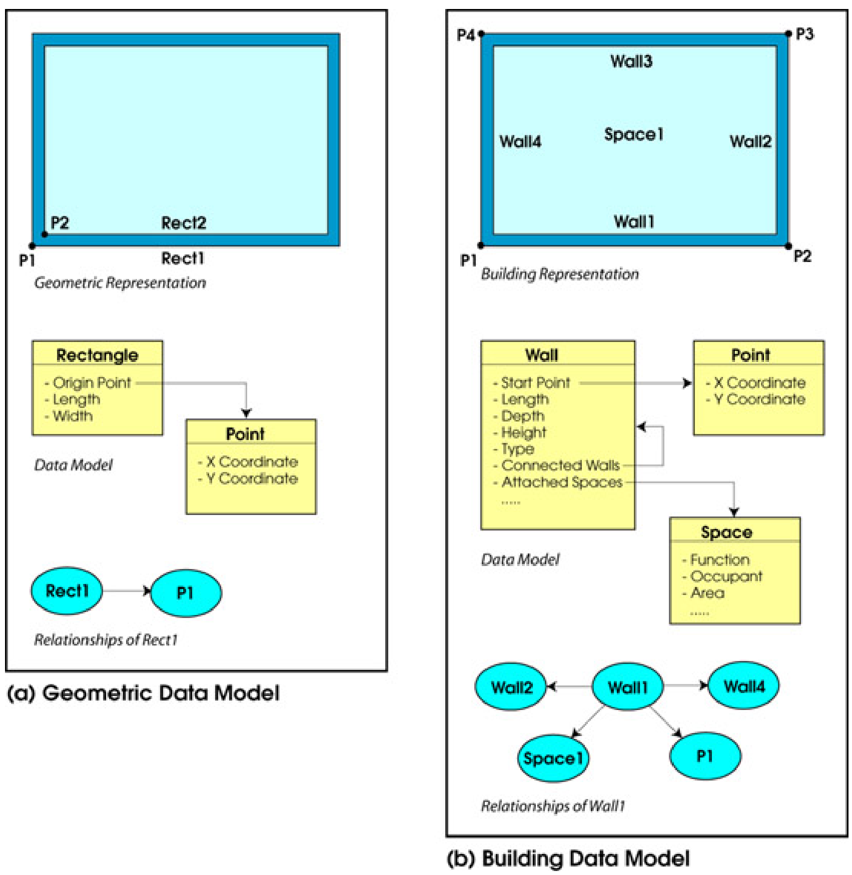


Figure 2.7 (a) Geometric data model vs. (b) Building data model (Khemlani, 2004)

As shown in Figure 2.8, BIM can be applied during the whole lifecycle of a facility from design to demolition phase. Operation and maintenance, guaranties, and other facilities management-related information can be covered by BIM. By applying a BIM procedure, Information is transferred from one phase to another. The provided data flow through BIM increases the quality and integrity of information transmission and avoids unnecessary reworks of information management (BuildingSMART, 2011).

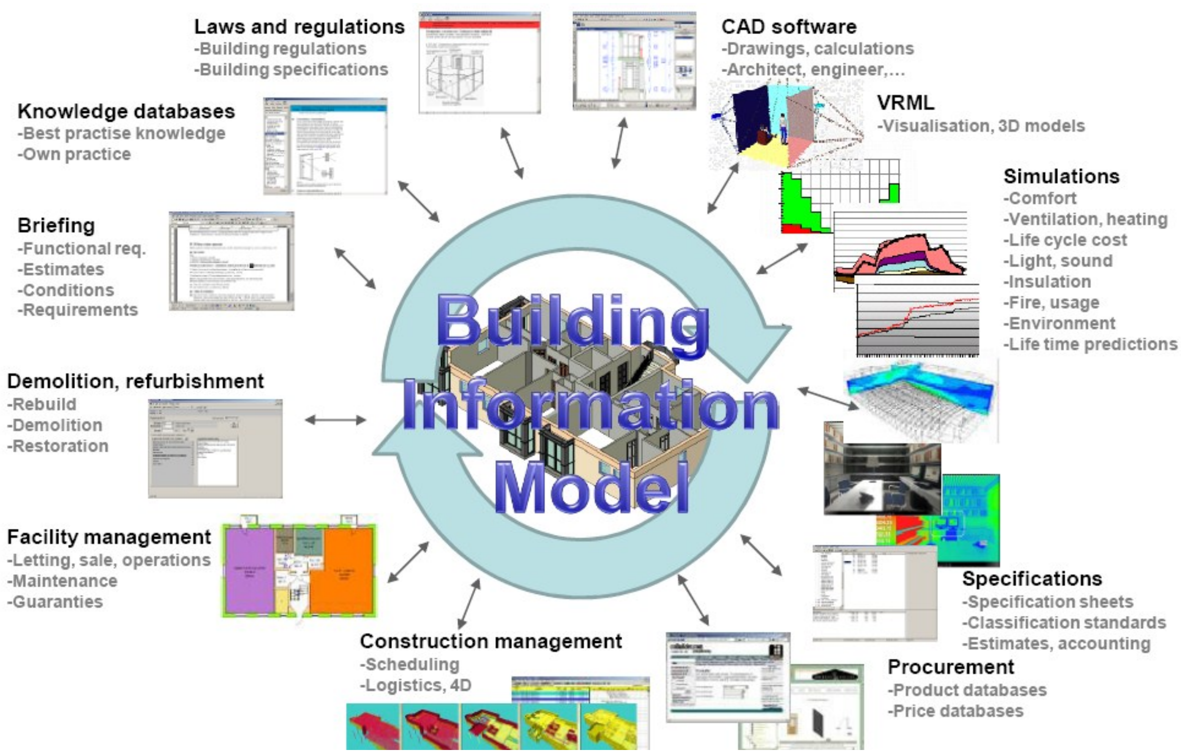


Figure 2.8 Lifecycle information view in BIM procedure (BuildingSMART, 2011)

Industry Foundation Classes (IFC)

Building owners are involved in a significant cost that arises from the lack of interoperability with regard to electronic facility information. BuildingSMART®, formerly the International Alliance for Interoperability (IAI), has created a non-proprietary construction operations data model called Industry Foundation Classes (IFC). Their goal is providing “a universal basis for process improvement and information sharing in the construction and facilities management industry” (East, 2007).

IFC is a common data schema that provides all the proprietary software applications with a common framework to keep and exchange the facility information during all the phases of a facility’s lifecycle (BuildingSMART, 2011). IFC leads to integration in the AECOO industry by defining a universal language to improve communication, productivity, delivery time, cost, and quality throughout the design, construction, operation and maintenance lifecycle of facilities (Mitchell & Schevers, 2005). IFC2x4 is the recent version and IFC is still under development to encompass more data related to facilities lifecycle (WBDG, 2011). STandard for the Exchange of Product model data (STEP) is another effort prior to IFC. STEP was initiated by the International Standard Organization (ISO) and focuses on the standard definitions for the representation and exchange of product information in general. SETP is used in various design disciplines such as mechanical design, ship design, etc. The experience gained in STEP is used to develop a more domain-specific model for the representation of building data by people involved in STEP (Khemlani, 2004).

2.4.2 BrIM

One of the initial ideas of BrIM emerged from a model of space station in the late 80s. Basically, BrIM is a 3D model for the whole life cycle of a bridge project and related data. As the time goes and conditions change, the desired 3D data model should be able to provide the required data (Chen et al., 2006). The most immediate benefits of BrIM are better design and increased efficiency and productivity. Since design and construction documentation are dynamically linked, the time needed to evaluate more alternatives, execute design changes, and produce construction documentation is reduced significantly. Therefore, implementing BrIM processes during the whole life cycle of bridge projects facilitates project optimization by including visualization, simulation, and analysis of different aspects such as bridge rating, permitting and routing (Shirole et al., 2008).

Based on the existing projects in the construction industry, most of bridge and highway reconstruction projects overrun the budget due to the high cost of equipment and materials, change orders of work, meteorological and environmental factors, and potential conflict between stakeholders, economical and social activities, and a large number of unpredictable factors (Dawood & Shah, 2007; Hannon, 2007). Considering the above mentioned issues, developing a standard data model is essential in order to reduce cost and time, and improve the quality

Central 3D Data Model

Applying the BIM processes in bridge projects will streamline the project delivery by two aspects; first, the central integrated 3D bridge data model, and second, the interoperability between different software by providing a common language.

By having a comprehensive integrated 3D model, it would be expected to have an integrated environment of Computer-Aided Design (CAD), Computer-Aided Engineering (CAE), and Computer-Integrated Manufacturing (CIM) which results in faster and better quality project delivery and management. Figure 2.9 shows a precast concrete centralized data model including the 3D model for the integrated design and construction process (Sacks, 2002). The centralized data model will generate all drawings and provide information related to each stakeholder. It is essential that output data generated by the data models are readable by humans as well as by machines (Chen et al., 2006).

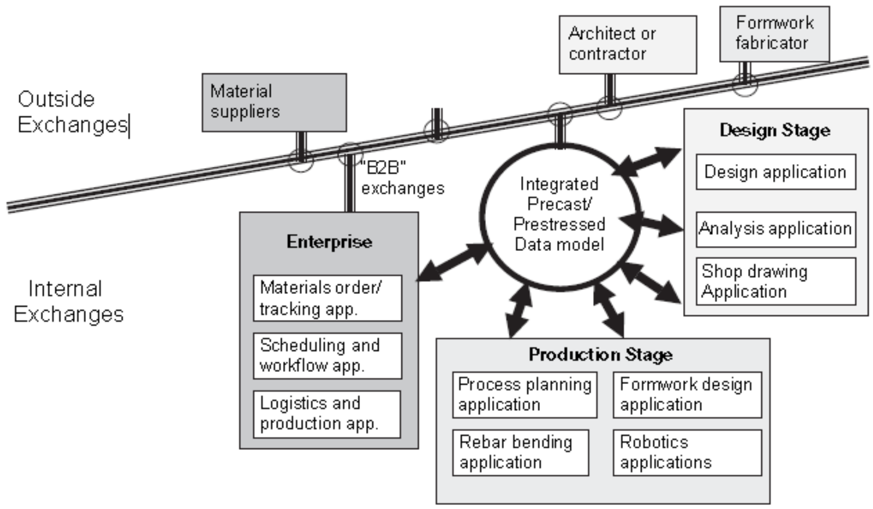


Figure 2.9 Centralized data model supporting integrated process (Sacks, 2002)

As the project progresses, the 3D model would get updated while its integrity is kept. The 3D model can be used in material procurement and management such as quantity takeoff, Computer Numerically Control (CNC) input file to drive the equipment, bridge assets management, virtual assembly instead of pre-physical assembly, etc. Figure 2.10 shows a 3D model of diaphragm to girder connection, which can be helpful for the erector to identify on-site problems of the erection process prior to the actual erection process (Chen et al., 2006). Table 2.1 presents the comparison between 3D model and 2D drawings.

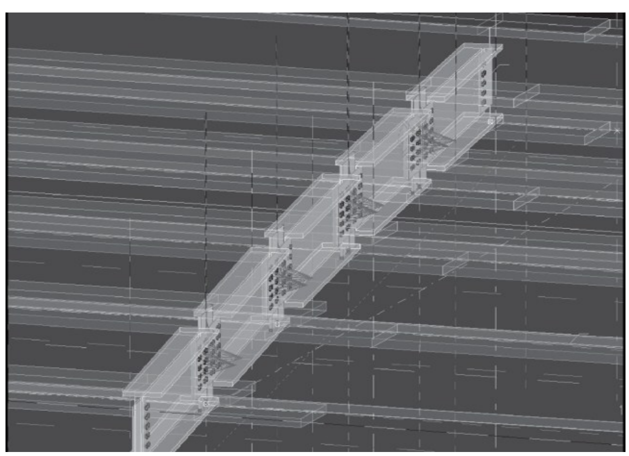


Figure 2.10 Diaphragm placements in 3D model (Chen et al., 2006)

Table 2.1 Comparison of 2D and 3D documentation processes (Sacks, 2002)

2D CAD provides an Electronic “drawing board”	3D enables a parametric model
2D drawings contain the information	3D model contains the information; 2D drawings are only reports
2D drawings intended to be human-readable; separate manual data entry is required for analysis	3D model is computer readable , such that direct analysis are possible
Coordination is difficult; information is scattered among different drawings and specifications clauses	Coordination is automatic: 3D model is the single source for all product information
Manual checking	Automated checking
No support for production	Potentially full support for production (via CNC codes etc.)

Desired Interoperability

Although there is no doubt about the advantages of 3D modeling compared to 2D drawings, the ultimate benefits of 3D modeling is achieved only through a common language to present and exchange the project data. In this manner, all stakeholders will be able to use the information without having to use the same software. To approach the full benefits of data model “the industry must endorse the extension TransXML (or development of bridge XML) to support more comprehensive bridge data modeling in all aspects of the bridge life cycle. Bridge owners need to conceive themselves as owners–stewards of the bridge data as they evolve, not just as owners–stewards of the constructed bridge itself” (Chen et al., 2006).

Development in BrIM

With the purpose of developing a standard data model, a Japanese group introduced a bridge product model for pre-stressed concrete bridges. This model was developed based on IFC in a collaborative work with the Japan Pre-stressed Concrete Contractors Association (JPCCA). In order to have an international interoperable bridge data model, the Japanese model was integrated with the IFC-BRIDGE data model which was introduced by a French group (Yabuki et al., 2006). Recently, an American group of software developers and bridge experts backed by NIST are working on developing an integrated bridge data model for steel bridges (AASHTO/NBSA, 2011). However, there is no BrIM accepted standard at the time being.

2.5 3D and 4D Modeling

2.5.1 3D Modeling

Application of 3D models for design has improved the design process by reducing the time needed for building design (Khemlani, 2004). In case of elevated urban highway projects, the application of 3D models is more essential due to the complex geometry of such projects. As explained in Section 2.4.2, the application of 3D model results in faster and better quality project delivery and management. Advanced technologies, such as 3D modeling approach, have significant benefits for highway projects. Visualization is used to facilitate the communication of project information to project stakeholders and the public. Understanding the characteristics of a highway project with high level of geometric complexity is much easier through a 3D model compared to the traditional 2D methods. In addition to the application of 3D design in visualization, the 3D model is needed for Automated Machine Guidance (AMG), detection of design errors prior to construction, computing earthwork quantities, and presenting the design intent in a more comprehensive way. Figure 2.11 shows the results of a survey of all State Highway Agencies (SHAs) in the U.S. to rank the importance of benefits of 3D design method.

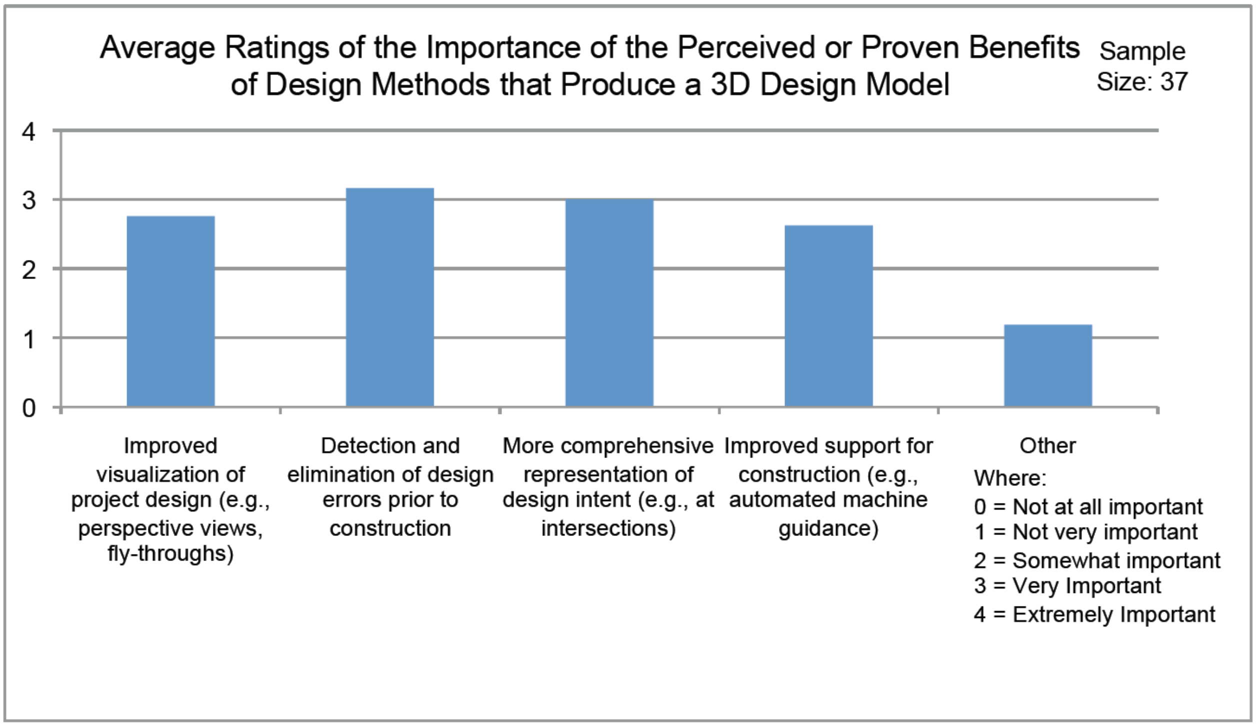


Figure 2.11 Importance of benefits of 3D design methods (Vonderohe & Hintz, 2010)

2.5.2 Need for 4D Modeling

As explained in Section 2.3, scheduling is a significant factor in the success of projects and it demands a considerable amount of work. A typical construction schedule is a complicated chart or network which consists of activities and the time needed to deliver those activities. As the project progresses, the construction manager collects the data and measures the progress in order to update the schedule with respect to any change specially related to the design. The reliability of the schedule mainly relies on the accuracy of construction managers in reviewing the data and drawings and in considering the availability of resources of each time period. Obviously, this process is a time consuming procedure and would lead to a high potential of errors due to the manual data collection. Applying 4D modeling procedure overcomes the mentioned deficiencies and results in better collaboration and more efficient schedule. Therefore, the construction managers will have more time to coordinate other tasks, and the schedule misinterpretation can be mitigated via the visualized schedule by linking the 3D model with schedule (Hardin, 2009).

2.5.3 4D Modeling Definition

4D modeling is one of the recent computer technologies that have emerged into the AECOO community. A 4D model can be defined as a 3D model linked to the construction schedule (Koo & Fischer, 2000). A 3D model is linked with the desired schedule through specialized software. Navisworks (Autodesk Incorporated, 2011) and ProjectWise Navigator (Bentley Systems Incorporated, 2010) are examples of such programs that provide a collaborative environment to extend, review, and modify the 3D model. Prior research efforts have investigated the application of 4D modeling for resource management (Akinci et al., 2003), coordination of mechanical, electrical, plumbing, and fire protection systems (Khanzode et al., 2005), and constructability analysis in building projects (Ganah et al., 2005).

In 4D modeling, it is important to understand the difference between the product and process models. For creating a 4D model, these two components must be planned accordingly. A product model represents the physical components of the project such as beams and columns. However, a process model provides the logic between the scheduled activities (Kunz & Fischer, 2005). The process of developing 4D has been developed by several researchers in past years. The most known process is proposed in “Using 4D CAD and Immersive Virtual Environments to Improve Construction Planning” (Yerrapathrumi, 2003). This process model is divided into three levels. Level 0 defines the inputs, controls, mechanisms, and outputs. Level 1 focuses on the 3D design model and construction methods, and level 2 represents the development of a 4D construction plan as shown in Figure 2.12.

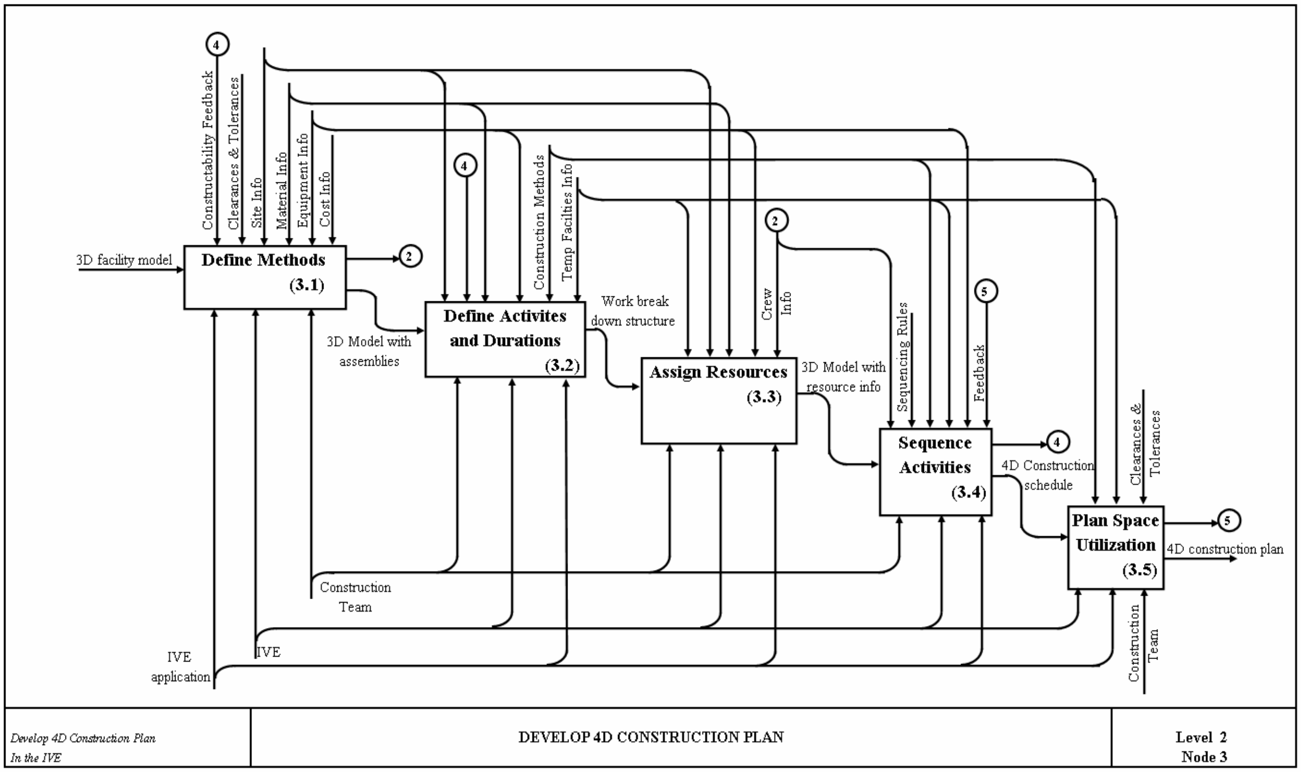


Figure 2.12 Developing a 4D construction plan (Yerrapathruni, 2003)

2.5.4 4D Modeling for Highway Projects

Urban highway projects involve complex geometry which necessitates the applications of new technologies in data communication between the involved parties. Moreover, the changing geometric configuration of such projects makes the overall project management more complicated. Regarding these issues, 4D visualization is inevitable to optimize both construction sequencing and traffic planning. For effective visualization in highway projects, the geometric database should include site model, existing and proposed models of the projects, highway context, and library of highway and traffic elements (Liapi, 2003; Vonderohe & Hintz, 2010).

Considering the impact on traffic in highway projects, the construction phasing of such projects is highly affected by traffic phasing. Several researchers have shown that 4D modeling is an essential tool for construction and traffic planning visualization in order to communicate the project information to traffic engineers and contractors. In this case, there is no need to show the adjacent buildings or to elaborate rendering. Figure 2.13 shows the 4D model used for planning in a High Five Interchange project in Dallas, Texas (Liapi, 2003).

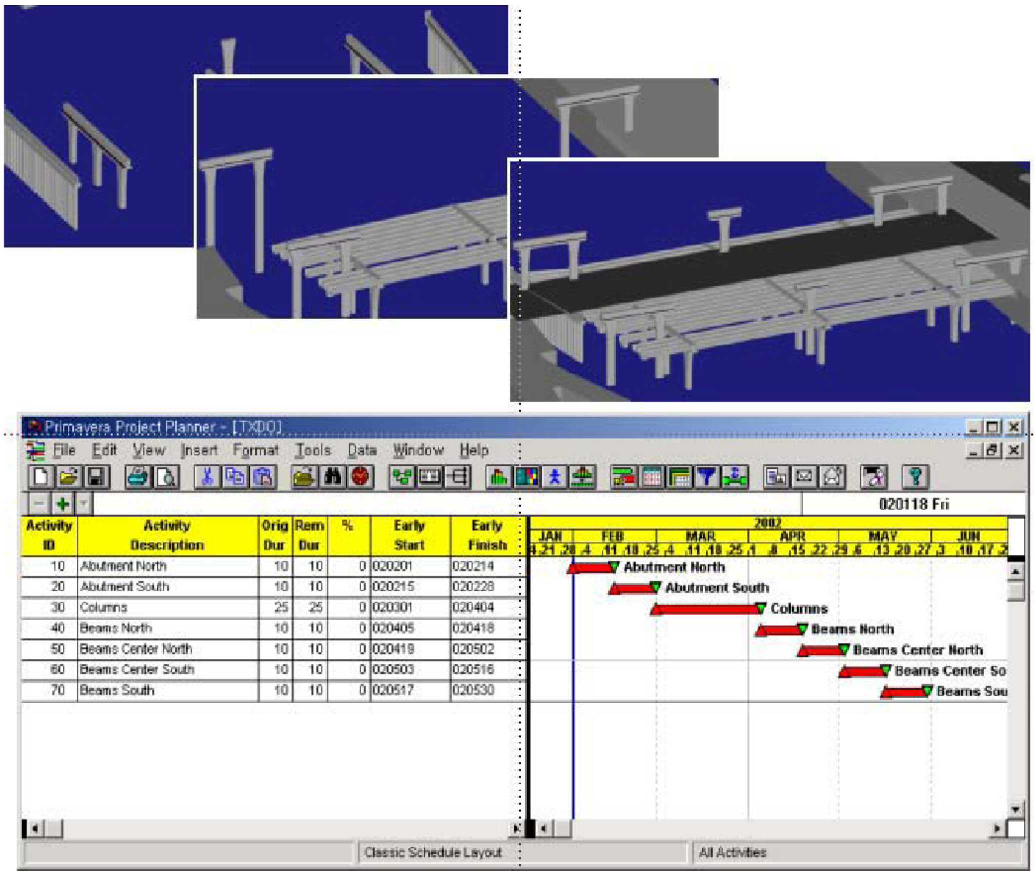


Figure 2.13 Linking 3D model with construction schedule (Liapi, 2003)

4D modeling can be also used for constructability reviews to address the challenges such as design complexity, right-of-way acquisition, and utility relocations. Figure 2.14 shows a conflict between future work and existing utility detected by the developed 4D model of President George Bush Turnpike (PGBT) project (O'Brien et al., 2012). Platt (2007) investigated the main applications of 4D CAD for highway construction projects by conducting a questionnaire and focus group discussions. Communication, planning and scheduling, safety issues, legal claims, and dispute resolution were highlighted as the main 4D applications in highway construction projects (Platt, 2007). Figure 2.15 shows the 4D CAD model of a highway interchange project developed for this study.

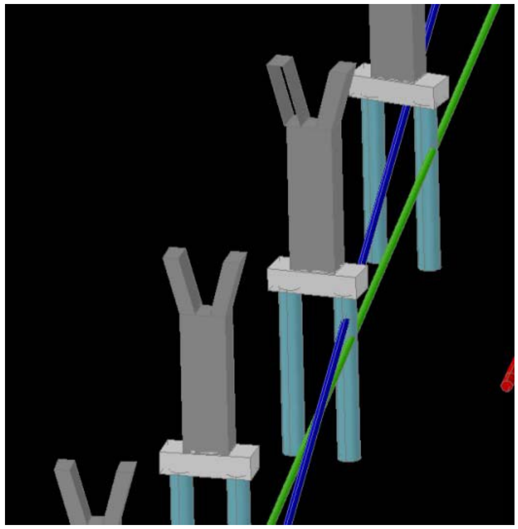


Figure 2.14 Conflict of existing utilities and new drilled shafts on PGBT Project (O'Brien et al., 2012)

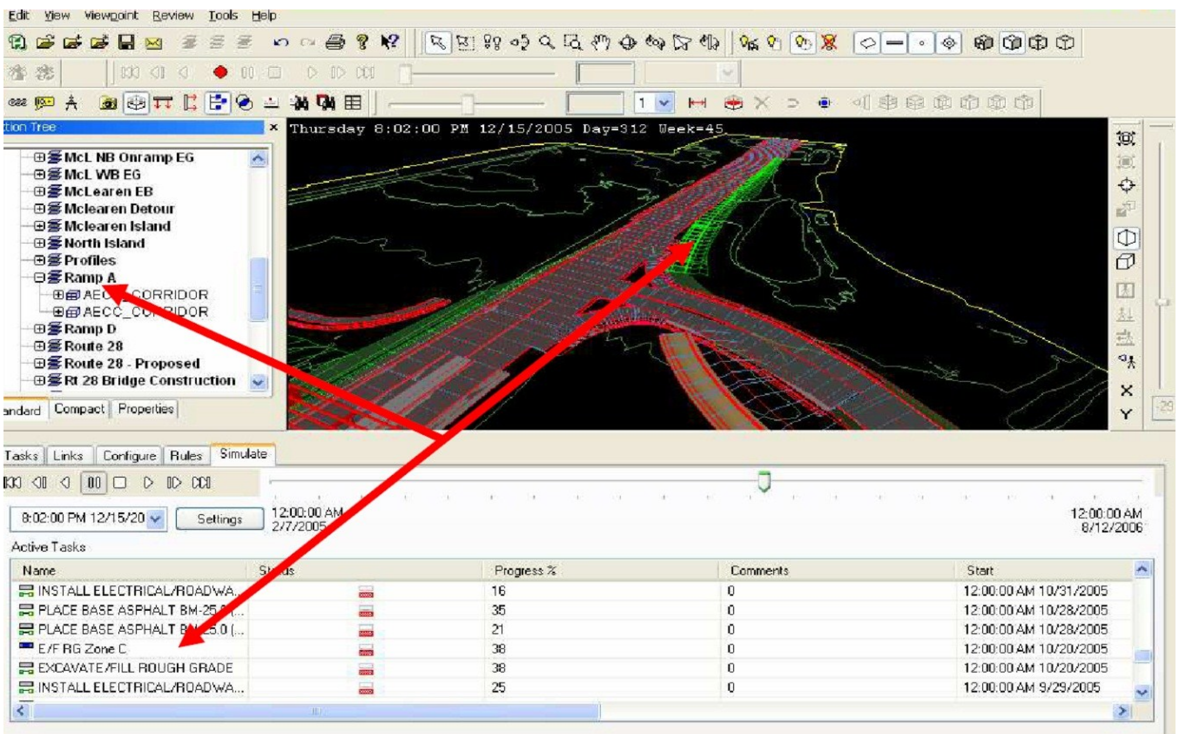


Figure 2.15 Example of 4D models: linking 3D model and schedule in Navisworks with Timeliner (Platt, 2007)

2.5.5 Clash Detection

Time and space coordination can be checked to virtually eliminate workflow issues at the planning stage (Kwak et al., 2011). Spatio-temporal conflict analysis, which is one of the key usages of 4D modeling, occurs when an activity's space requirements interfere with another activity's space requirements, or with work-in-place (Akinci et al., 2002). Two main types of spatio-temporal conflicts have been identified which are: (a) hard conflicts: interferences between physical components (e.g. conflict between old and new elevated highway structures); and (b) soft conflicts: interferences between different clearance volumes and work spaces (e.g. the space clearance required by an equipment) (Staub-French & Khanzode, 2007).

Defining clash detection setting is a simple two-step process, in which the user can define two geometry selection sets, which will be compared to each other during the clash detection process. Once the clash detection settings are defined, an automated detection can be run, the system finds the clashes, stores them in the project database, and presents a listing of the clashes.

2.6 Summary

The transportation developments are shifting from construction of new highways to reconstruction of existing facilities. As a result, a large amount of reconstruction and rehabilitation work is expected on existing highways. The most important factor in the reconstruction of urban highway projects is the duration needed for construction processes. The scheduled duration not only affects the user of highways, but it also has impact on the whole community around the project area.

There is a need for automated schedule generation because of the inability of CPM method to assess uncertainty and schedule correctness in terms of process duration for a specific amount of resources. Therefore, simulation of construction scheduling has been proposed by many researchers as a powerful tool to investigate construction schedules. Simulation techniques can be used to mimic the behavior of real-world systems over time (Law et al., 1991). Simulation in construction is used for planning and resource allocation, risk analysis, site planning and productivity measurement (AbouRizk et al., 1992; Wainer, 2009). In urban highway reconstruction projects, maintaining the traffic service in corridors is essential because of the high traffic level in urban areas. Hence, an effective traffic management plan is needed to be integrated with the construction management plan.

The literature also showed that BIM, BrIM, and related standards are under development to solve the interoperability issues in the highly fragmented AECOO industry. 4D modeling is also one of the recent computer technologies that have emerged in the AECOO industry. A considerable amount of research in the area of 4D has been done which shows the benefits of this approach. However, little research investigated the application of 4D modeling in highway projects. For instance, Liapi (2003) defined a framework for developing 4D CAD models for highway construction projects, and Platt (2007) investigated the applications of 4D modeling process in highway construction projects. Although the benefits of applying simulation and 4D modeling are proved by many researchers, the resulting benefits of integrating these two techniques are not explored. 4D modeling can study and visualize the impact of uncertainty in project schedules using the results of simulation techniques.

The performed literature review showed that there is an academic and industry interest in applying 4D modeling in planning and scheduling processes. The high level of complexity in planning and scheduling of highway reconstruction projects emphasizes the relevance of the research performed in this thesis.

CHAPTER 3 Proposed Methodology

3.1 Introduction

As mentioned in Section 2.3, the planning and scheduling phase is a major step in the success of urban highway projects and it demands a considerable amount of work due to the complexity of these projects. Elevated urban highway reconstruction projects involve complex geometry and limited space available which lead to spatio-temporal conflicts. Additionally, maintaining acceptable flow of traffic without compromising safety in highway construction zones is a major issue for planners. Overall, the phasing of construction work in such projects is complicated due to the structural complexity, large number of involved contractors, independent resource utilization planning by each contractor, and the vast number of activities that will be taking place at the same time (Dawood & Shah, 2007; Hannon, 2007).

This chapter discusses a simulation-based 4D modeling approach for planning and scheduling of elevated urban highway reconstruction projects. First, the overview of the proposed method is provided accompanied by a brief description of the workflow steps. Then, the latter sections describe the three main parts of 3D modeling, sequence assessment, and probabilistic 4D modeling of the proposed method. Clash detection as the final step of the proposed methodology is explained in Section 3.3.3, and the new benefits of the proposed probabilistic 4D modeling are highlighted in Section 3.6.

3.2 Overview of the Proposed Method

This research proposes the application of 4D modeling and simulation in the planning and scheduling phases of elevated urban highway reconstruction projects to detect spatio-temporal conflicts. The proposed methodology introduces a new approach for minimizing the risk of such problems and facilitating the planning and scheduling processes.

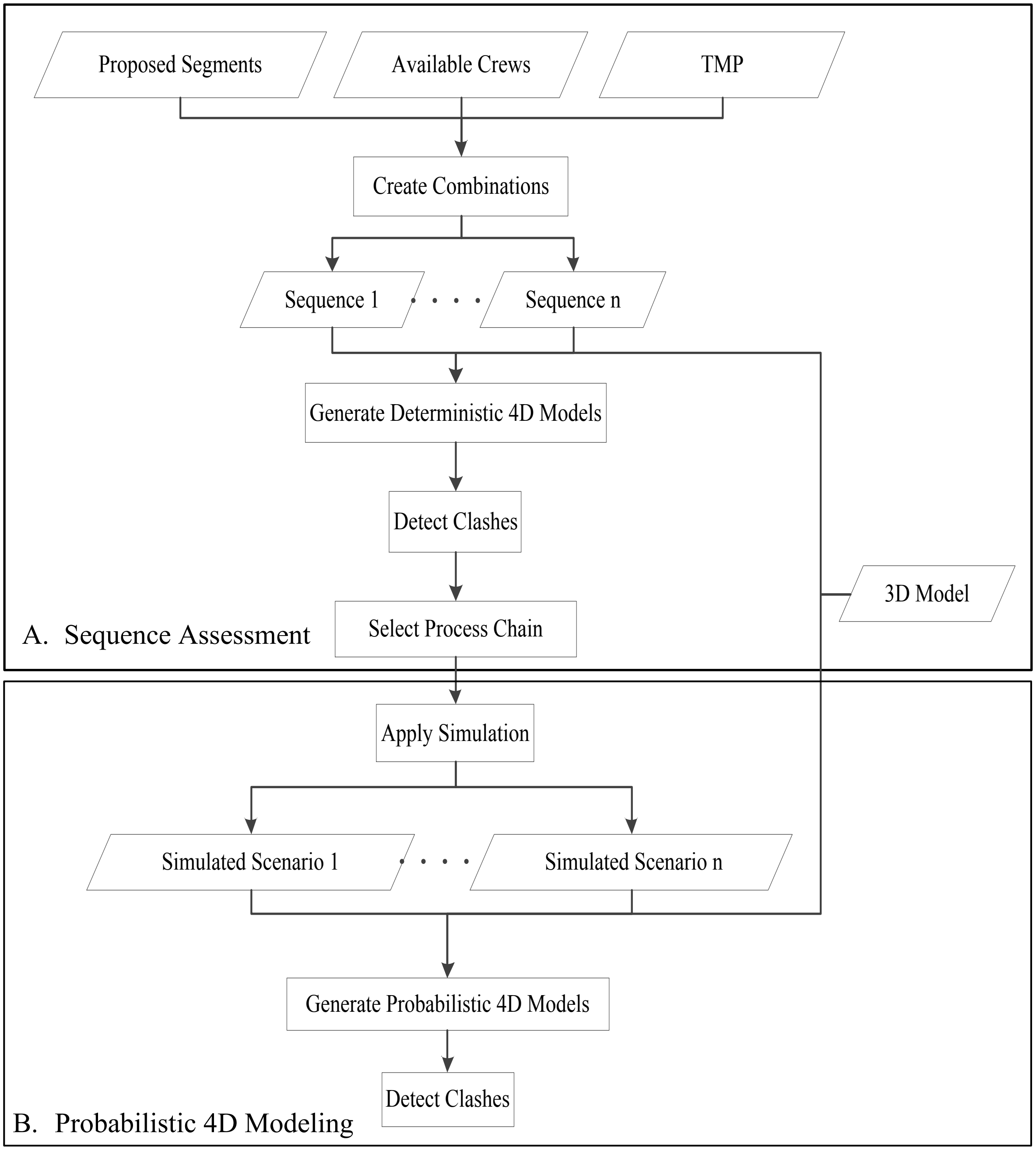


Figure 3.1 Architecture of proposed methodology

As presented in the architecture of proposed methodology shown in Figure 3.1, this research conducts a sequence assessment approach in the planning stage using a deterministic 4D model (details in Section 3.4). The deterministic 4D model is developed by linking a 3D model of the project with a deterministic schedule. The sequence assessment step aims to define the order in which the segments should be constructed or demolished based on the number of segments, number of available crews, , and the constraints imposed from TMP. The result of this step is a sequence representing a deterministic schedule which will be used as the process chain for simulation techniques. The next step is generating probabilistic schedules using simulation techniques. At the end, a probabilistic 4D model is created by linking the 3D model of the project with the generated probabilistic schedules (details in Section 3.5.2). This probabilistic 4D model is run for a large number of schedules in order to identify any potential conflicts in different scenarios. Furthermore, a method is presented to calculate the probability associated with each scenario and identifying the scenarios with the highest potential conflict. This approach can be also used to examine different starting points of demolition operations in order to avoid any potential conflicts.

Figure 3.2 shows the workflow steps of the proposed methodology. Basically, these steps are divided into three main sections of 3D modeling, sequence assessment, and probabilistic 4D modeling as explained below. The following sections provide an in-depth description of these steps and the development processes employed to create the proposed method.

3D Modeling

(A) Creating Digital Terrain Model (DTM) of the existing land by triangulating the 3D points of the ground taken from aerial photos.

(B) Defining the horizontal and vertical alignments of roads along the existing terrain in road design software. Once road corridors are generated, they are exported in LandXML format (a text-based file format which saves vector-based drawing information) in order to be used in the modeling software.

(C) Importing the LandXML file and using bridge and road modeling software to create the 3D models of the existing and new interchanges. The direct exchange of project information through LandXML allows created centerlines to be used in modeling software in order to create parametric 3D models of the existing and new interchanges.

Before initiating the modeling procedure, it is necessary to determine the desired time-space resolution as mentioned in the step C of Figure 3.2. In general, this resolution varies based on the project type, construction method, and the purpose of investigation. In this research, the investigation of project schedule is carried out based on a daily basis with respect to the chosen construction and demolition methods and the criticality of the project.

(D) Exporting the created bridge and road models into an interchangeable format suitable for the 3D visualization software. File interoperability enables the integration of models by exporting data from one application and importing it into another using a format that both applications can read.

(E) Importing the exported bridge and road models into 3D software in order to assemble the whole interchange geometry.

Sequence Assessment

(F) Creating all possible combinations of assigning crews on the desired segments based on the number of available crews, number of segments, and the constraints imposed from TMP. Considering the deterministic durations of activities in this step, each different sequence is considered as a different deterministic schedule.

(G) Linking the 3D model with different sequences representing different deterministic schedules by assigning the 3D components of the project to the relevant activities.

(H) Running developed deterministic 4D model for each different sequence.

(I) Applying clash detection by 4D modeling software in order to find an acceptable process chain as an input for simulation techniques.

Probabilistic 4D Modeling

(J) Creating a large number of possible schedules for both construction and demolition operations using Monte-Carlo and Discrete Event simulations.

(K) Linking the 3D model with probabilistic schedules thorough 4D modeling software.

(L) Running developed probabilistic 4D model for each different scenario.

(M) Applying clash detection by 4D modeling software. In this step, all types of conflicts such as hard and soft conflicts are identified.

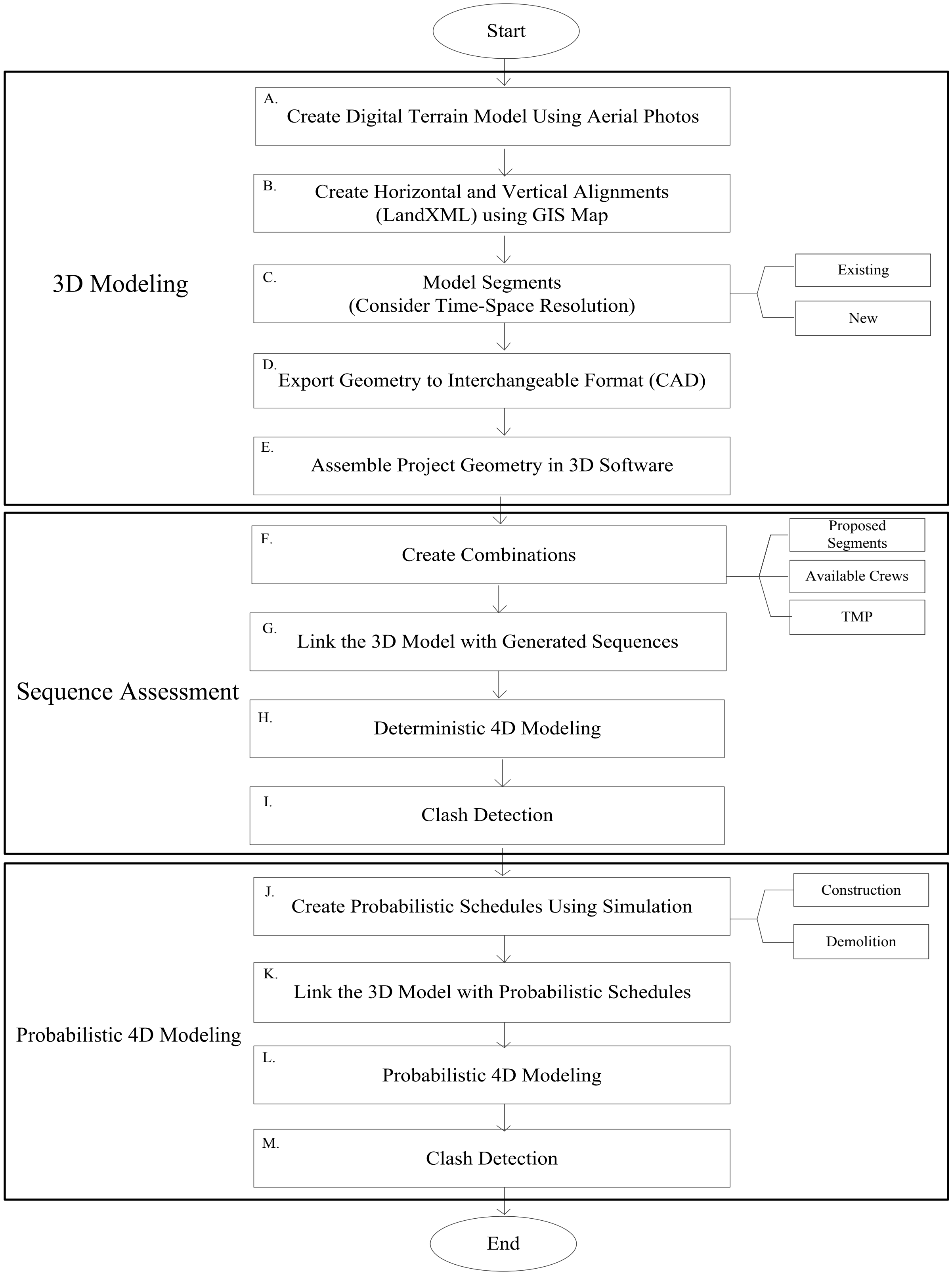


Figure 3.2 Workflow steps of proposed methodology

3.3 3D and 4D Modeling Development

3.3.1 3D Modeling

Elevated urban highway projects involve complex geometry which converts the process of 3D modeling to a laborious and heavy job. Overall, the shifting from 2D design environment to 3D modeling is considered as a significant improvement in software technologies. In order to take full advantage of 3D model, road and bridge modeling tools from different software families were used to create a parametric 3D model. Figure 3.3 shows a 3D model of a bridge created by Autodesk Revit Structure with Bridge Plug-in. As it is mentioned in Section 2.4.2, although there are several research groups working to develop an integrated bridge data model, there is no BrIM accepted standard at the time being because of the lack of software interoperability.

Even though at present 3D design software is available for highway projects, in most cases the design is created in 2D. Therefore, this research starts from 2D drawings and aims to propose a new procedure for developing a 3D model of the project. In this procedure, the 3D model is developed by using original 2D drawings and other related data. These drawings are often designed using CAD-based software and need to be converted to an interoperable format for 3D modeling software.

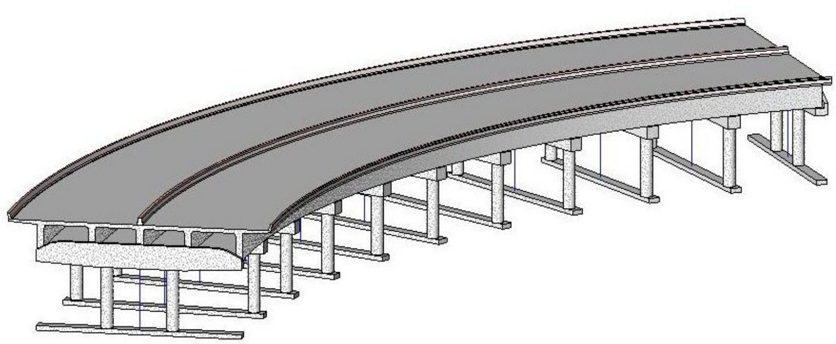


Figure 3.3 A bridge 3D model created by Autodesk Revit Structure

The first step in developing the 3D model is creating the 3D surface model of the existing land within the project's boundaries. The site model is an essential element in highway 3D modeling. This surface model as a DTM represents the topographical information of the existing land and other features such as roadway centerlines. As shown in Figure 3.4, the Triangular Irregular Network (TIN) model is generated from the 3D points of the existing land. The first step is providing 3D points of the ground, which could be collected using photogrammetry, laser scanning or surveying. In aerial photogrammetry, multiple photos of the ground are processed in a stereo plotter in order to extract the 3D points. These 3D points include the points of the top surfaces of existing buildings, highways, and other features. In order to model the existing terrain, a tedious effort is made to remove the points reflecting those features. The final step results in a TIN model by converting the 3D points to triangles. The detailed procedure for creating a TIN model is presented in Section 4.4.1. After generating the TIN model, a geo-referenced image can be draped on top of the TIN model to provide an enhanced visualization of the existing site. Figure 3.5 shows a TIN model (a) and a TIN model with draped image (b).

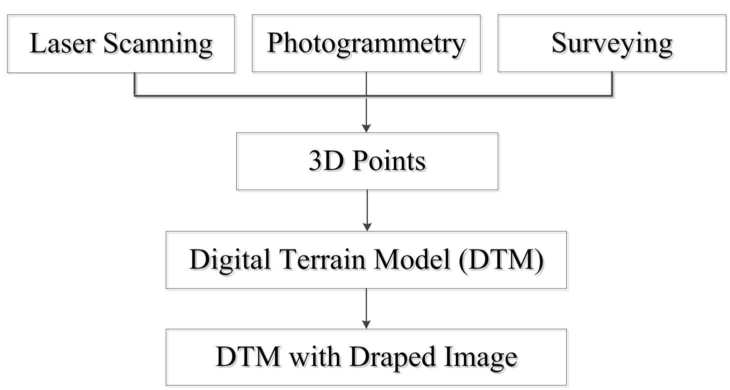
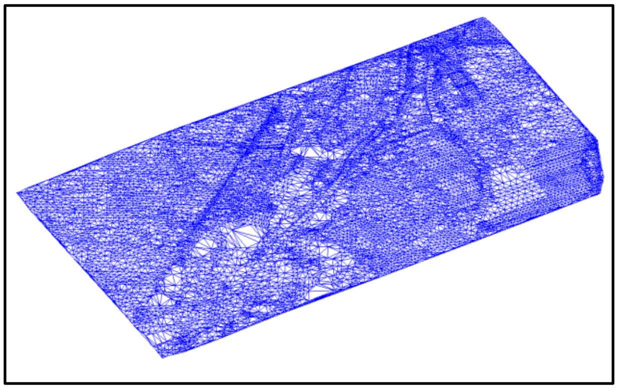


Figure 3.4 Site modeling procedure



(a) (b)

Figure 3.5 (a) TIN model, (b) TIN model with draped image

It is important to understand that all data such as 3D points and road maps (containing the road centerlines) taken from different sources should be geo-referenced. Therefore, once the surface model is generated, the 2D drawings of the highway will fit on the developed surface. In the next step, the horizontal and vertical alignments of road and bridge segments are defined along the existing land. Section 4.4.2 gives a detailed process of creating horizontal and vertical alignments. Figure 3.6 shows an example of a profile including vertical alignments representing the elevation of a bridge superstructure (upper line) and the related cross section of the existing land (dashed line).

The next step is creating the 3D model of each segment based on the generated horizontal and vertical alignments. Each generated alignment must be exported to a compatible format (LandXML) in order to be used in the modeling software. After creating all segments, the whole 3D model of the project is integrated by merging all the created segments together. To do so, each segment is exported to an interchangeable format supported by the integrating software. Having a parametric 3D model of the project facilitates the process to link the objects of the 3D model with the corresponding activity from the schedules. In other words, the created objects are not just simple shapes, but they represent the actual components of the project such as abutments, piles, and girders.

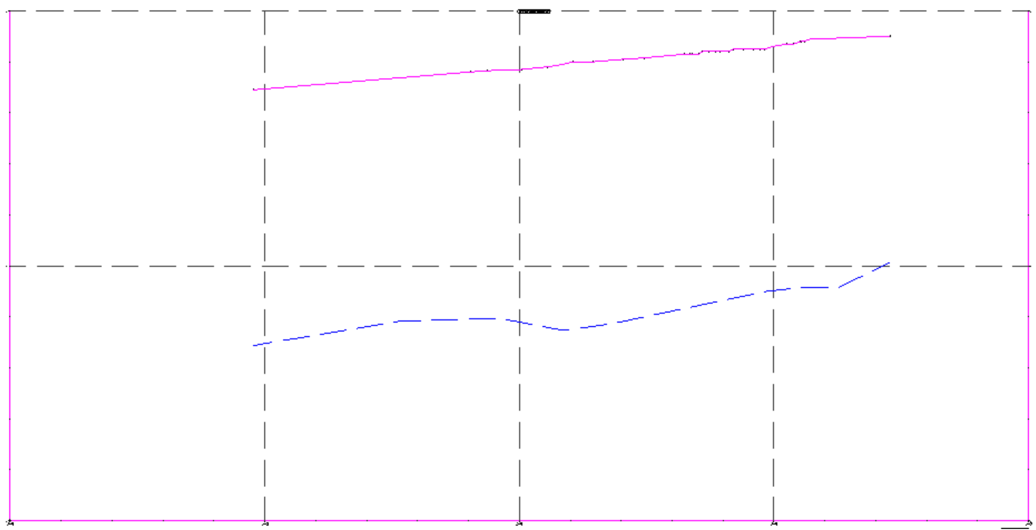


Figure 3.6 A profile showing a vertical alignment generated

3.3.2 4D Modeling

As mentioned before in Section 2.5.3, product and process models are the two main elements in creating a 4D model. Product model represents the physical components of the project, and process model defines the order of schedule activities. These two models have to be defined, and their level of complexity is based on the desired level of detail needed for each project with respect to the time-space resolution as explained in Section 3.2. Figure 3.7 shows a hierarchy of level of detail in a bridge product model.

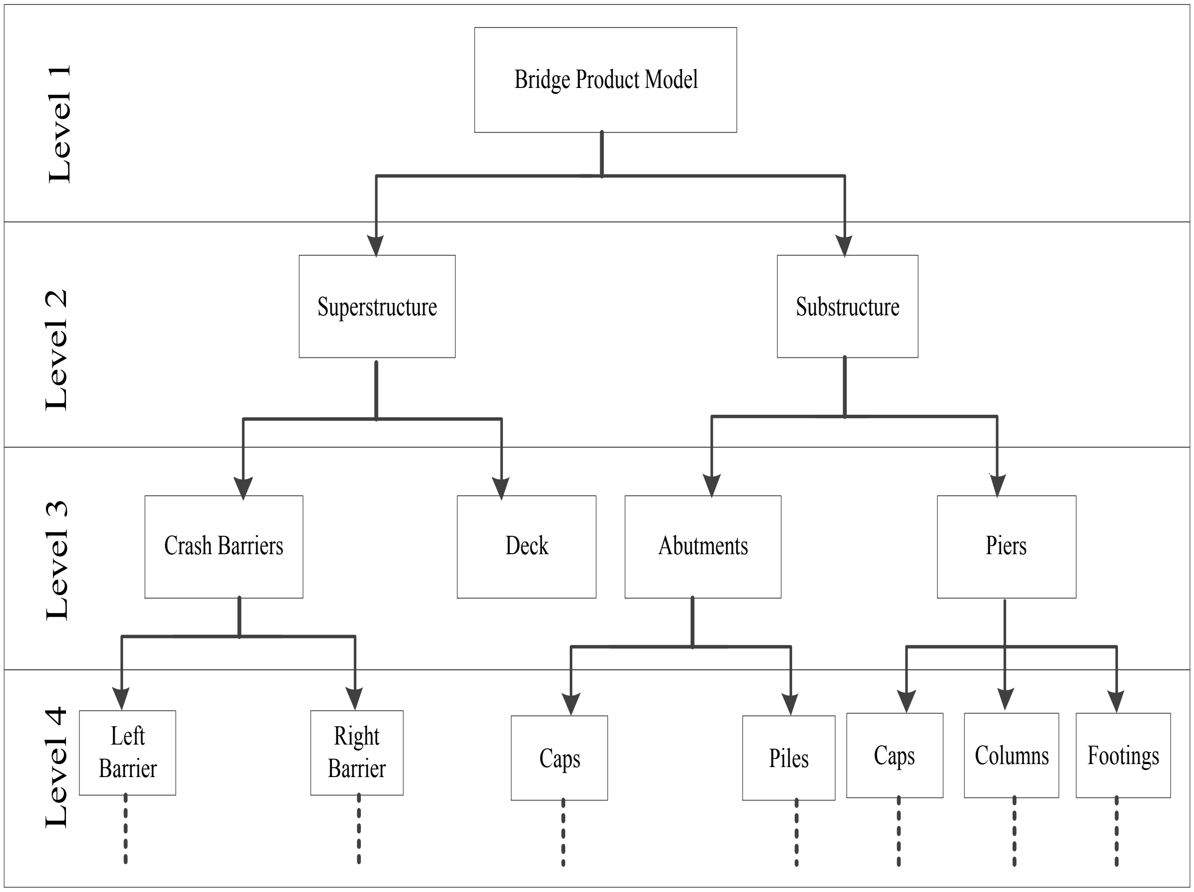


Figure 3.7 Levels of details in a bridge product model

As explained in Section 2.5.3, a 4D model is defined as a 3D model of the project linked with the construction schedule. Basically, the main task for generating a 4D model is the linkage between the product and process models. In the proposed probabilistic 4D model, this step needs to be automated due to the large number of generated schedules. Interconnecting software can provide this ability by defining rules such as mapping a component to the relevant activity of the process model with the exact same name in a semi-automated way. Based on the desired level of details considered in modeling procedure, each component of the product model is saved with the same name as the corresponding activity's name from the process model. Therefore, the linkages between the components and relevant activities are semi-automated by importing each generated schedule. As shown in Figure 3.8, the output of simulation is used to generate different scenarios of schedules by traditional scheduling software. In other words, the result of each replication of simulation is used to create a different scenario. This process also needs to be automated because of the large number of replications. There are a number of tools available that can be used to generate Monte-Carlo simulation within the traditional scheduling software such as Microsoft Project. Although these tools are just used to generate Monte-Carlo simulation within the scheduling software, this integration can be considered as a starting point to automatically create different schedules using the result of each replication. Eventually, each generated schedule resulting from traditional scheduling software is imported by interconnecting software to generate the proposed probabilistic 4D model. At the same time, the created 3D model of the project is exported to an interchangeable format in order to be used in interconnecting software.

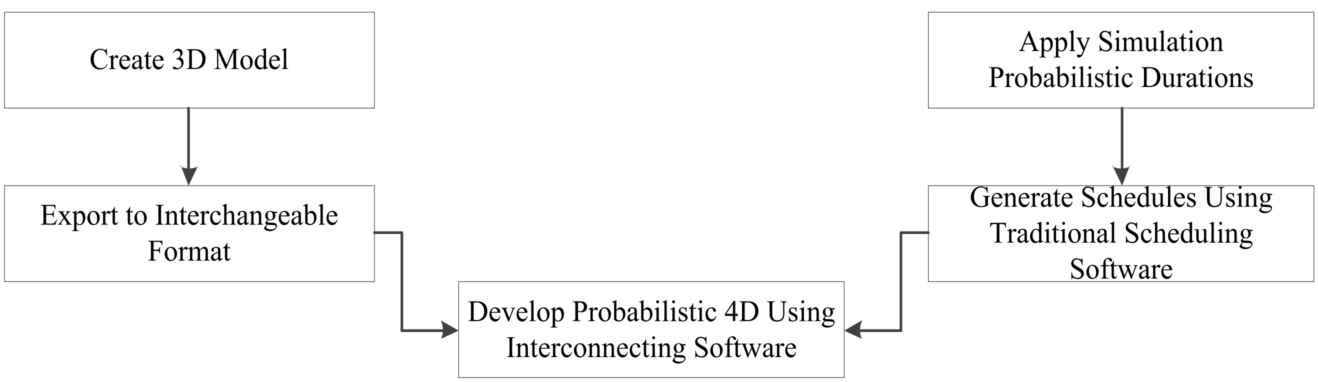
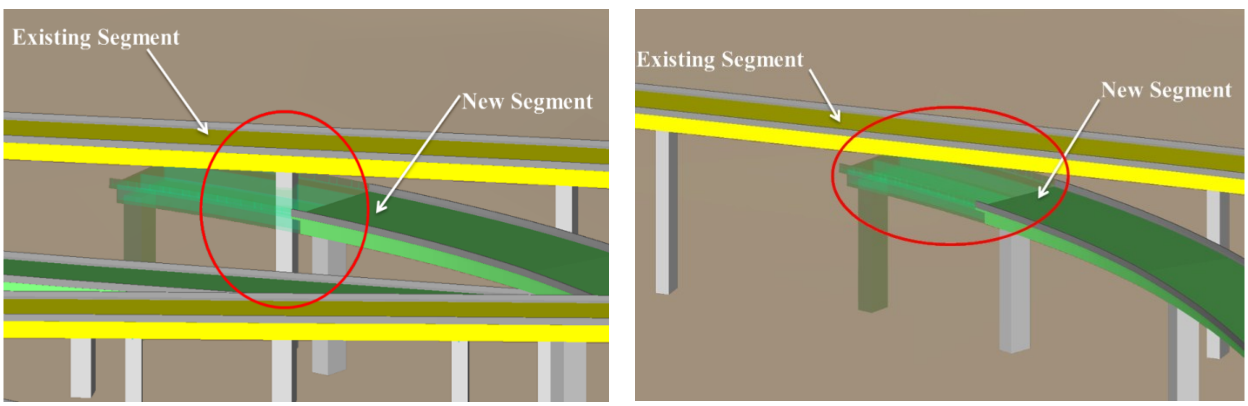


Figure 3.8 Development of proposed probabilistic 4D model

3.3.3 Clash Detection

Applying probabilistic 4D modeling generates a large number of different scenarios which need to go through the clash detection process. This process is simply done by defining two selection sets for construction and demolition geometries. Once the process runs, the two selection sets will be compared to each other and will result in a list of clashes. There are usually many duplicate instances of the same clash which necessitates applying a process to analyze the identified clashes.

This research aims to identify both hard conflicts resulting from the interferences between physical components (e.g. conflict between old and new elevated highway structures), and soft conflicts where there are interferences between clearances and work spaces (e.g. the space clearance required by an equipment). Figure 3.9 shows a hard conflict between the superstructure of the a segment and a pier of the existing segment (a), and a soft conflict resulting from the lack of available space needed for crews to progress (b).



(a) (b)

Figure 3.9 (a) Hard conflict, and (b) soft conflict

3.4 Sequence Assessment

There are a large number of activities in large scale elevated urban highway reconstruction projects. As a result, a large number of different sequences are possible due to the multitude of requirements, technological dependencies, and needed resources. Finding the optimum sequences is difficult since the current highway is demolished while the newly designed one is under construction. Scheduling these projects demands a high level of coordination between different work flows to avoid any physical and time-space conflicts. Any delay in a process may lead to a conflict because different sequences of activities are carried out concurrently. Because of the large number of activities and different possible sequences in these projects, it is tedious to find potential conflicts just by going through the 2D drawings and relevant schedules.

In the sequence assessment approach proposed in this research (Figure 3.1, Part A), the objective is to define the order in which the segments should be planned for construction or demolition. First, all the possible sequences are generated based on different strategies of resource allocation. In other words, all different combinations of assigning crews to the desired segments are created based on the number of segments, number of available crews, , and the constraints imposed from TMP. Considering the deterministic durations assigned to the activities, each sequence represents a different deterministic schedule. Next, each schedule is linked with the 3D model of the project for the purpose of running the clash detection process. By analyzing the identified conflicts, the sequence which has the least duration and no conflicts is selected as the process chain for simulation techniques.

Before creating different sequences, it is necessary to count the number of possible combinations. Equation 3.1 calculates the number of different combinations when crews have the same production rate and the amounts of work assigned to each crew are equal. Moreover, the continuity of work in each segment is considered as a critical factor in scheduling linear projects. In other words, by allocating a crew to each specific segment, that crew is kept to fully deliver the assigned segment. It is also assumed that both construction and demolition processes can start from both sides of the segments.

$$x = 2^s \times \prod_{n=0}^{\left[\frac{s}{c}-1\right]} \binom{s-nc}{c} \qquad \text{Eq. (3.1)}$$

The derivation of this equation is given below where c is the number of available crews, s is the number of segments, and $c < s$. As the first assignment, c distinct segments are randomly resulting in $\binom{s}{c}$ combinations. Since in selecting segments the order does not matter (starting at the same time with equal crews), the equation is formulated in combinations (unlike permutations which consider the arrangements of segments in particular orders). For example, if the number of segments is four and there are two crews available, the first action is a combination of $\binom{4}{2}$. Assuming $c <$ remaining s, this action is repeated n times until the condition $s - nc \leq c$ is reached which means the number of remaining segments is less than the number of crews (the number of combinations is equal to one when $s < c$), and the condition can be written as:

$$s - nc \leq c \ \Rightarrow s \leq (n+1)c \Rightarrow \frac{s}{c} - 1 \ \leq n$$

And since n is an integer, $\Rightarrow n = \left[\frac{s}{c} - 1\right]$

Considering that all the combinations are independent, the total number of combinations is:

$$\prod_{n=0}^{\left[\frac{s}{c}-1\right]} \binom{s - nc}{c}$$

Assuming two starting points for each segment would multiply the total combinations by 2^s resulting in equation 3.1.

Figure 3.10 shows a simple example of an interchange consisting of 4 segments. Each segment has two starting points (marked with arrows) which results in 8 total starting points. Assuming there are 2 crews available gives the following according to Equation 3.1:

$c = 2$
$s = 4$
$x =$ number of combinations

$x = 2^4 \times \prod_{n=0}^{1} \binom{s-nc}{c} = 2^4 \times \binom{4}{2} \times \binom{2}{2} = 96$

Based on the mentioned above assumptions, there are 96 different combinations for this case. Obviously, this equation does not consider the cases involving crews with different production rates which are difficult to represent and are beyond the scope of the current thesis. For those scenarios with different crews and different amounts of work assigned for each crew, an intelligent system is needed to take into consideration all the mentioned variables. Future research should apply optimization techniques to fully optimize this step and select the optimum sequence as the process chain for simulation process. Although constraint-based simulation (Wu et al., 2010) can be used to overcome the limitation of fixed process chain, different strategies of allocating resources and continued utilization of resources should be considered for the sequence assessment of highway projects.

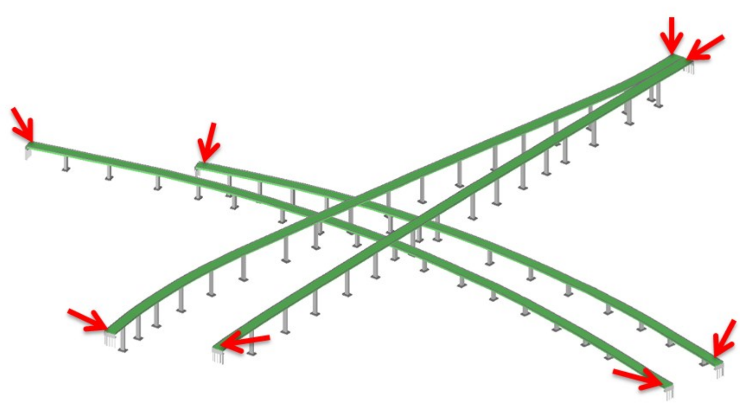


Figure 3.10 Simple interchange with 8 starting points

3.5 Simulation and Probabilistic 4D Modeling

Traditionally, scheduling of highway construction projects can get very complicated in terms of checking schedule correctness, especially the total duration for a specific amount of resources, and finding spatio-temporal conflicts that may result from the limited space available. These conflicts may lead to delays in the project and overrun in project budget. The proposed method aims to integrate simulation techniques and 4D modeling to detect spatio-temporal conflicts.

3.5.1 Simulation-based Schedule Generation

As mentioned in Section 2.3.2, simulation is a powerful tool which can be applied to investigate the uncertainty involved with schedules. This research applies two different simulation techniques, Monte-Carlo and Discrete Event simulations, in order to generate the schedules based on different levels of available details. Monte-Carlo simulation uses the assigned durations of activities to calculate the total project duration using pre-defined network. In other words, Mote-Carlo studies the impact of uncertainty by assigning a variation to the duration of each activity. However, Discrete Event simulation estimates the project duration and productivity rate of the operation by studying the interaction between different resources.

(1) Monte-Carlo Simulation-based Scheduling

Monte-Carlo simulation is applied to study the impact of uncertainty in scheduling construction activities. The result of Monte-Carlo integrated with 4D modeling is applied for minimizing the risk of time spatio-temporal conflicts and facilitating the planning and scheduling process. In order to develop a Monte Carlo simulation, activities should have probabilistic distribution of the durations, such as the normal distribution, instead of deterministic ones. Monte-Carlo simulation will run several times resulting in different schedules in each run which are linked with the 3D model to generate the probabilistic 4D models as will be explained in Section 3.5.2. Moreover, time and space coordination can be checked to virtually eliminate workflow issues at the planning stage.

(2) Discrete Event Simulation-based Scheduling

A Discrete Event simulation of elevated urban highway reconstruction projects is applied in order to estimate the productivity rate and durations of construction and demolition activities in highway elevated projects. This approach will consider the construction method, the number of crews utilized, and the potential spatio-temporal conflicts between the equipment and the existing structures. Discrete Event simulation models are developed by breaking down activities into tasks. Each of these tasks' durations is presented by a probabilistic distribution, such as the normal distribution, instead of a deterministic one. Discrete Event simulation will run a large number of times resulting in a different schedule in each run. In the same manner as in the case of Monte-Carlo simulation, these schedules are linked with the 3D model to generate the probabilistic 4D models and to identify the critical activities which have high potential of creating conflicts. Two simulation models were developed to mimic the construction of a full-span pre-cast concrete box girder bridge using launching gantry and the demolition of a concrete box girder bridge using cut-and-lift method:

Construction operations

The developed simulation model of bridge construction using launching gantry is shown in Figure 3.11 (Mawlana et al., 2012). This construction method has been used in several projects around the world (Benaim, 2008; Hewson, 2003). The simulation starts by initializing the queues that hold the resources needed for the construction operations. Next, a trailer will be driven to be loaded with a pre-cast concrete box girder span using a gantry crane available in the yard. Then, the trailer will travel to the construction site where the onsite crane will unload the pre-cast span and load it to a trolley. After being unloaded, the trailer will return to the pre-cast yard to be loaded again. At the same time, the trolley will travel to the point where the span will be launched. When the trolley reaches the desired location, the launching gantry will reposition to the new span's location. Then, the launching gantry will pick up the span from the trolley. Afterwards, the trolley will return to be loaded again. At the same time, the launching gantry will place the new span in its location. Finally, the stressing crew will post-tension the new span.

Demolition operations

The developed simulation model of bridge demolition using the cut-and-lift method (Hammad et al., 2007) is shown in Figure 3.12 (Mawlana et al., 2012). In this method, two crawler cranes are used to lift the span after being cut by diamond saw wires and place it on a trailer to be transported to the dumping site. The simulation starts by initializing the queues that hold the resources needed for the demolition operations. Next, the preparing team will prepare the span so that it can be ready for rigging before moving to the next span. Then, the rigging team will hook the span to the cranes. After being hooked, the saw team will start cutting the span at both ends. Afterwards, the loading team will place the span on a trailer which will go to the dumping site to be dumped. Then, the loading team will reposition to be ready for the next span. When the trailer is unloaded, it will go back to the demolition site to be loaded again.

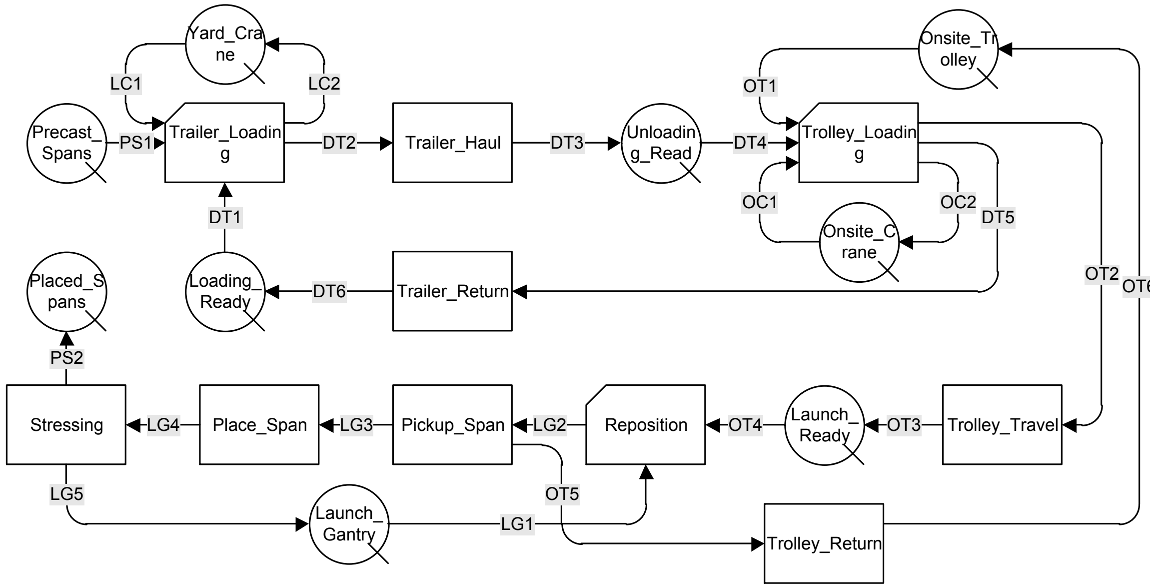


Figure 3.11 Simulation model for construction operations (Mawlana et al., 2012)

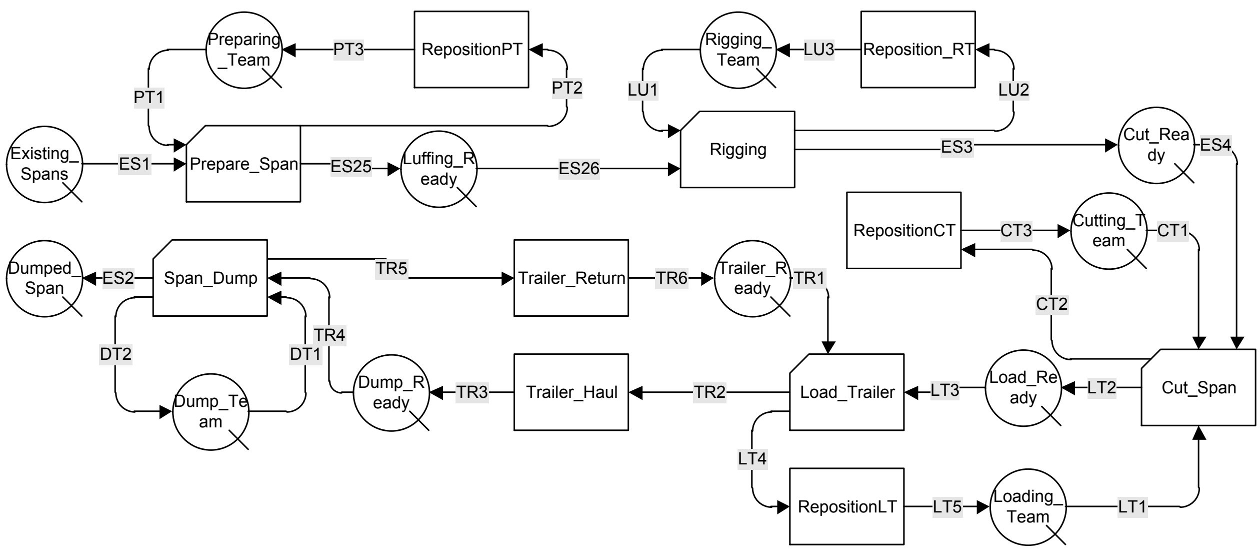


Figure 3.12 Simulation model for demolition operations (Mawlana et al., 2012)

3.5.2 Probabilistic 4D Modeling

As the proposed 4D model reflects the probabilities of generated schedules from the embedded variations in each project task, the developed 4D model is called probabilistic 4D model where in each selected schedule *i,* there is a probability assigned to the duration of each activity *j.* For instance, the duration of activity j in schedule i (t_{ij}) is associated with a specific probability p_{ij} corresponding to it. S represents all the simulated schedules, and matrices P and T represent the durations and their associated probabilities of all the activities involved in construction and demolition processes. These two matrices will be used to link with the 3D model in order to generate the probabilistic 4D model.

$$S = \left(t_{ij}, p_{ij} : \forall i \in \{1,2,3,\dots,m\}, \forall j \in \{1,2,3,\dots,n\} \wedge \forall t_{ij} \in T \wedge p_{ij} \in P\right)$$

m : number of schedules
n : number of activities

$$T_{m\times n} = \begin{bmatrix} t_{11} & \cdots & t_{1j} & \cdots & t_{1n} \\ \vdots & & \vdots & & \vdots \\ t_{i1} & \cdots & t_{ij} & \cdots & t_{in} \\ \vdots & & \vdots & & \vdots \\ t_{m1} & \cdots & t_{mj} & \cdots & t_{mn} \end{bmatrix} \quad P_{m\times n} = \begin{bmatrix} p_{11} & \cdots & p_{1j} & \cdots & p_{1n} \\ \vdots & & \vdots & & \vdots \\ p_{i1} & \cdots & p_{ij} & \cdots & p_{in} \\ \vdots & & \vdots & & \vdots \\ p_{m1} & \cdots & p_{mj} & \cdots & p_{mn} \end{bmatrix}$$

Using these probabilities, this research proposes a method to identify the scenarios with the highest potential conflict and to calculate the probabilities associated with those scenarios. This method is summarized in the following steps:

(A) Running probabilistic 4D model for each schedule i

(B) Detecting a potential conflict in schedule i, and stopping the 4D simulation at the point of identified conflict. As shown in Figure 3.13, a simple network consisting of both construction and demolition operations is presented to explain the following steps. By running the probabilistic 4D model, a point of conflict is detected which is marked with an oval.

(C) Isolating the segments of construction and demolition processes ending up at that conflict.

(D) Generating combined probability distributions ($f_1(x)$ and $f_2(x)$) for the construction and demolition operations till the point of conflict, respectively. The combined distributions are generated based on the probability of all activities involved in each operation. Figure 3.14 shows the probability distributions (in this case normal distribution) assigned for each activity, and Figure 3.15 shows the combined distribution generated for each operation till the point of conflict.

(E) Identifying all the scenarios which lead to that conflict. Clearly, all the scenarios in which the finishing time of the demolition operation (F_D) exceeds the finishing time of the construction operation (F_C) have potential conflicts ($F_C < F_D$). Figure 3.16 shows the overlap interval between the two generated distributions representing the interval of potential conflict.

(F) Calculating the probability associated with each scenario of potential conflict, and highlighting the scenarios with the highest potential conflict. In this case, the conflict interval is 8 to 12.8 days, and the scenarios with the highest potential conflict are found at day 10.

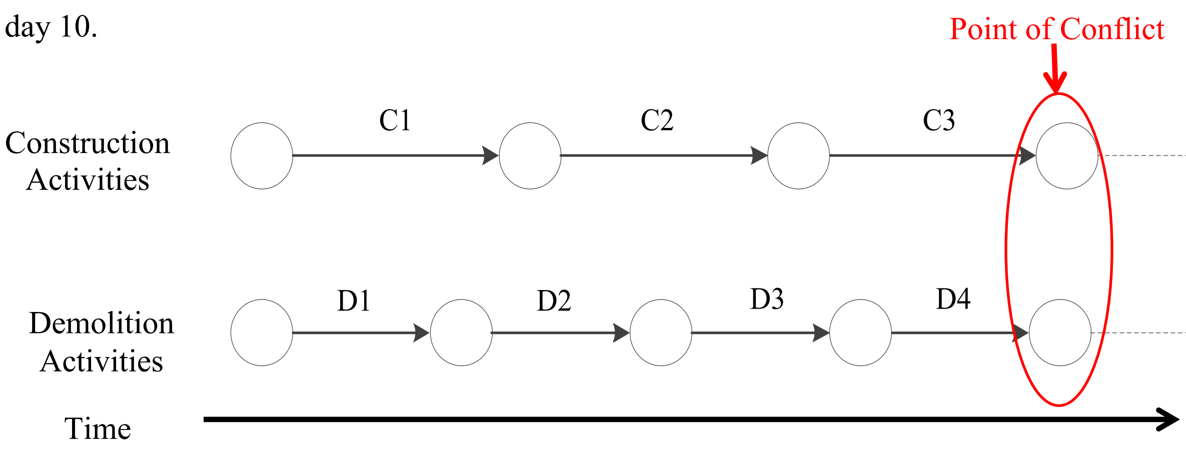


Figure 3.13 Simple network consisting of construction and demolition operations

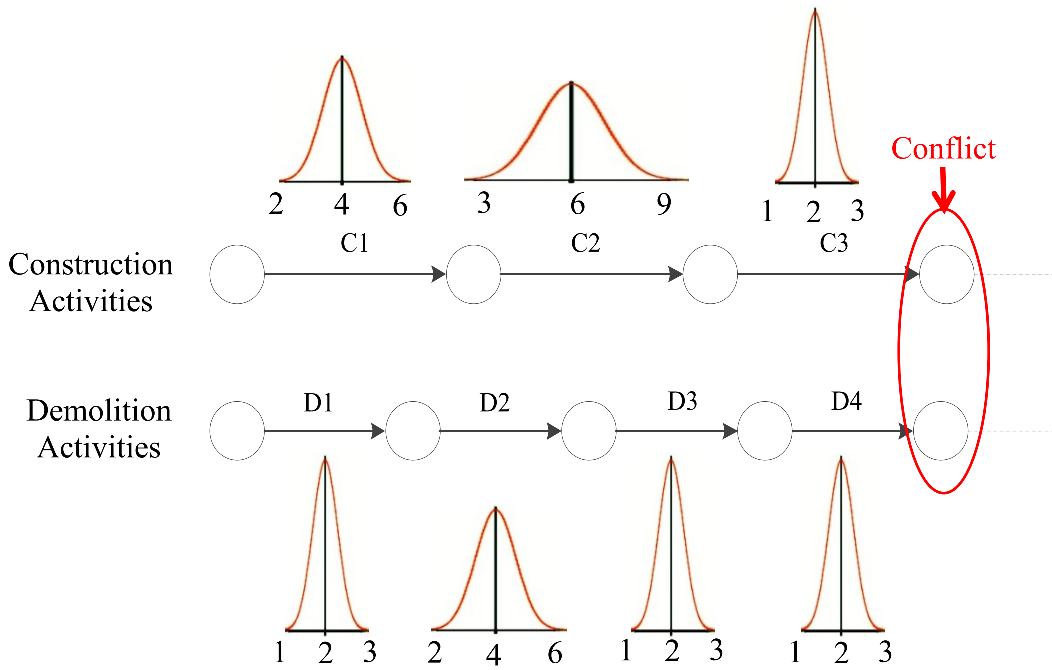


Figure 3.14 Probability distributions assigned for each activity

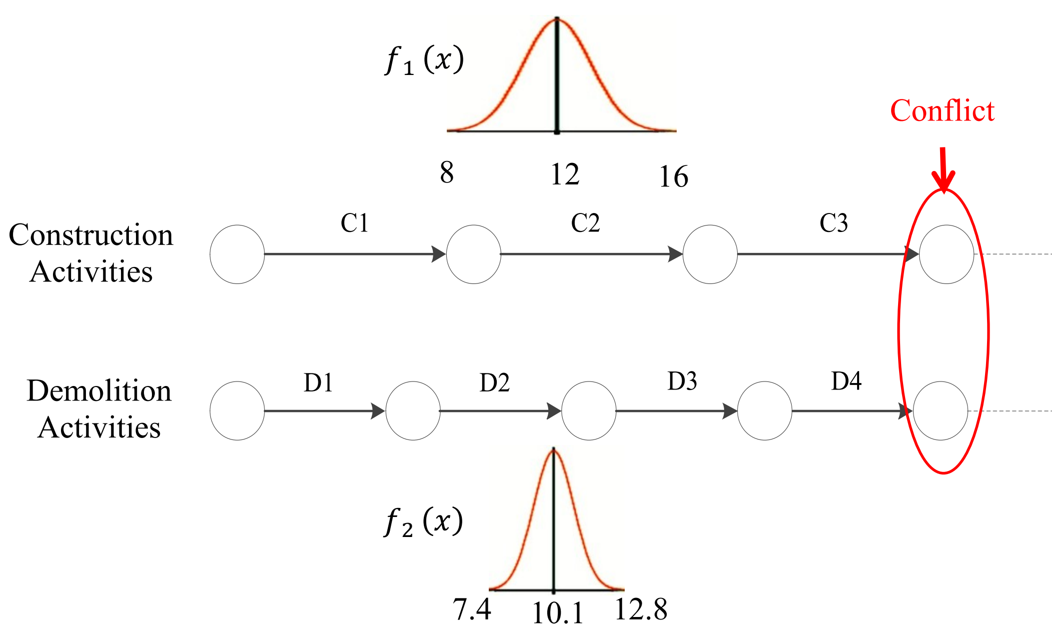


Figure 3.15 Combined probability distributions for each operation

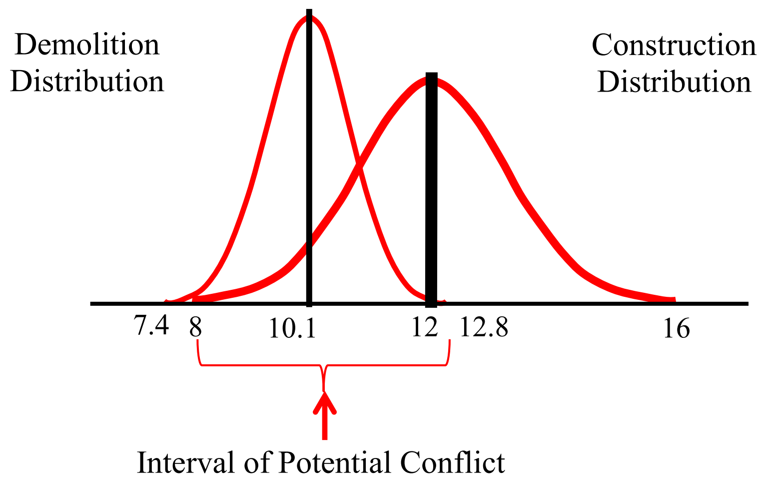


Figure 3.16 Example of overlapping distributions in the case of demolition and construction activities starting at the same time

Calculating Conflict Probability

To identify the point with the highest potential conflict and to calculate its associated probability, the probability of all the scenarios with potential conflict within the interval should be calculated. The probability of each date (point of time) within the interval is the multiplication of the probability of finishing the construction operation at that date by the probability of finishing the demolition operation with a duration exceeding that date which satisfies the inequality $F_C < F_D$. To calculate the probability of finishing the construction operation at point x, a strip dx representing a unit of time is assigned to that point where x is the midpoint of dx, and the probability of this point is equal to the area under the curve of $f_1(x)$ between $\left(x - \frac{dx}{2}\right)$ and $\left(x + \frac{dx}{2}\right)$, which can be written as:

$\int_{x-\frac{dx}{2}}^{x+\frac{dx}{2}} f_1(x)$, where $f_1(x)$ is the function of the construction probability distribution.

The probability of finishing the demolition operation longer than this point (x) is equal to the area under the demolition probability distribution from $\left(x - \frac{dx}{2}\right)$ till infinity, which is:

$\int_{x-\frac{dx}{2}}^{+\infty} f_2\,(x)$, where $f_2\,(x)$ is the function of the demolition probability distribution.

Consequently, the probability P of the potential conflict at each selected point is:

$$P = \int_{x-\frac{dx}{2}}^{x+\frac{dx}{2}} f_1\,(x) \times \int_{x-\frac{dx}{2}}^{+\infty} f_2\,(x)$$

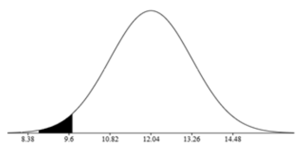
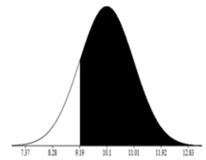
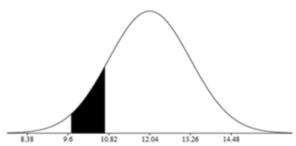
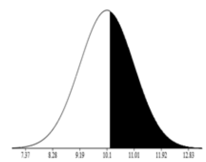
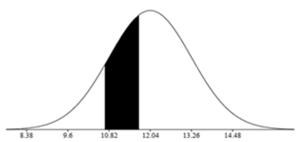
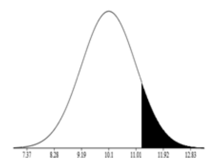
Table 3.1 shows the probability of three selected points within the interval including the point with the highest potential conflict (Scenario 2).

Selecting Starting Date for Demolition Operation

Selecting a starting date for the demolition operation in order to avoid any potential conflict is important in highway reconstruction projects. One of the applications of the proposed method is examining different starting dates for a demolition operation. This method is capable of calculating the probability of scenarios with a potential conflict when the starting date of demolition operation is changed just by sliding the probability distribution of the demolition operation. In other words, when the starting date of the demolition operation occurs earlier by X days, the corresponding probability distribution slides X days to the left which results in a different overlap interval and a corresponding lower probability of the potential conflict.

Figure 3.17 shows an example in which the demolition operations starts 2 days earlier compared to the previous example shown in Figure 3.16 where construction and demolition start at the same time.

Table 3.1 Probability of different points within the conflict interval

Scenarios	Construction Duration → Probability	Demolition Duration → Probability of Potential Conflict	Combined Probability
1	 $F_c = 9$ → 1.68%	 $F_d > 9$ → 88.92%	1.49%
2	 $F_c = 10$ → 8.7%	 $F_d > 10$ → 54.42%	4.73%
3	 $F_c = 1$ → 23.28%	 $F_d > 11$ → 15.87%	3.69%

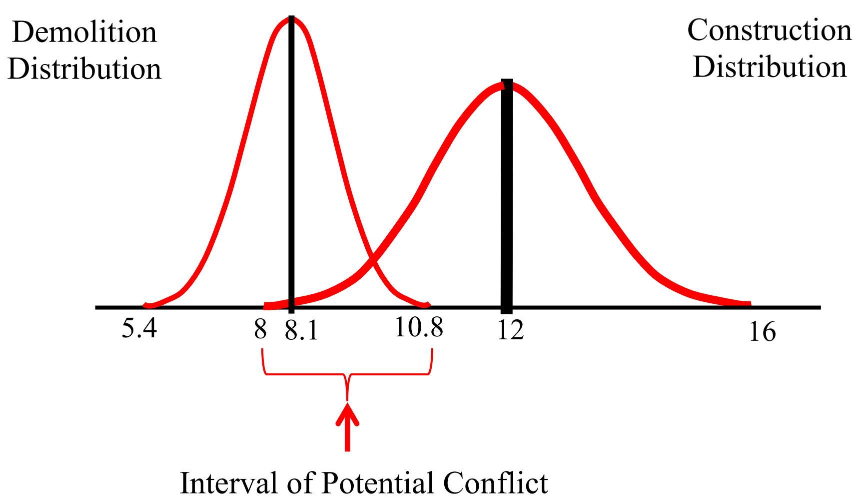


Figure 3.17 Example of Overlapping distributions in the case of demolition and construction activities not starting at the same time

3.6 Benefits of Proposed Probabilistic 4D Modeling

As mentioned in Section 2.5.3, the 4D modeling process has been used by several researchers in past years. Different applications of 4D modeling have been investigated such as communication applications, visualization of project plan and schedule, and conflict detection. Other 4D modeling applications such as legal issues and dispute resolution are also identified as the future applications. The proposed probabilistic 4D modeling approach in this research is capable of delivering all the above-mentioned benefits and the following new benefits for highway reconstruction projects:

(1) Shifting from construction to reconstruction projects in transportation development has introduced the demolition operation as a parallel process to construction. The proposed 4D modeling approach identifies potential conflicts when both construction and demolition operations are carried out at the same time.

(2) This research investigates the application of 4D modeling for sequencing in the planning phase with the purpose of finding an acceptable sequence as the process chain for simulation techniques. The proposed method is used to assess all the possible sequences in order to find the sequence with the least duration and no conflict. However, the proposed 4D model is also capable of visualizing construction schedule and phasing. Other applications of 4D modeling in the planning and scheduling phases are reviewing schedule, highlighting milestones, and confirming job orders.

(3) The probabilistic 4D modeling approach introduced a method to identify the scenarios with the highest potential conflict, and also to calculate the probability associated with each scenario. This method can be used for examining different starting points of the demolition operation in order to avoid any potential conflict.

(4) This research applied 4D modeling procedure to evaluate different construction and demolition methods and equipment. Simulating a construction operation with the visualized equipment in a virtual space can identify the hard and soft conflicts for each chosen method and equipment as example is shown in Chapter 4.

3.7 Summary and Conclusions

Planning and scheduling of elevated urban highway reconstruction projects are time consuming and difficult due to the complexity of such projects. Elevated urban highway reconstruction projects involve complex geometry and limited space available which lead to spatio-temporal conflicts. This research has proposed a simulation-based 4D modeling approach for planning and scheduling of elevated urban highway reconstruction projects, and the main conclusions are:

(1) Considering the intensive amount of reconstruction work needed for existing highways, this research has proposed the application of 4D modeling and simulation in the planning and scheduling phases of such projects to detect those spatio-temporal conflicts. The proposed methodology presents a sequence assessment approach in the planning stage using a deterministic 4D model. The sequence assessment method aims to define the order in which the segments should be constructed or demolished. The result of this step is a sequence which will be used as the process chain for simulation techniques.

(2) Furthermore, this research has investigated a simulation-based probabilistic 4D modeling approach for scheduling of elevated urban highway reconstruction projects. A probabilistic 4D model is created by linking the 3D model of the project with generated probabilistic schedules provided from Monte-Carlo or Discrete Event simulations. This probabilistic 4D model is run for a large number of schedules in order to identify any potential conflicts

involved with different scenarios. The proposed approach is capable of identifying the scenarios with the highest potential conflict and calculating the probability associated with each scenario. Different starting points of demolition operation can be examined in order to avoid any potential conflicts.

(3) This chapter has also suggested a new process for realizing the proposed methods by integrating a variety of available tools (GIS, road and bridge design tools, aerial photos, scheduling tools, and simulation tools). A new approach of 3D and 4D modeling development process is employed to realize the proposed methodology of this research.

CHAPTER 4 Case Studies

4.1 Introduction

This chapter provides an in-depth description of three case studies. The project chosen (The Turcot Interchange) for this research is the same in all cases; but in each case a different research objective is validated. This chapter provides the background information of the chosen project and describes the 3D modeling development processes and the proposed methodology steps to realize the three cases. The objective of Case 1 is to conduct the proposed sequence assessment approach, while Case 2 and Case 3 aim to investigate the application of the proposed probabilistic 4D model for identifying potential conflicts applying Monte-Carlo and Discrete Event simulations, respectively.

4.2 Background of the Turcot Interchange Project

The case studies are inspired by the Turcot Interchange reconstruction project in Montreal, Canada. This interchange, built in the sixties, has to be reconstructed because of major structural problems. The interchange provides the connection between three main highways (20, 15, and 720) serving the Island of Montreal. It is composed of several bridge structures located at three different levels, where the maximum height is 28 meters, and the average height is 18 meters. Figure 4.1 shows the existing Turcot Interchange and the proposed new interchange. The estimated duration and budget of the project are about 7 years and $4 billion, respectively (Transport Quebec, 2009).

(a) (b)

Figure 4.1 (a) the existing Turcot Interchange, and (b) the proposed new interchange (Transport Quebec, 2009)

This project is scheduled in four phases, and the durations of the four phases are approximately 3, 2, 1, and 1 years, respectively. Because this high-profile project is still in the planning stage, it was not possible to get any details about the geometry or the scheduling of the project. Therefore, the case studies are based on the limited data that were published about the project or obtained directly from the project office. Many assumptions have been introduced to create the geometry of the 3D model and the activity durations used in the simulation. Furthermore, the structural details of the model are simplified in order to focus on the main issues related to spatio-temporal conflicts. Consequently, the case studies should be considered as a semi-hypothetical and they do not accurately represent the actual project.

4.3 Implementation Steps of the Proposed Probabilistic 4D Model

This section briefly presents the implementation steps applied for the proposed probabilistic 4D modeling approach. The succeeding sections provide an in-depth description of these steps and describe the development processes employed to create the proposed 4D model. Figure 4.2 shows the steps of implementing the workflow of the proposed probabilistic 4D model:

(A) Defining the alignments and profiles of roads along the existing terrain in road design software (using InRoads (Bentley Systems Incorporated, 2010)). This software facilitates the integration of CAD and Geographic Information System (GIS) to create the DTM where features, such as roadway centerline, can be incorporated. This allows for greater accuracy through the application of design rules established in the software. Once road corridors are generated, they can be exported in various formats such as LandXML, a text-based file format which saves vector-based drawing information.

(B) Importing the LandXML file and using LEAP Bridge (Bentley Systems Incorporated, 2010) to create the 3D models of the existing and new bridges. The direct exchange of project information through LandXML allows centerlines created in InRoads to be used in LEAP Bridge in order to create parametric bridge modeling with substructure and superstructure modeling capabilities.

(C) Exporting the bridge models into an interchangeable format suitable for the 3D visualization software (LandXML). File interoperability enables the integration of models by exporting data from one application and importing it into another using a format that both applications can read.

(D) Importing the exported bridge models into InRoads in order to assemble the whole interchange geometry. LEAP Bridge was used to create the geometry for each ramp. It is not possible to have more than three bridges at the same time in a project file. Therefore, all the ramps were modeled and exported to InRoads in order to have all the bridges in a file representing the whole project model.

(E) Creating a large number of possible schedules for both construction and demolition processes using Monte-Carlo and Discrete Event simulations.

(F) Loading the whole bridge model into Navisworks. This program enables construction simulation and whole-project schedule analysis while identifying clashes and interferences before construction begins. In this step, the 3D model is linked with each schedule by assigning the bridge components to the relevant activity.

(G) Running the 4D visualization for each different scenario.

(H) Applying clash detection by the 4D simulation software. Since InRoads software has the ability to run the 4D directly, the model created by this software does not need to be exported into a 4D software. In this case, the 4D model can be directly used for applying the visualization and clash detection.

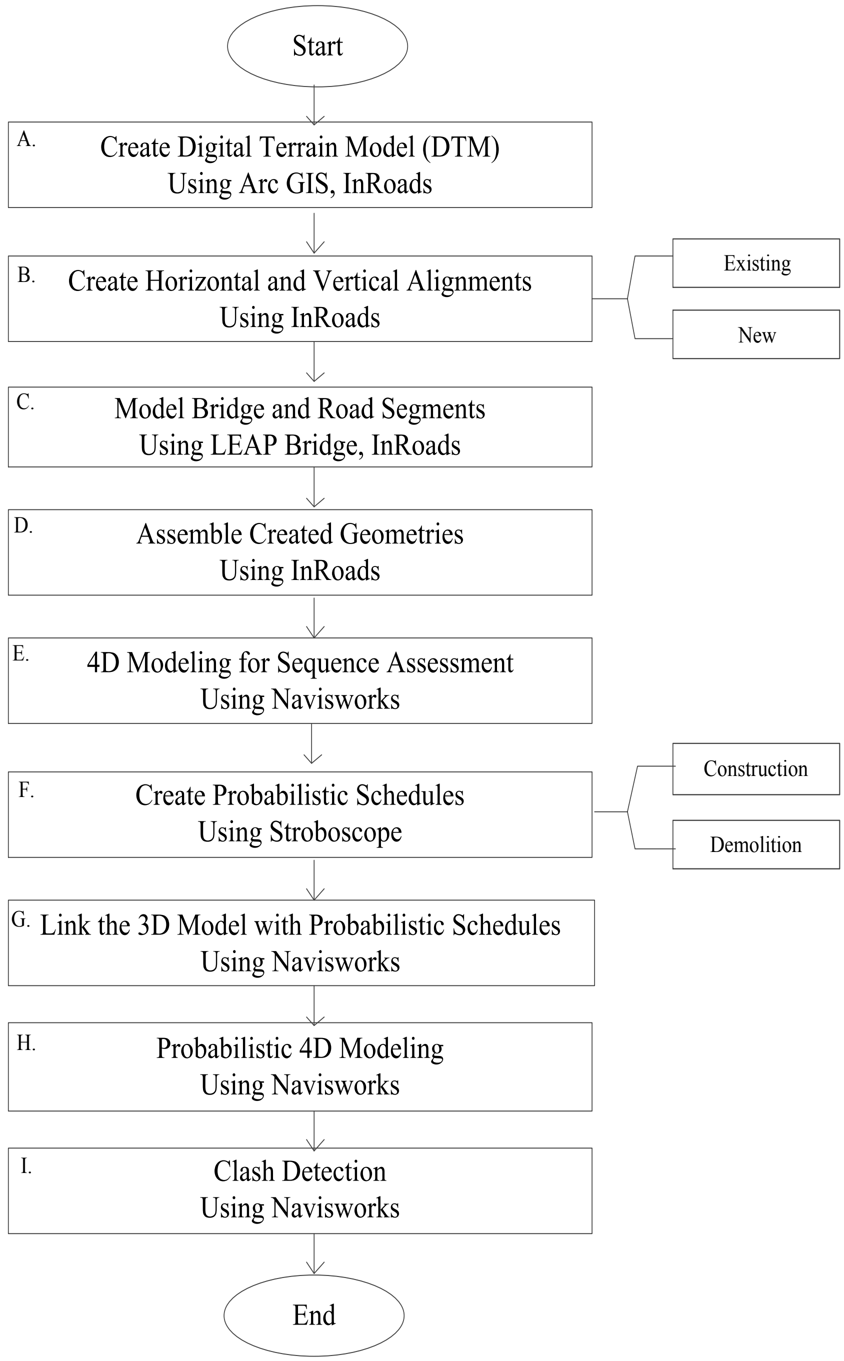


Figure 4.2 Workflow implementation steps

4.4 3D Modeling Development

4.4.1 Site Modeling

The surface model was generated by Bentley InRoads V8i using the 3D points of the existing ground provided from the city of Montreal. The 3D points of the existing land are taken from Aerial Photogrammetry and processed in a stereo plotter. This instrument provides the ability to see the overlapping photos at once in 3D. The 3D points are transformed uding ArcGIS software (ESRI, 2012) in to a Shapefile in order to be used in Bentley InRoads V8i Software. Figure 4.3 shows the 3D Shapefile of the existing ground in ArchGIS software.

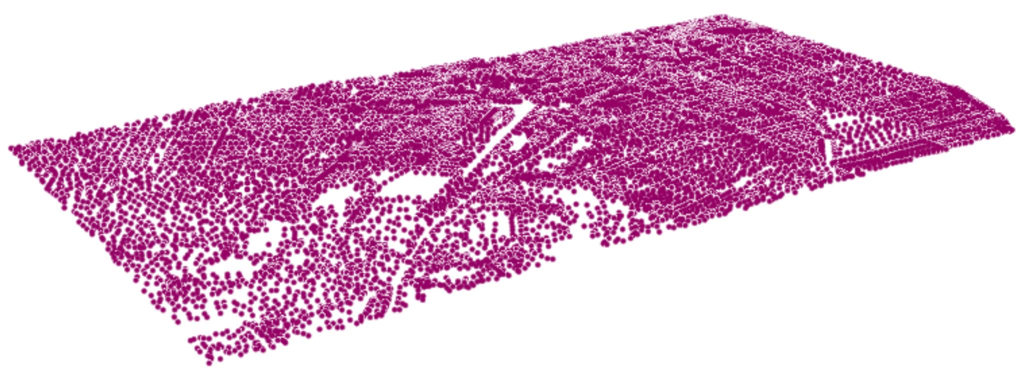


Figure 4.3 3D shapefile of the existing terrain in ArcGIS software

Eventually, the surface model in Shapefile format is imported into InRoads to generate a TIN model by using the "Triangulate Surface" tool embedded in surface tab. Applying triangulation from InRoads interface results in the TIN model of the existing ground. Figure 3.5 (a) shows the TIN model of the existing ground in InRoads software.

InRoads software also provides a facility to drape a geo-referenced image onto the generated TIN model. This is done by attaching a geo-referenced image using "Raster Manager" tool.

Shown in Figure 3.5 (b), the image is clipped to the TIN model as a material and provides an enhanced visualization of the site.

4.4.2 3D Modeling of the Existing Interchange

As mentioned, Bentley software offers a family of bridge and road software to provide a foundation for BrIM. Although other software packages such as Autodesk Civil 3D with Bridge Plug-in or Autodesk Revit Structure with Bridge Plug-in form Autodesk family can be used to create the 3D model, Bentley software was found to be more specialized in elevated urban highway 3D modeling. The 3D model was developed by using the original 2D drawings and the provided data from the City of Montreal.

Once the surface model is opened in InRoads, the 2D drawing of the highway is overlaid on the active surface. By selecting the graphic lines representing horizontal alignments from the 2D drawing, the horizontal alignments of the project is generated. Figure 4.4 shows the original 2D drawing of the existing interchange. The horizontal alignment (centerline) for each segment is highlighted in white color. By selecting each line, the relevant horizontal alignment is created from that line using File >Import > Geometry command in InRoads shown in Appendix A (Figure A.5).

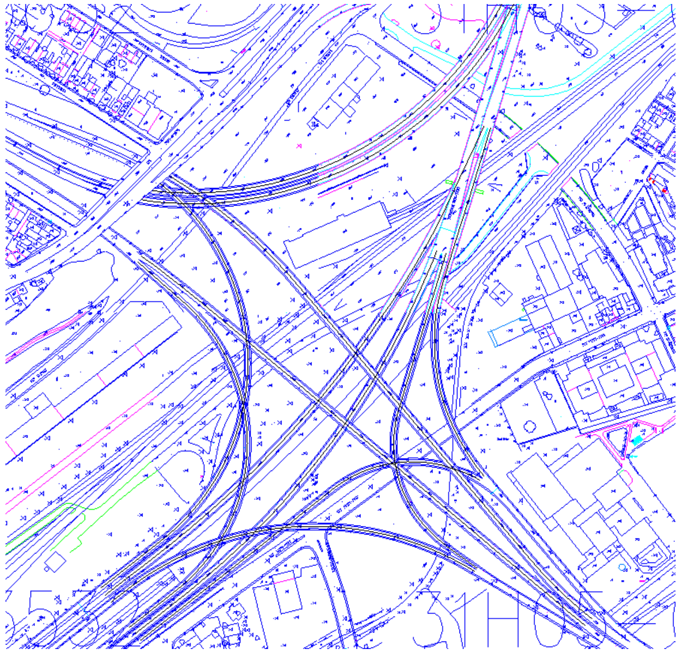


Figure 4.4 2D drawing of the existing Turcot Interchange

The generated horizontal alignments should be stationed for creating vertical alignments. InRoads normally starts stationing at 0+00; however it could be changed to any specific starting station. As shown in Appendix A (Figure A.6), the stationing will be displayed by using Geometry > View Geometry > Stationing in InRoads. The next step is creating vertical alignments by entering the elevation number of generated stations in Table Editor. Table Editor can be accessed from Geometry > Vertical Curve Set > Table Editor in InRoads. Before creating vertical alignments, it is important to active the correct horizontal alignments because the vertical alignments are generated as a sub category of the active horizontal alignment.

The final step in InRoads is exporting the generated geometry project file including the horizontal and vertical alignments to LandXML format, so the exported file is readable in LEAP Bridge software. LEAP Bridge is a fully object oriented software for geometry, substructure, and superstructure analysis, design, and rating. Appendix A (Figure A.1) shows the dialog box for exporting the geometry project of segment F to LandXML format in InRoads. Appendix B shows a part of an XML file of a bridge model created in LEAP Bridge.

LEAP Bridge software generates the whole bridge geometry model using a three step tool called ABC Wizard. In order to create each segment (bridge), the alignments and ground information should be imported into ABC Wizard through LandXML format. After loading the horizontal and vertical alignment into ABC Wizard, the superstructure type and dimensions of the interchange cross section are defined in the first step as shown in Figure 4.5. In this step, the pier stations extracted from InRoads should be used for the station numbers in ABC Wizard in order to have the piers at the exact position of the original 2D drawing. The second step of the ABC Wizard is defining the dimensions of piers and foundations. Figure 4.6 shows step two of the ABC Wizard in LEAP Bridge software. Finally, the last step is defining the materials and bearing data. Figure 4.7 presents a bridge 3D model (segment F of the existing interchange) created in LEAP Bridge software by following the three steps of the ABC Wizard. The same procedure is applied to create all the elevated segments (the whole existing interchange and some elevated parts of the new interchange). Eventually, all generated segments in LEAP Bridge software are exported into CAD file (DGN or DXF) in order to have the whole interchange 3D model. Although exporting the bridge segments into CAD files will result in losing data attached to the objects (e.g. names and properties of different objects such as piers), there is no other way of transferring data to other software. The limitations and lack of interoperability between different software (even between software from the same family) is explained in Section 5.3.

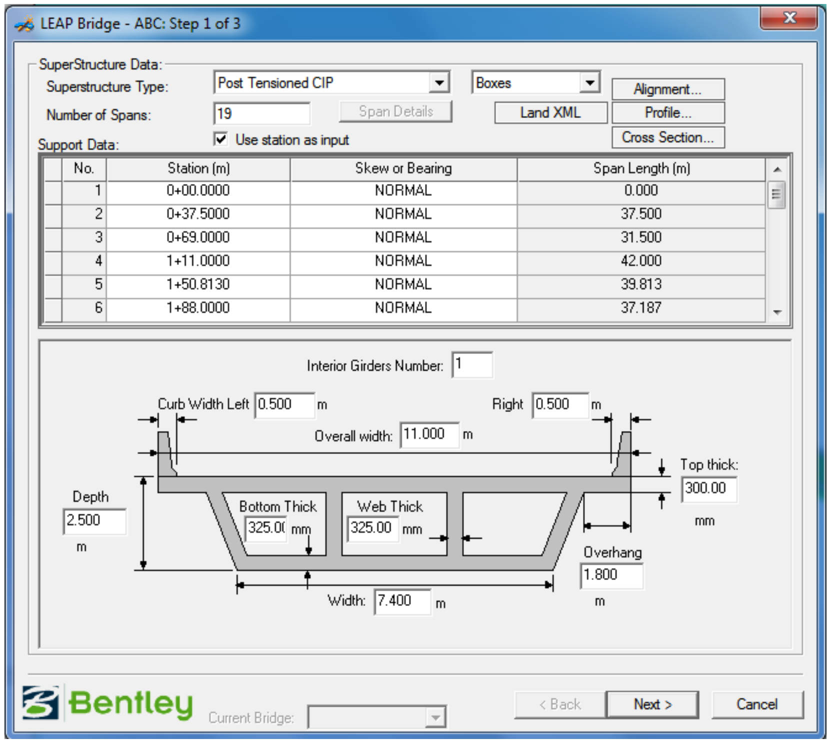


Figure 4.5 Defining the superstructure type and dimensions in LEAP Bridge

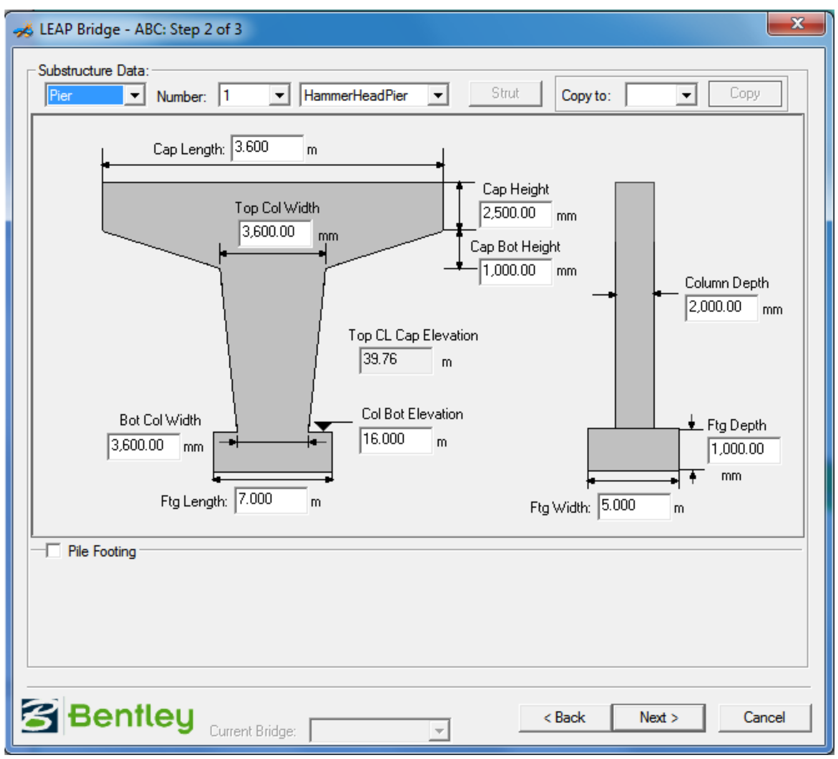


Figure 4.6 Defining the substructure type and dimensions in LEAP Bridge

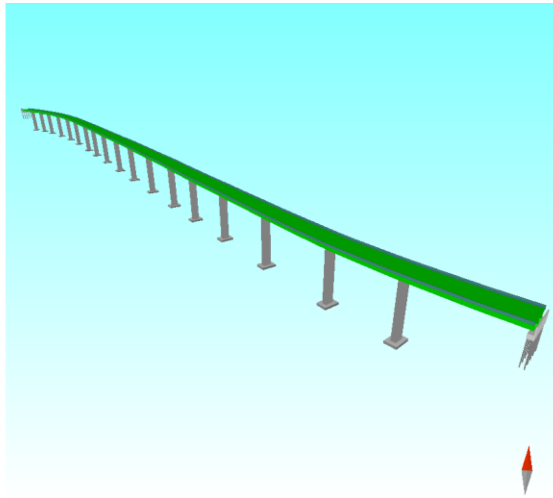


Figure 4.7 A bridge 3D model created by LEAP Bridge

By importing all the created segments and merging the developed TIN model in InRoads, the whole interchange 3D model is generated. In order to integrate all the created segments, any CAD-based software can be used. In this research, all the generated segments and the developed TIN model are imported to Navisworks for developing the 4D model. Figure 4.8 shows the entire existing interchange 3D model in InRoads.

Figure 4.8 Existing Turcot Interchange 3D model in InRoads

4.4.3 3D Modeling of the New Interchange

The new Turcot Interchange project will be largely constructed with embankments below the level of the existing interchange. As a result, this project involves both roads (embankments) and elevated parts (bridges). Basically, the procedure explained in Section 4.4.2 is applied for the new interchange by starting from the 2D drawings of the designed interchange. Figure 4.9 shows the 2D drawing of the new Turcot Interchange introduced by the Ministry of Transport of Quebec (MTQ).

Modeling the elevated parts (bridges) follows the exact same procedure as before by integrating InRoads and LEAP Bridge. The road parts are completely modeled in InRoads. Following the same procedure of creating horizontal and vertical alignments, the alignments of road parts are generated. Next, the model of each segment is created by using the Roadway Designer command and applying project templates. A project template is a typical section of the roadway and stored in the Template Library File (.itl). The project templates could be modified in order to meet the specific needs of each project. Appendix A (Figure A.2) shows a two lane road template in InRoads. Roadway Designer embedded in the Modeler tab is used to assign the appropriate template to the specific sections along the defined alignments. In other words, a template is assigned to specific intervals called template drops, and the Roadway Designer integrates these points (template drops) to create a road model (Bentley Systems Incorporated, 2010)

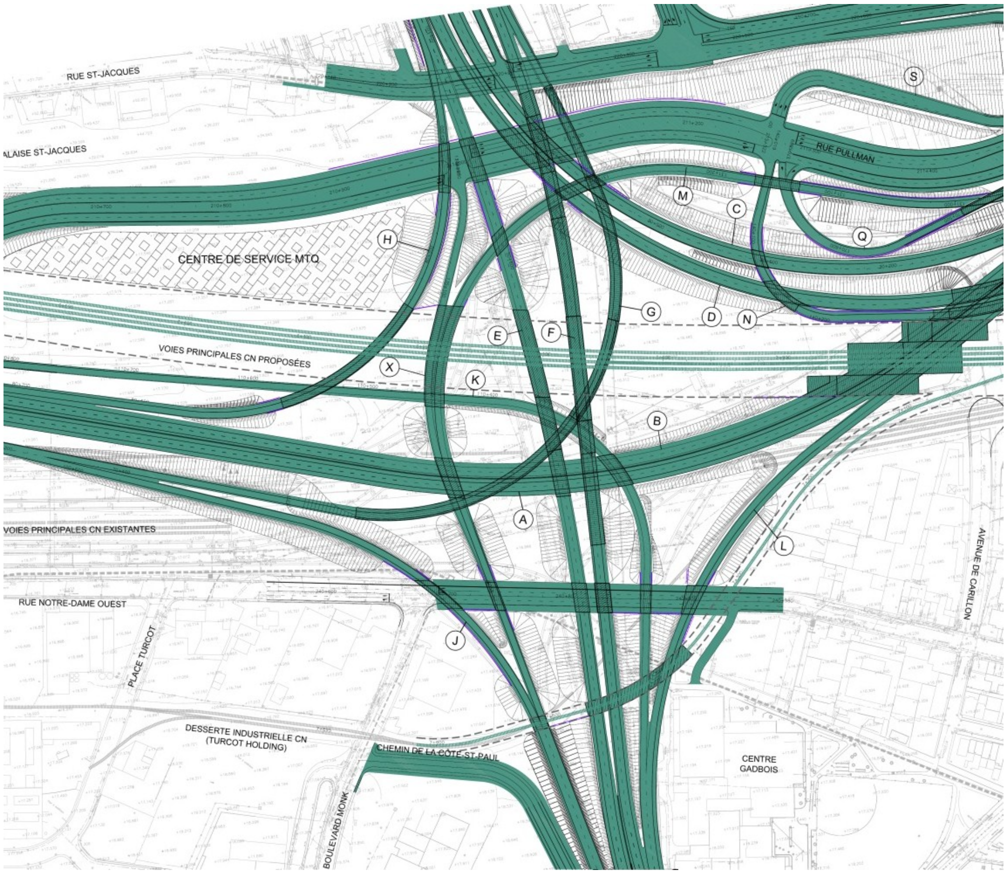


Figure 4.9 2D drawing of the new Turcot Interchange (Transport Quebec, 2009)

The last step in creating the new interchange 3D model is integrating the generated bridge parts in LEAP Bridge with the road parts in InRoads. To do so, all the elevated parts will be exported from LEAP Bridge to a CAD format (.DGN) and then imported into InRoads. As the elevated parts are based on the alignments taken from InRoads, the imported bridges will completely match with the road parts. Figure 4.10 shows the developed 3D model of segments A, B, E, F, and G of the new Turcot Interchange. These segments involve both roads with the embankment shown in red and elevated parts (bridges) shown in green.

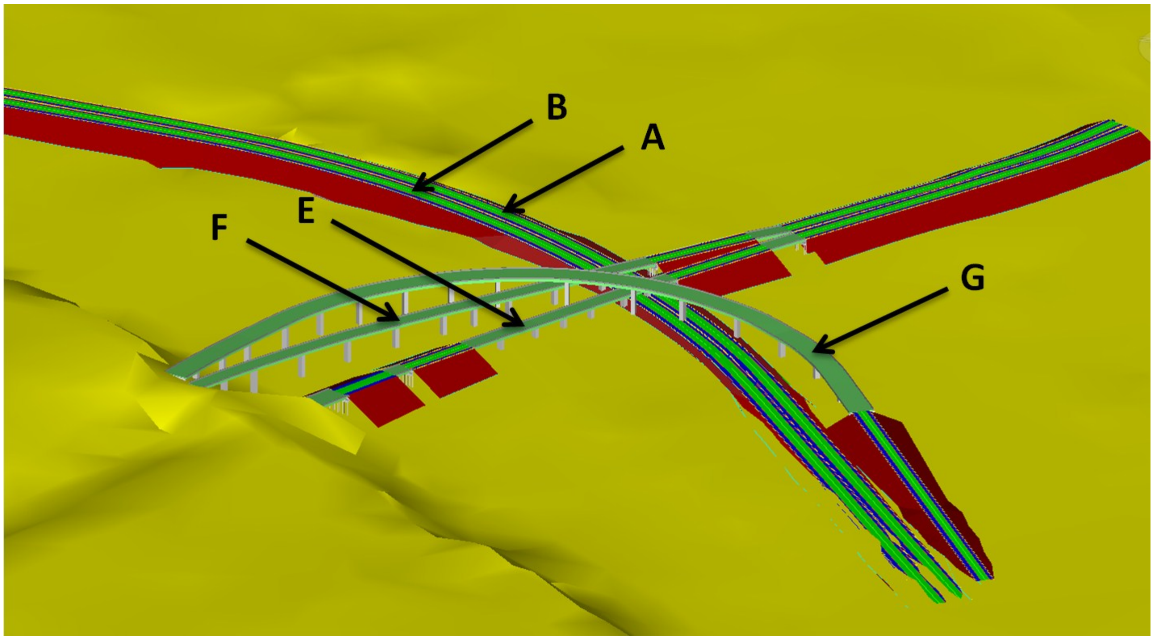
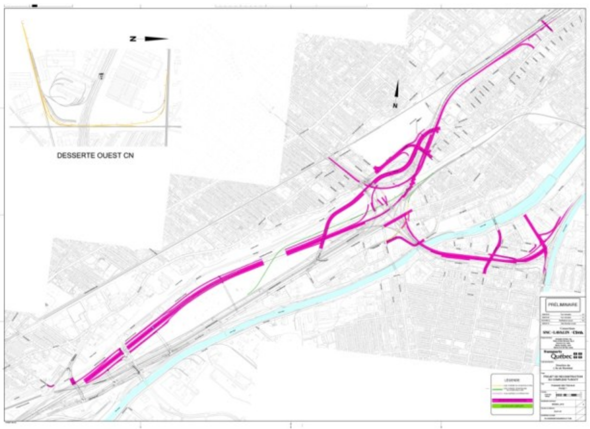


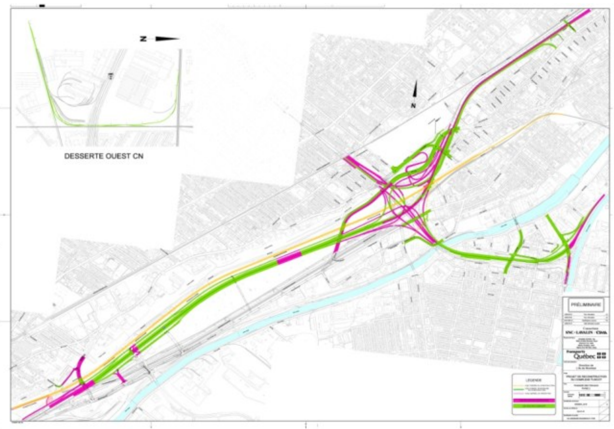
Figure 4.10 3D model of segments A, B, E, F, and G of the new Turcot Interchange in InRoads

4.5 Construction Phasing Plan

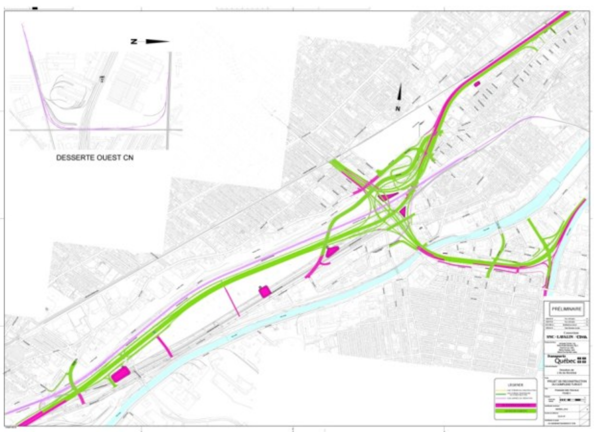
As mentioned in Section 4.2, the Turcot Interchange project is scheduled in four phases, and each phase is divided into 4 sub-phases. Figure 4.11 shows the four main phases of reconstruction work scheduled for this project. The estimated total duration of the project is 7 years, and the scheduled start and end dates of each phase are presented in Table 4.1. The case studies provided in this research focus on the interchange part which is the most critical part of the project having high potential of conflicts. As shown in Figure 4.11, the interchange part is mainly scheduled in Phase 2. The reconstruction work undertaken in this project is divided into 5 categories presented in Table 4.2, and Figure 4.12 demonstrates an example of development process of reconstruction work phasing. In Phase 1, the process starts with the construction of retaining walls and embankments of segments A and B. Then the next phase is commissioning the new built segment A and demolishing the existing elevated segment A. Phase 3 will transfer the traffic from segment B towards the newly built segment A and demolish the existing elevated segment B. Finally, Phase 4 is commissioning the newly built segment B and landscaping the surrounding area.



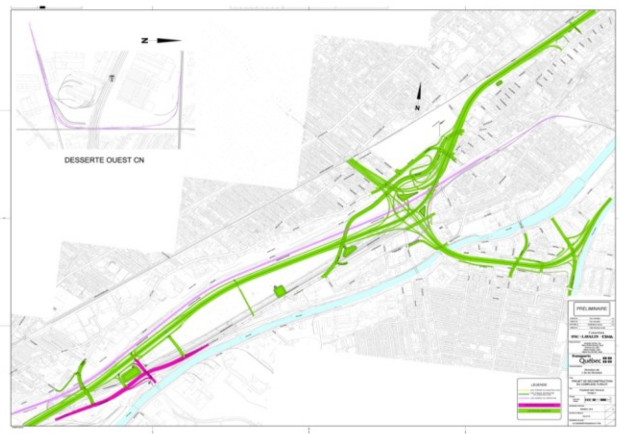
(a) Phase 1



(b) Phase 2



(c) Phase 3



(d) Phase 4

Figure 4.11 The four main reconstruction phases of the Turcot Interchange (Transport Quebec, 2009)

Table 4.1 Estimated durations of four main reconstruction phases (Transport Quebec, 2009)

Phase	**Start – End of Work**	**Duration**
Phase 1	Fall 2009 to Summer 2012	+/- 3 years
Phase 2	Summer 2012 to Fall 2014	+/- 2 years
Phase 3	Fall 2014 to Fall 2015	+/- 1 year
Phase 4	Fall 2015 to Fall 2016	+/- 1 year

Table 4.2 Breakdown of reconstruction work (Transport Quebec, 2009)

Type of Construction	% of the Project
Embankment construction	45 %
Grading	28 %
Cut	11 %
Cut and Fill	8 %
Structure	8 %

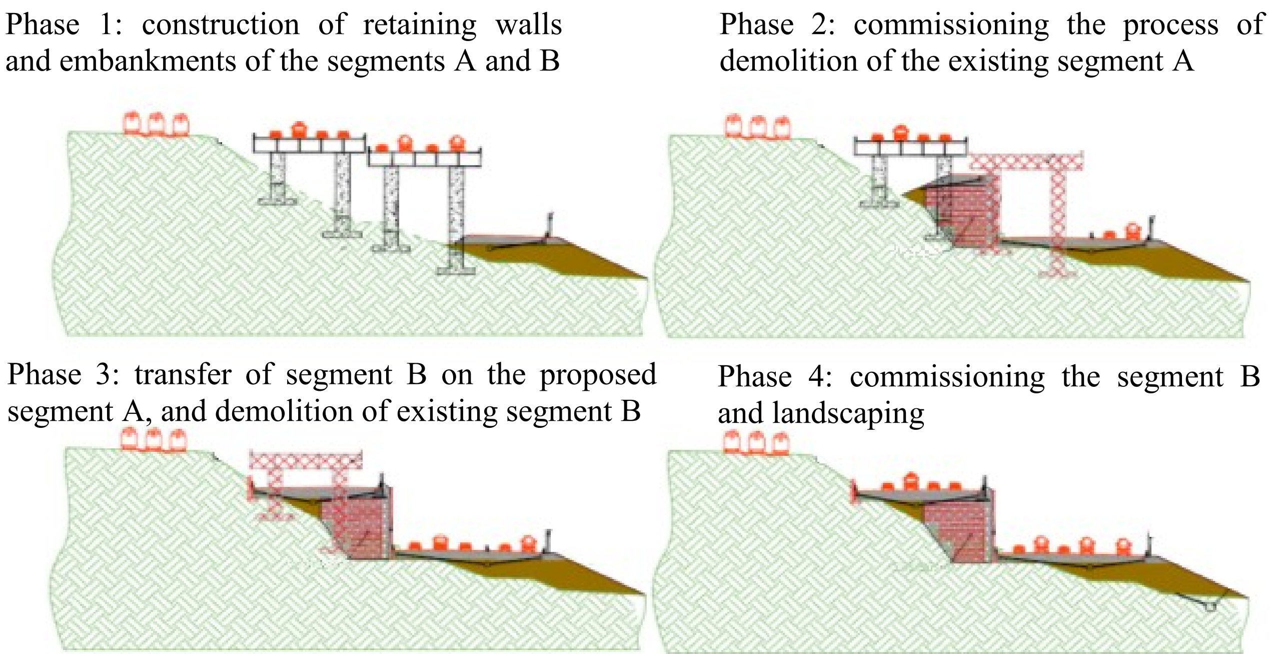


Figure 4.12 Example of reconstruction work phasing (Transport Quebec, 2009)

4.6 Case 1: Sequence Assessment Approach

This case is provided to show the functionality of the proposed sequence assessment approach and how conventional planning can result in a potential conflict. Reviewing the sub-phases of construction work plan shows that segments E, F, and G of the new interchange have the most priority to start for construction operation. As shown in Figure 4.13, these segments will initially start in sub-phase 1-A. Since the mentioned segments are located in the zone of high potential conflict, they were selected for the case study of the sequence assessment approach. To demonstrate the case study, these segments were modeled and combined with the existing interchange 3D model. Figure 4.14 presents a plan view of the developed 3D model showing the start and end points (arrows) of the elevated parts of each segment of the new interchange as the possible starting points for construction operations. The existing interchange is shown in yellow, and the selected segments of the new interchange are presented in green.

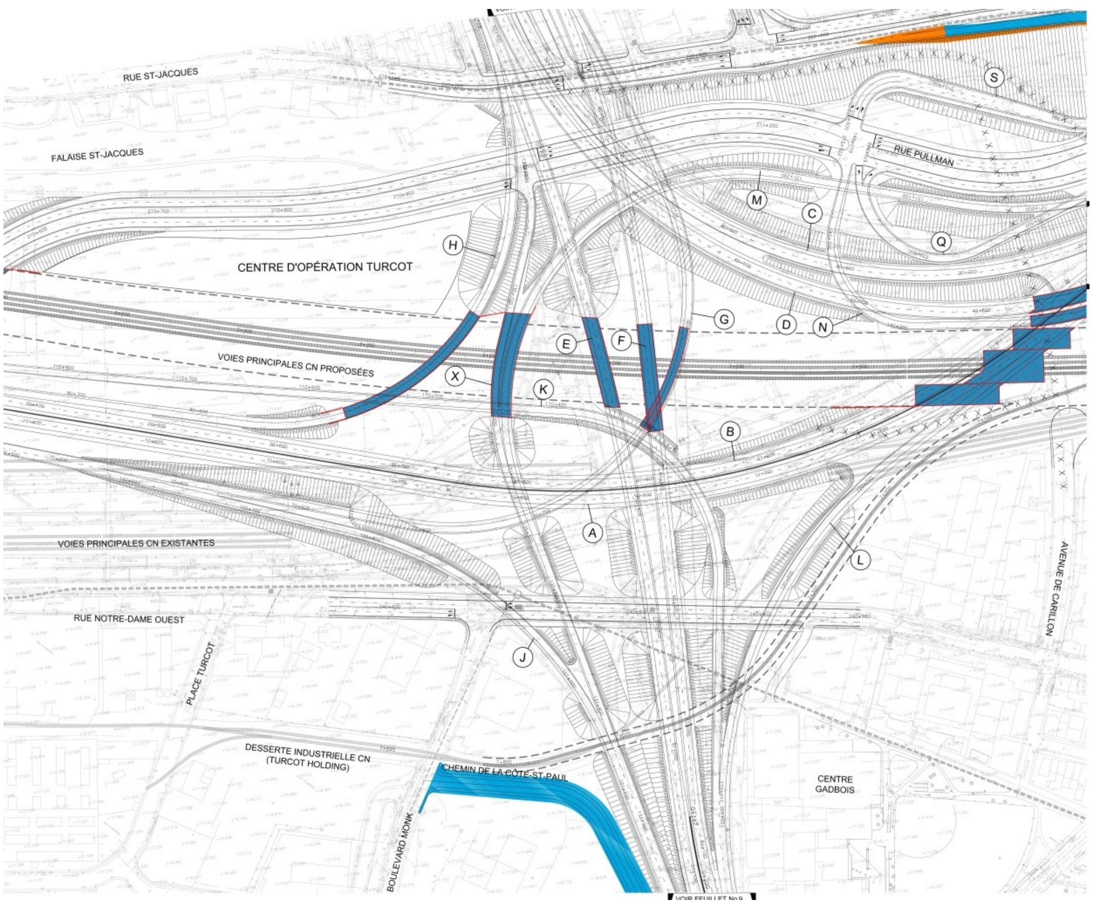


Figure 4.13 Sub-phase 1-A of the phasing plan (Transport Quebec, 2009)

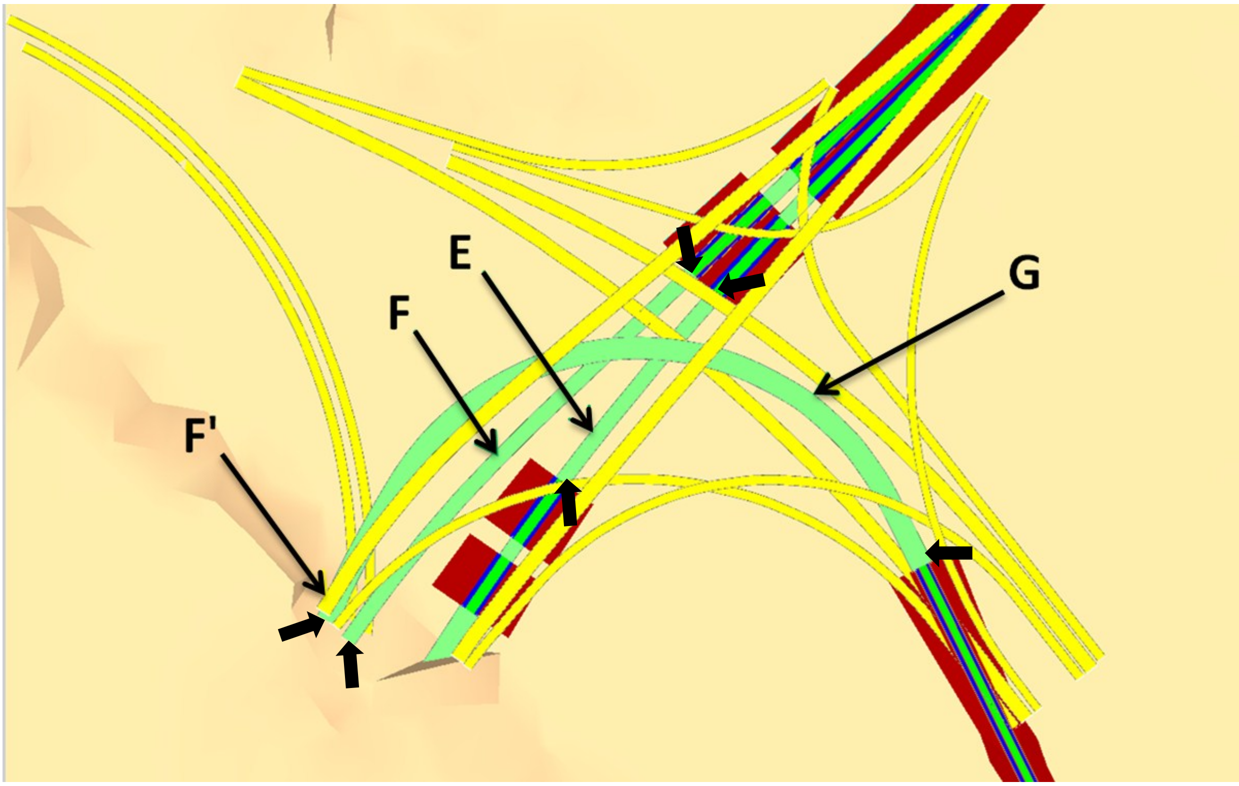


Figure 4.14 Existing interchange (yellow), and segments E, F, and G of the new interchange (green)

The scope of this case involves the construction of segments E, F, and G of the new interchange, and the demolition of segment F' of the existing Turcot Interchange shown in Figure 4.14.

It is assumed that there are two crews available for the construction of segments E, F, and G of the new interchange, while there is one crew responsible for the demolition of segment F' of the existing interchange. The general contractor should coordinate the schedules of the two subcontractors while consulting with the management team representing the owner (the transportation agency) in order to eliminate the spatio-temporal conflicts between the subprojects and to reduce the impact on the traffic. It should be noted that in order to provide the continuity of traffic in the interchange, it is assumed that the existing segment F' cannot be demolished without having an alternative route. In other words, the demolition process of segment F' of the existing interchange cannot be initiated until either segment E or segment F of the new interchange is ready for traffic operation.

Considering the number of segments and available crews, the number of different possible sequences (combinations) for delivering the job would be counted by applying Equation 3.1:

Number of (almost equal) segments (s) = 3

Number of available crews (c) = 2

$$x = 2^{s} \times \prod_{n=0}^{\left[\frac{s}{c}-1\right]} \binom{s-nc}{c} \Rightarrow x = 2^{3} \times \prod_{n=0}^{[0]} \binom{3}{2} = 24$$

All these different scenarios consider the continuity of work as a critical factor in scheduling linear projects. To show the impact of different sequences on the project workflow, two different scenarios (sequences) of the construction schedule are selected. Figure 4.15 presents the order of allocating available construction crews to the new segments (E, F, and G) in Scenario 1. In the first stage of this scenario, Crew 1 and Crew 2 are assigned to segment G and segment E, respectively. Since segment E is shorter than segment G, Crew 2 will finish the assigned segment (segment E) sooner and will be moved to the remaining segment (segment F). However, in Scenario 2, Crew 1 and Crew 2 start the construction processes on segment G and segment F, respectively. Considering the shorter length of segment F compared to segment G, Crew 2 will deliver the assigned segment (segment F) earlier and start segment E. Figure 4.16 shows the crew allocation strategy explained for Scenario 2.

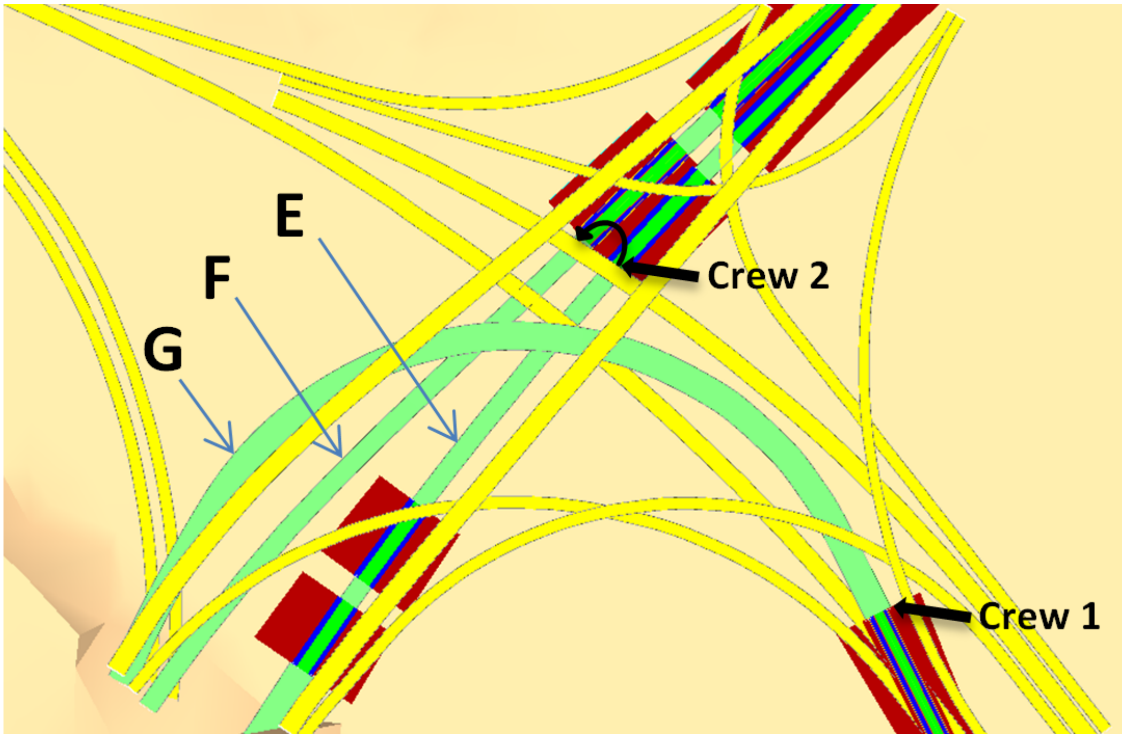


Figure 4.15 Order of allocating crews in Scenario 1

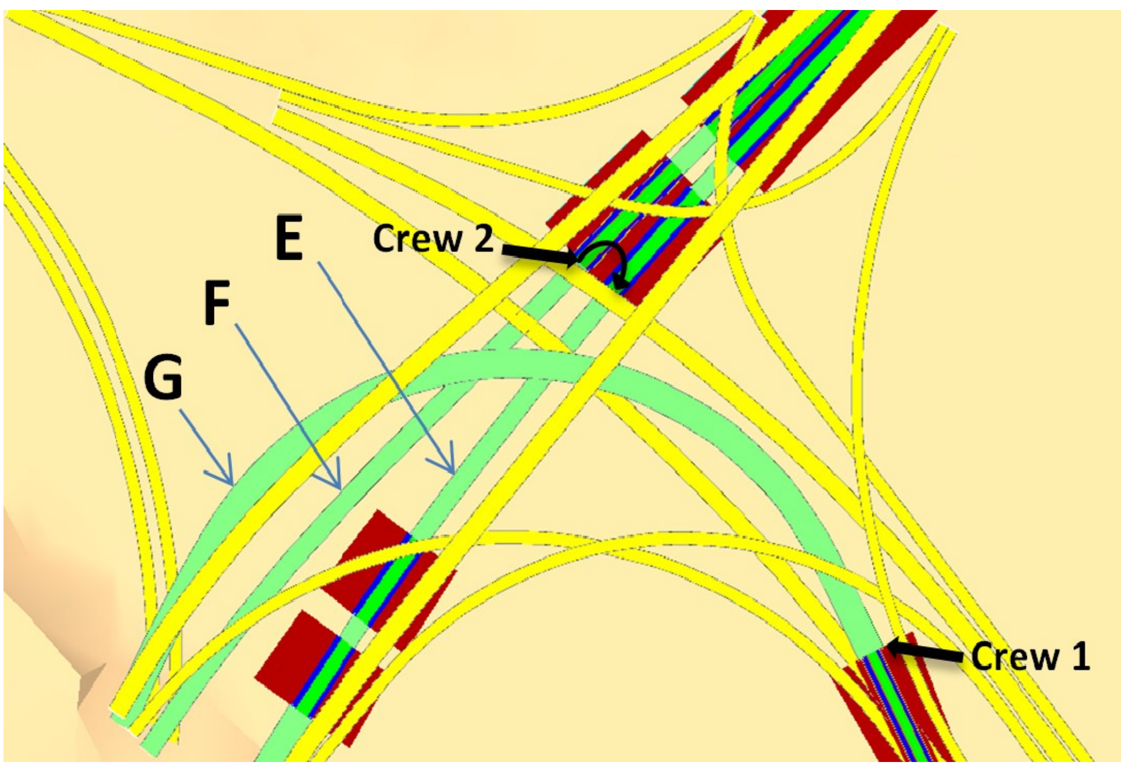


Figure 4.16 Order of allocating crews in Scenario 2

The construction duration for each span is considered 20 hours, while the demolition duration is considered 1 hour for each span based on rough estimation (Zhang, Zayed, & Hammad, 2008). The construction method used a full-span pre-cast concrete box girder bridge by launching gantry and the demolition operation is done using cut-and-lift method. Using the steps discussed in the proposed methodology, the 3D models of the existing interchange and segment E, F, and G of the new interchange are linked with the selected sequences. Navisworks software is used to link the 3D models with the schedules and to run the 4D visualization.

As shown in Figure 4.17, the developed 4D for scenario 1 will not cause any spatio-temporal conflicts between the segments under construction and the one under demolition. In this case, when the construction operation of segment G of the new interchange comes to the point of potential collision with segment F' of the existing interchange, segment F' is already demolished. Hence, the clearance space needed for construction crews to progress is provided. On the other hand, scenario 2 will result in both soft and hard conflicts. As mentioned in Section 2.5.5, a soft conflict is resulting from the lack of clearance space needed for the construction crews and equipment to progress. Even if the required clearance is available, a hard conflict exists between the ninth span of the new segment G and a pier of the existing segment F'. Figure 4.18 shows a snapshot of the developed 4D model taken at the same point of time of Figure 4.17 . In this case, the demolition process on the existing segment F' has not started since the alternative route (new segment F) is still under construction. These conflicts will delay the progress of the segment under construction, which in return will delay the project and may cause an overrun in the budget. By applying the proposed methodology, planners can focus their attention on the areas of potential conflicts and avoid these conflicts by, for example, expediting the demolition process.

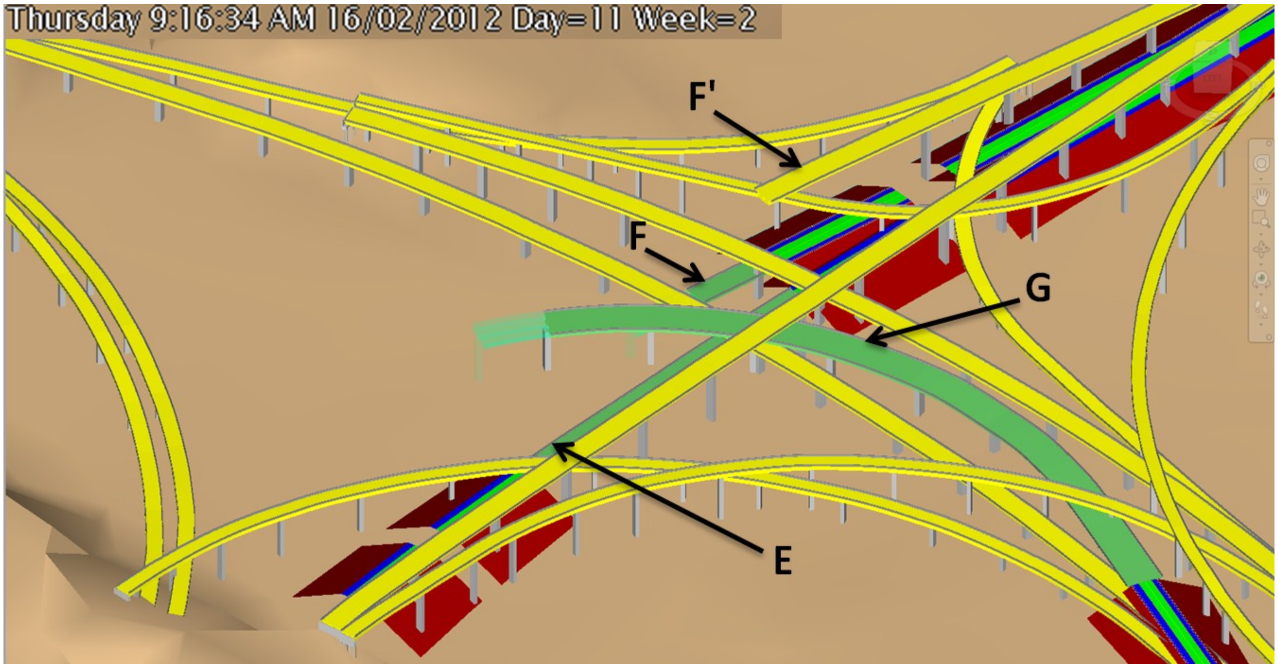


Figure 4.17 Scenario 1: No conflict

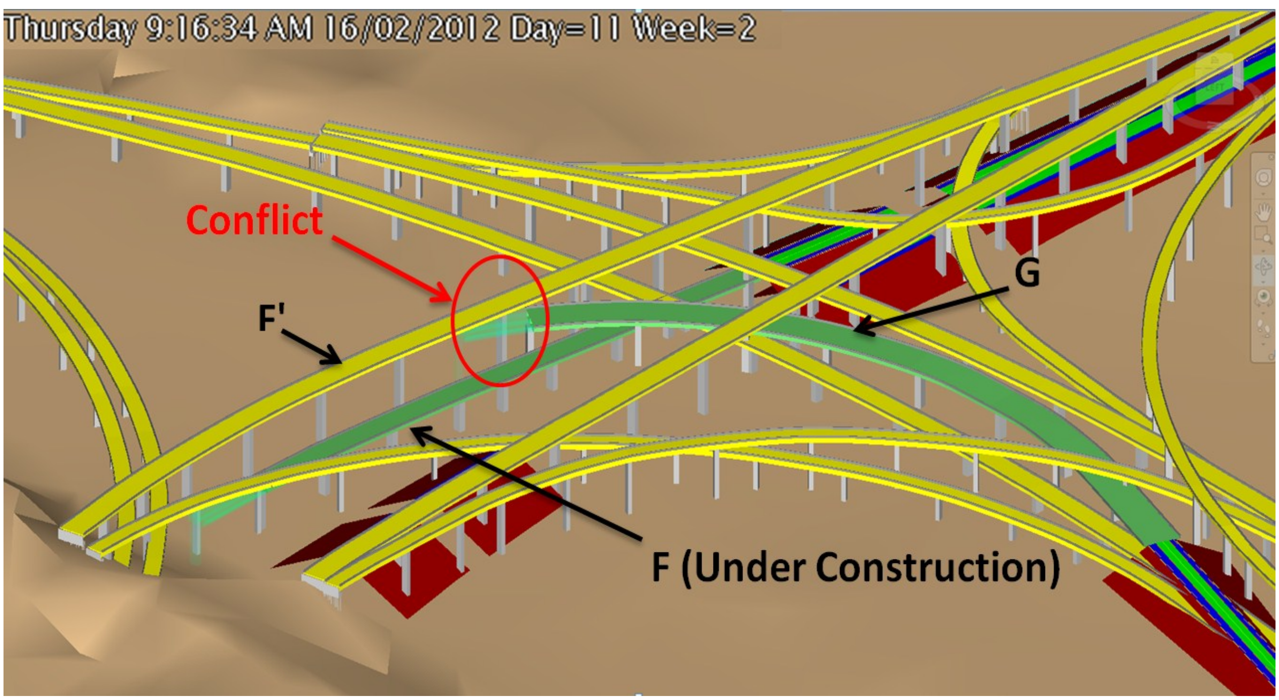


Figure 4.18 Scenario 2: With conflict

4.7 Probabilistic 4D Modeling

As mentioned in Chapter 3, this research applies two different simulation techniques, Monte-Carlo and Discrete Event simulations, in order to generate the probabilistic schedules based on different levels of details. Case 2 applies Monte-Carlo simulation and uses the assigned durations of activities to calculate the total project duration using a pre-defined network. This technique is to study the impact of uncertainty by assigning a variation to the duration of each activity. However, Case 3 uses Discrete Event simulation to estimate the project duration, and the productivity rate of the operation by studying the interaction between different resources. In this case, the construction and demolition operations are broken down to small tasks, and Discrete Event simulation integrated with 4D model is used to detect potential spatio-temporal conflicts that can result from the variations in tasks durations. For simplicity, the segments with potential conflict, segment G of the new interchange and segment F' of the existing interchange, identified from Case 1 are considered for investigation in Case 2 and Case 3.

4.7.1 Case 2: Probabilistic 4D Modeling Using Monte-Carlo Simulation

In this case, Monte-Carlo simulation is applied to study the impact of uncertainty in scheduling construction activities. It is assumed that only one construction crew and one demolition crew are available to work sequentially on one span at a time. The quantities of work for estimating the durations of activities are found from InRoads/LEAP Bridge software. The productivity rates for column and footing demolition were taken from RS Means cost data (RSMeans Engineering Department, 2011) and the productivity rates for constructing the superstructure, columns, footing, and demolition of superstructure were taken from Florida Department of Transportation (Flordia Department of Transportation, 2010). The triangular distribution functions of those productivities are used in the simulation. The Monte-Carlo simulation is implemented in construction simulation software, STROBOSCOPE, an acronym for STate- and ResOurce-Based Simulation of COnstruction ProcEsses (Martinez, 1996). STROBOSCOPE can accommodate deterministic and stochastic modeling of the highway reconstruction operations. The following describes the steps for generating Monte-Carlo simulation schedules using STROBOSCOPE:

(1) Build the CPM network in ProbSched shown in Figure 4.19: the horizontal relationship between the activities represents the logic of construction work flow. The vertical relationship between the activities represents the order of which activities will use the resources.

(2) Determine the quantity for each activity

(3) Insert the durations as a triangular distribution into ProbSched. Set the replications value to 1, and then run the simulation.

(4) The simulation results will appear in the STROBOSCOPE output window.

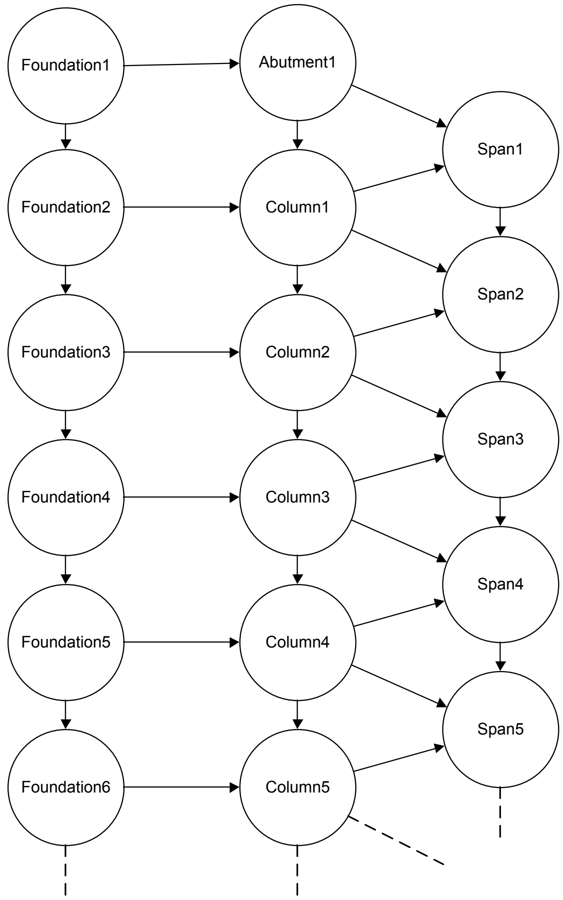


Figure 4.19 A part of CPM network in ProbSched

The proposed methodology was implemented to examine the project schedule for a period of 146 weeks. As Figure 4.20 shows, it is assumed that one contactor is working on the subproject of constructing segment G of the new interchange, while another contactor is responsible of the demolition of segment F' of the existing interchange. It should be noted that in order to provide the continuity of traffic in the interchange, an existing segment cannot be demolished without having an alternative route. The general contractor should coordinate the schedules of the two contactors while consulting with the management team representing the owner (the transportation agency) in order to eliminate the spatio-temporal conflicts between the subprojects and to reduce the impact on the traffic.

Two different schedules were selected from the results of simulation. For simplicity, both selected schedules have the same duration for constructing the new segment. The durations of construction activities of segment G up to span 9 (the point of the potential conflict) are presented in Table 4.3. The durations of demolition activities of segment F' up to span 8, the point of potential conflict, for the two selected scenarios are presented in Table 4.4. The durations of the above-mentioned two schedules are linked to the 3D models of the existing and new interchanges.

Table 4.3 Activity durations for construction (days)

Activity	Construction Durations (days)
Construction of Segment G, Span 1	53
Construction of Segment G, Span 2	62
Construction of Segment G, Span 3	67
Construction of Segment G, Span 4	66
Construction of Segment G, Span 5	88
Construction of Segment G, Span 6	75
Construction of Segment G, Span 7	70
Construction of Segment G, Span 8	73
Construction of Segment G, Span 9	54

Navisworks software is used to link the 3D models with the schedules and to run the 4D model. As shown in Figure 4.20, Scenario 1 will not cause any spatio-temporal conflicts between the segments under construction and the one under demolition. On the other hand, Scenario 2 will cause a conflict because of the collision of span 9 (S 9) of the new segment G and one pier of span 8 (S 8) of existing segment F' (week 82).

Table 4.4 Activity durations for demolition (days)

Activity	Scenario 1 (No Conflicts)	Scenario 2 (With Conflict)
Demolition of Segment A, Span 1	12	13
Demolition of Segment A, Span 2	12	13
Demolition of Segment A, Span 3	13	15
Demolition of Segment A, Span 4	15	16
Demolition of Segment A, Span 5	17	18
Demolition of Segment A, Span 6	18	18
Demolition of Segment A, Span 7	17	17
Demolition of Segment A, Span 8	14	18

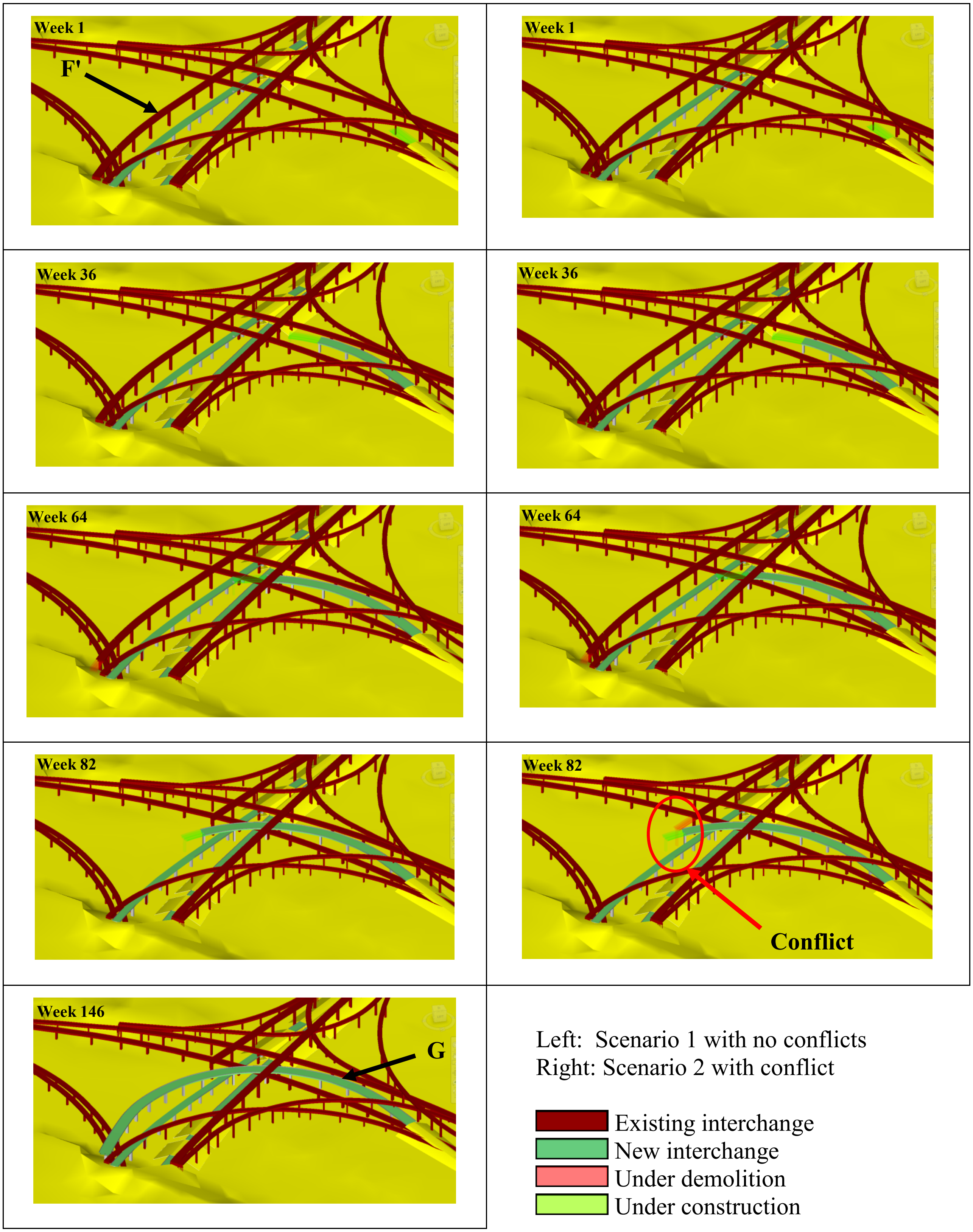


Figure 4.20 5 Snapshots of the developed 4D models of the existing and new interchanges

After identifying the potential conflict, the probability of all the scenarios with potential conflict within the conflict interval can be calculated using the proposed method explained in Section 3.5.2. As explained before, the probability of each point within the interval is the multiplication of the probability of finishing construction operation at that point by the probability of finishing demolition operation longer than that point. To calculate the probability of finishing construction operation at each point a small strip is assigned to that point. Since the conflict is an event happening during the construction of one specific span, the mean duration of one span construction resulted from Monte-Carlo simulation is considered as the small strip (in this case 40 days). Figure 4.21 shows the combined probability distribution for the construction and demolition operations. In this case, the demolition operation is started 290 days after starting the project and results in a conflict interval shown in Figure 4.22. Table 4.5 shows the calculated probability of three different scenarios including the interval in Scenario 2. This interval is between day 378 and day 418 with the highest potential conflict with a probability of 32.67 %.

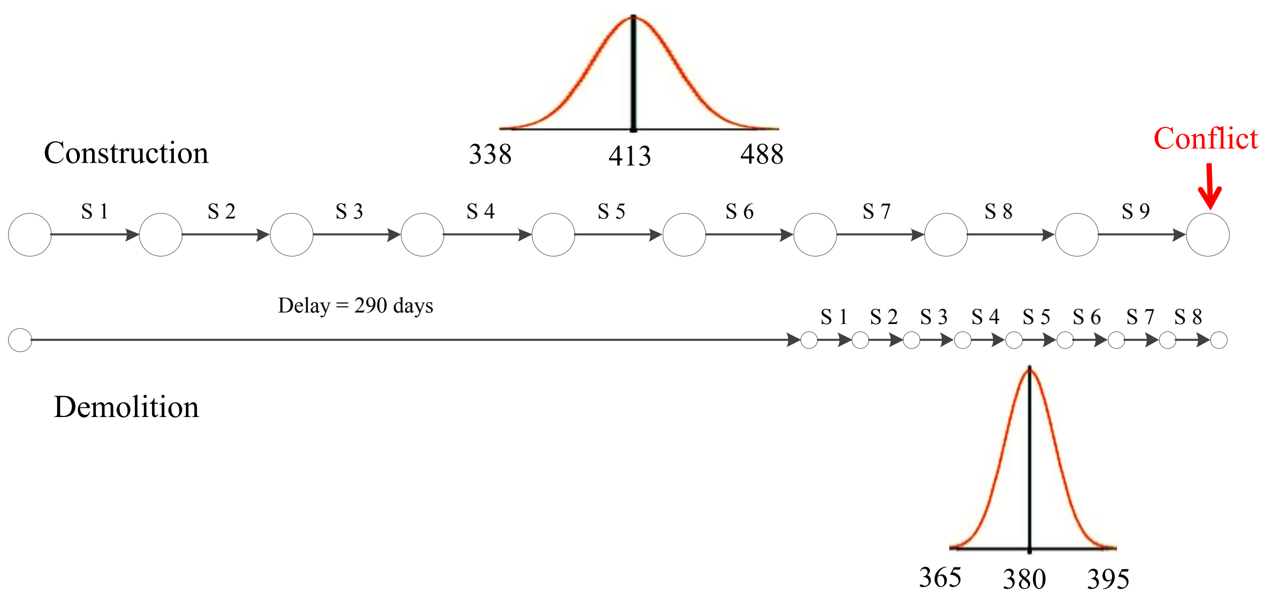


Figure 4.21 Combined probability distributions for each operation

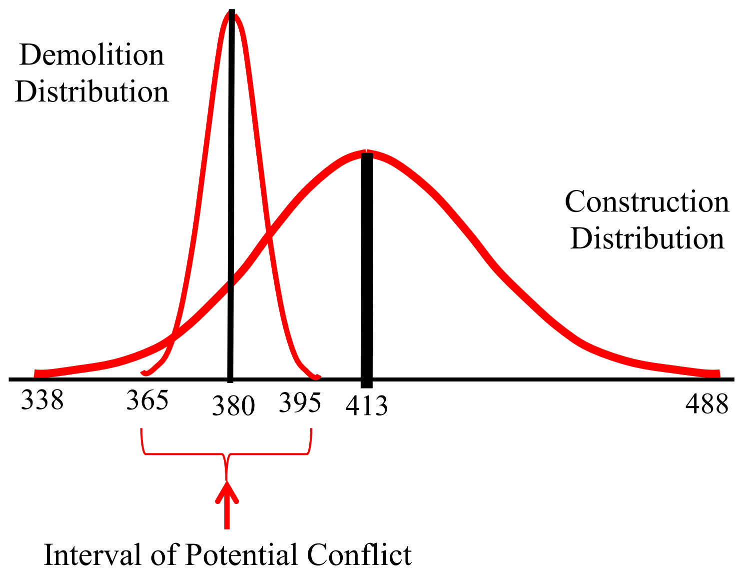
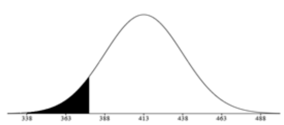
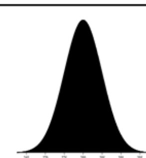
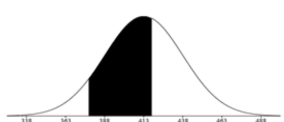
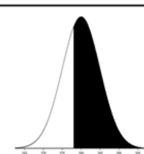
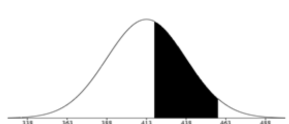
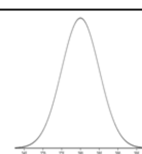


Figure 4.22 Resulting overlapped interval of potential conflict

Table 4.5 Probability of different scenarios within the conflict interval

Scenarios	Construction Duration → Probability	Demolition Duration → Probability of Potential Conflict	Combined Probability
1	 F_c = 338-378 → 7.94%	 F_d > 338 → 100%	7.94%
2	 F_c = 378-418 → 49.85%	 F_d > 378 → 65.54%	32.67%
3	 F_c = 418-458 → 38.48%	 F_d > 418 → 0%	0%

4.7.2 Case 3: Probabilistic 4D Modeling Using Discrete Event Simulation

Discrete Event simulation is done using STROBOSCOPE in order to generate different scenarios of the schedule. The durations of the tasks used in the construction and demolition operations are presented in Table 4.6. These data were collected from (Zhang, Zayed, & Hammad, 2008) and the industry. Table 4.7 shows the construction duration of segment G up to span 8 (the point of conflict), and the demolition durations of segment F' for the two selected scenarios. The construction method used a full-span pre-cast concrete box girder bridge by launching gantry and the demolition operation is done using cut-and-lift method. So, the achieved durations are much less compared to the previous case where a cast in place method was applied for construction operations. Navisworks software is used to link the 3D models with the schedules and to run the 4D visualization. The durations of each span's construction and demolition are directly provided from the results of the developed Discrete Event simulation models shown in Section 3.5.1.

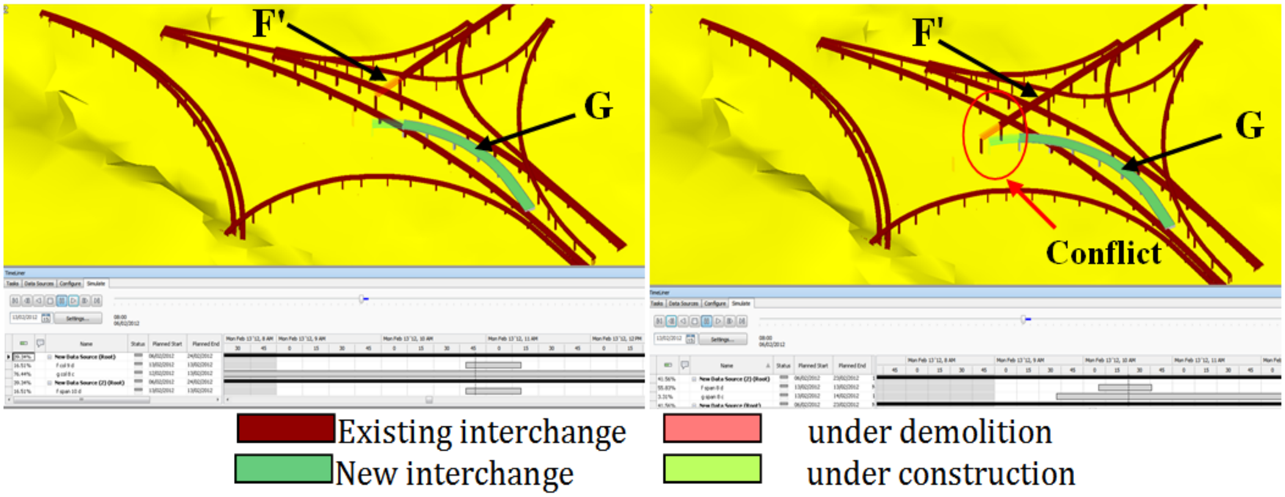
Table 4.6 Activity durations used in the simulation models

Construction Model		Demolition Model	
Task	Duration (minutes)	Task	Duration (minutes)
Trailer_Loading	Normal[15.03,1.71]	Prepare_Span	Triangular[10,15,20]
Trailer Haul	F (Distance, Speed)	Reposition PT	Triangular[8,10,12]
Trolley_Loading	Normal[15.03,1.71]	Rigging	Triangular[5,10,15]
Trailer_Return	F (Distance, Speed)	RepositionRT	Triangular[8,10,12]
Trolley_Travel	F (Distance, Speed)	Cut_Span	Normal[30,2.11]
Reposition	Triangular[180, 210, 240]	RepositionCT	Triangular[8,10,12]
Pickup_Span	Triangular[180, 210, 240]	Load_Trailer	Normal[15.03,1.71]
Trailler_Return	F (Distance, Speed)	RepositionLT	Normal[17.69,1.42]
Place_Span	Triangular[120, 150, 180]	Trailer_Haul	F (Distance, Speed)
Stressing	Triangular[360, 420, 480]	Span_Dump	Normal[5.42,1.3]
		Trailer_Return	F (Distance, Speed)

As shown in Figure 4.23 (a), Scenario 1 will not cause any spatio-temporal conflicts between the segment under construction and the one under demolition. On the other hand, Scenario 2 (Figure 4.23 (b)) will result in both a soft and a hard conflict. The soft conflict is resulting from the lack of clearance space needed for the equipment (launching gantry) to progress. Even if the required clearance is available, a hard conflict exists between the ninth span of the new segment G and a pier of the existing segment F'.

Table 4.7 Duration of span construction and demolition (hours)

Activity	**Scenario 1 (No Conflicts)**		**Scenario 2 (With Conflict)**	
	Construction	**Demolition**	**Construction**	**Demolition**
Span 1	18.52	1.23	17.47	1.27
Span 2	17.32	1.10	15.97	0.99
Span 3	17.51	1.04	16.11	0.98
Span 4	17.96	1.08	16.86	1.01
Span 5	16.46	1.09	15.81	1.11
Span 6	16.85	1.10	15.14	1.00
Span 7	15.91	0.99	16.34	1.03
Span 8	17.06	1.15	16.33	1.00



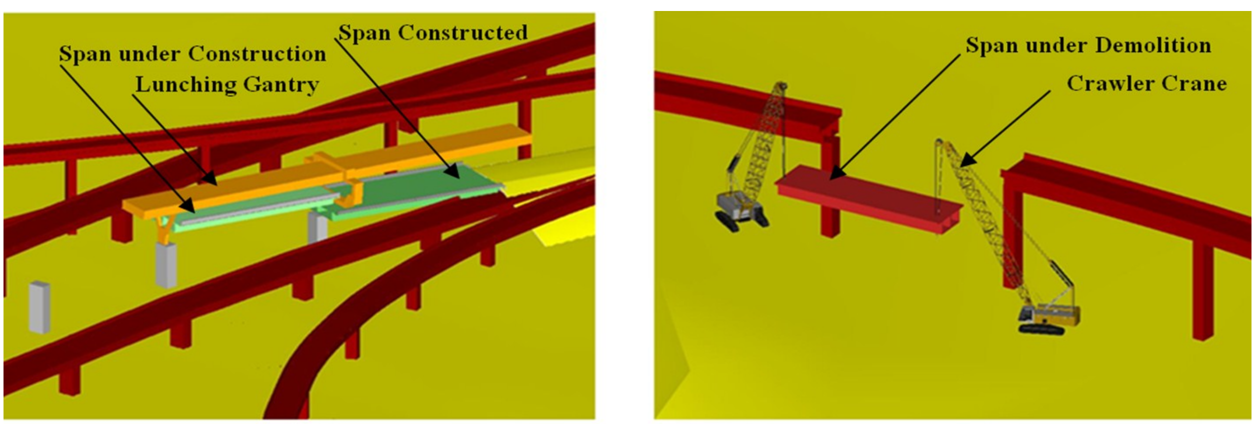
(a) (b)

Figure 4.23 (a) Scenario with no conflict, and (b) scenario with conflict

4.8 Clash Detection

Clash detection is the final step applied in all three cases in order to identify any potential conflicts. Clash detection is done by using clash detective, a feature embedded in Navisworks Manage, from Autodesk software. The first step in clash detection starts with Batch tab which shows the saved project's clashes. Rules tab sets the parameters to run clash detection and can be used to create and modify new rules. Rule tab provides the flexibility to ignore specific types of geometry and items in the same file. Appendix A (Figure A.3) shows the Rules Editor dialog box in Navisworks for creating new rules. In order to create the desired rule for clash detection in Turcot Interchange project, the existing and the new interchange segmnts are saved as two different selection sets. Next, by selecting the "Specified Selection Sets" template from the Rules Editor dialog box, each one of the geometry (existing and new) is assigned to a selection set. The final step before running clash detection is selecting the type of considered conflict and linking the clash detection with the developed timeline as shown in Appendix A (Figure A.4).

Additionally, in order to select the most suitable construction and demolition methods and equipment, a 3D model including the utilized equipment for both construction and demolition operations was created. The developed 3D model is linked with the schedule to create a 4D simulation and to identify the project timeline issues. As mentioned in Scenario 2, a space conflict between the gantry and span 8 of the existing segment F was detected by applying 4D simulation (Figure 4.24 (a)). On the other hand, Figure 4.24 (b) shows two crawler cranes lifting a span as part of demolition operations. This 4D simulation provides a good tool to study the maneuvering space needed for the equipment and to investigate the impact of the selected construction methods and equipment locations on the construction process. Although space conflict detection is possible by assigning a buffer, representing the erected equipment, to the specific segments, modeling the equipment operation can enhance the visualization provided through the proposed 4D simulation.



(a) Launching gantry (b) Two crawler cranes

Figure 4.24 Workflow clash detection through visualized construction equipment

4.9 Summary and Conclusions

Three case studies provided for this research showed the functionality of the proposed methods. The same project (Turcot Interchange in Montreal Island) was selected for all cases, while in each case a different research objective was considered for investigation. This chapter presented an in-depth description of the 3D modeling development processes and proposed methodology steps employed to construct the three cases. Case 1 demonstrated the functionality of the proposed sequence assessment approach and resulted in a sequence as an appropriate process chain for simulation techniques. Case 2 and case 3 were developed to investigate the application of the proposed probabilistic 4D model for identifying potential conflicts based on Monte-Carlo and Discrete Event simulations, respectively. Furthermore, a clash detection process was implemented to identify potential conflicts involved with each case.

In addition, a 3D model of the project including the utilized equipment for both construction and demolition operations was created in order to select the most suitable construction and demolition methods and equipment. The enhanced visualization linked with the schedule of project was used for identifying workflow clashes which refer to the scheduling clashes for work crews, equipment including soft and hard clashes.

CHAPTER 5 Conclusions and Future Work

5.1 Summary of Research

An intensive amount of reconstruction and rehabilitation work is expected on the existing highway infrastructures in North America. Such activities affect drivers, highway workers, businesses and other community functions (Jeannotte & Chandra, 2005; Mahoney et al., 2007). Hence, the duration needed for construction processes is a vital factor in reconstruction of urban highway projects. Elevated urban highway reconstruction projects involve complex geometry and limited space available which lead to spatio-temporal conflicts. Maintaining acceptable flow of traffic without compromising safety in highway construction zones also complicates the planning process. Overall, the phasing of construction work in such projects is complicated due to the structural complexity of such projects, large number of involved contractors, independent resource utilization planning by each contractor, and the vast number of activities that will be taking place at the same time (Dawood & Shah, 2007; Hannon, 2007; Saag, 1999).

This research proposed the application of 4D modeling and simulation in the planning and scheduling phases of elevated urban highway reconstruction projects to detect any spatio-temporal conflict. The proposed methodology presented a sequence assessment approach using a deterministic 4D model in the planning stage. Then, a probabilistic 4D model is introduced by integrating simulation and 4D modeling for scheduling of elevated urban highway reconstruction projects. This research also used the 4D model of the project including the visualization of the utilized equipment in order to investigate the suitability of the construction and demolition methods and equipment. Furthermore, a new approach of 3D and 4D modeling development process is employed to realize the proposed methods of this research. The new benefits of the proposed approach are highlighted, and the feasibility of the proposed methods is explored through three case studies.

5.2 Research Conclusions

This research proposed a simulation-based 4D modeling approach for planning and scheduling of elevated urban highway reconstruction projects by integrating simulation and 4D modeling techniques. The main contributions of this research are:

(1) This research investigated the applications of 4D modeling for sequence assessment in the planning stage of elevated urban highway reconstruction projects. A deterministic 4D model is developed by linking the 3D model of the project with a deterministic schedule. The developed 4D model is integrated with the proposed sequence assessment approach to define the order in which the segments should be constructed or demolished. The result of this step is a sequence which will be used as the process chain for simulation techniques. The sequence assessment approach in this research is capable of assessing all the possible sequences in order to find an acceptable sequence to overcome the limitation of one fixed process chain.

(2) This research investigated a new approach integrating simulation with 4D modeling to create a probabilistic 4D model of elevated urban highway reconstruction projects. The probabilistic 4D model is created by linking the 3D model of the project with the generated probabilistic schedules from Monte-Carlo and Discrete Event simulations. The proposed approach is capable of identifying the scenarios with the highest potential conflict and calculating the probability associated with each scenario. Different starting points of the demolition operation can be examined in order to avoid any potential conflicts.

(3) This research also investigated a new process for realizing the proposed method using available tools.

5.3 Limitations

This section explores the challenges and limitations identified during this research which would be explained in two parts:

5.3.1 Software Limitations

The main issues encountered during this research are specific to the software applications used and the needed interoperability between different software. This research proposed a new process of 3D modeling to realize the proposed methods by using several tools. The 3D modeling software tools used for this research have limited functions which caused to use different applications and several data exchanges. For instance, InRoads software has limited functions for bridge modeling, so the bridge 3D modeling was done in LEAP Bridge software based on the road alignments extracted from InRoads; then importing the bridges designed in LEAP Bridge into InRoads (as DWG file) to integrate with the road parts. This process caused to lose the data attached to the objects of the bridge model in LEAP Bridge (e.g. names and properties of piers) which are useful to keep in the 4D model. Moreover, the LEAP Bridge software used for bridge 3D modeling is limited to the design of only three bridges at the same time in a project file as shown in Appendix A (Figure A.7). Therefore, all the ramps were modeled separately and exported to InRoads software in order to have the whole geometry of the project.

As mentioned in Section 3.5.2, the developed probabilistic 4D model should be run for a large number of schedules in order to identify any potential conflicts involved with different scenarios.

To do so, the result of each replication of simulation is used to create a different schedule. To investigate all the possible scenarios, this process needs to be automated due to the large number of replications. Another major issue was due to the inability of the 4D software to link the 3D model with the large number of schedules in a fully automated process. Overall, the desired interest in developing the probabilistic 4D model is finding a procedure to generate different scenarios of 4D modeling using the result of simulation in an automated way. This automation provides the ability to investigate all the possible scenarios and any potential conflicts involved with each scenario.

5.3.2 Case Study Limitations

The case studies are inspired by the Turcot Interchange reconstruction project in Montreal, Canada. Because this high-profile project is still in the planning stage, it was not possible to get any details about the final geometry or the scheduling of the project. Therefore, the case studies are based on the limited data that were published about the project or obtained directly from the project office. Many assumptions have been introduced to create the geometry of the 3D model and the activity durations used in the simulation. Overall, the case studies' limitations would be summarized as follows:

(1) Unavailability of complete data for creating a more realistic case study; and

(2) Lack of accessibility to sufficient highway construction firms to have more reliable task durations.

5.4 Future Work

Considering the explained challenges and issues for applying 4D modeling in highway projects, there are several opportunities that could be investigated in future research:

(1) The sequence assessment method proposed by this research evaluated all possible sequences based on different strategies of resource allocation. This method allows to assess all possible combinations and selected a sequence which has no conflict and the least duration. As explained before, this approach is applicable when the crews have the same production rate and the amount of job assigned to each crew is equal. Therefore, it would be more valuable to integrate optimization techniques with the proposed sequence assessment approach to consider other factors such as crews with different production rates, variable amounts of job, and the costs associated with each scenario

(2) As mentioned in Section 5.3.1, the result of simulation is used to create different schedules for developing the probabilistic 4D modeling approach. Future research should find an automated way for this process in order to consider the large number of schedules.

(3) Future research could explore methods of 4D modeling for the road parts of highway projects where the continuous earthwork activities would not fit with the finite objects needed for 4D modeling. Applying 4D modeling for the road parts would facilitate the process of quantity takeoff and other purposes such as AMG.

(4) Maintaining an acceptable flow of traffic in highway reconstruction planning is an essential element. Future research should integrate traffic simulation with the proposed 4D modeling approach for developing traffic and construction phasing plans.

(5) Developing a more integrated standard process in transferring data between different software would solve a large number of encountered issues in developing 4D models.

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APPENDIX A: Details of 3D Modeling Process

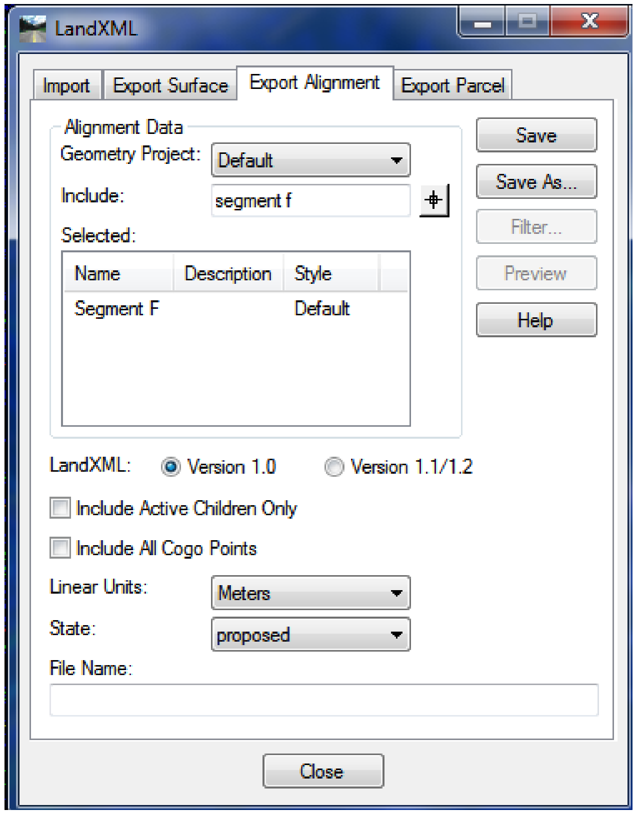

Figure A.1 Exporting geometry file into LandXML format in InRoads

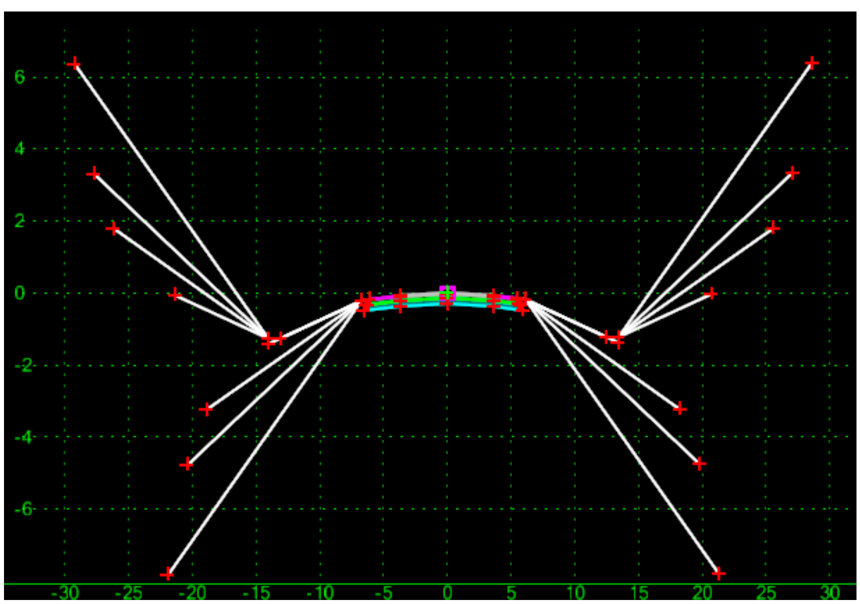

Figure A.2 A typical project template in InRoads

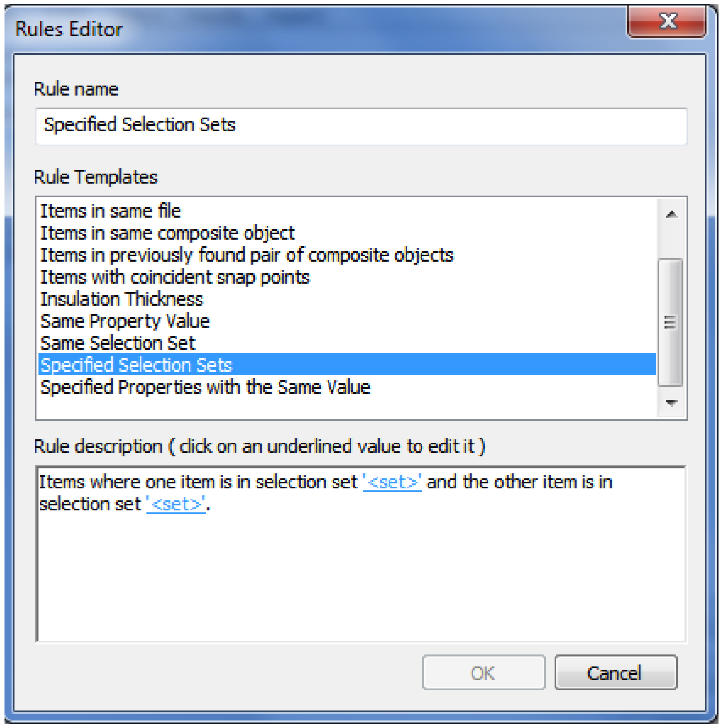

Figure A.3 Rules Editor dialog box in Navisworks Manage

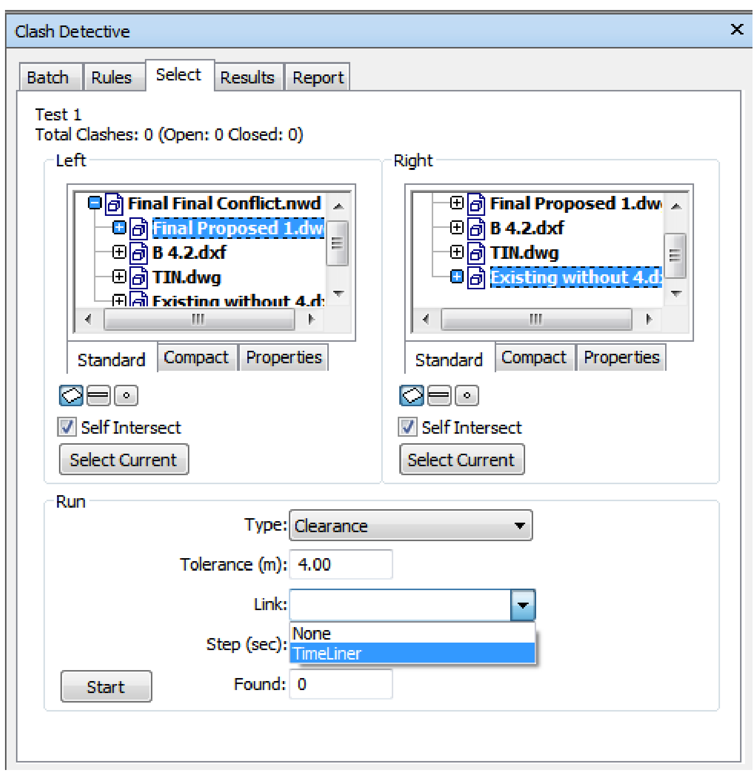

Figure A.4 Select tab in clash detective, Navisworks Manage

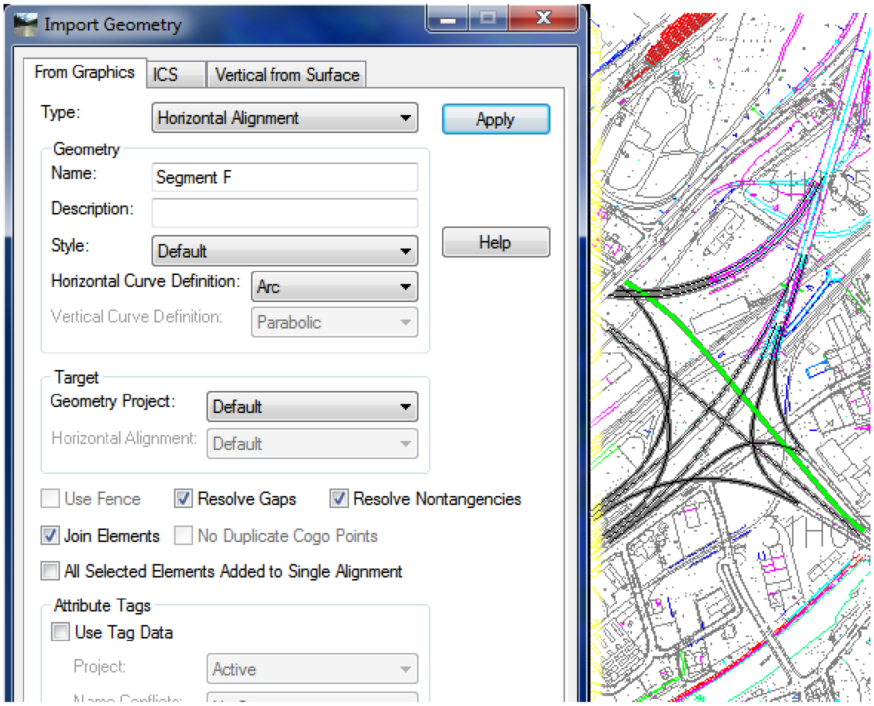

Figure A.5 Creating horizontal alignment (Segment F) form digital map data in InRoads

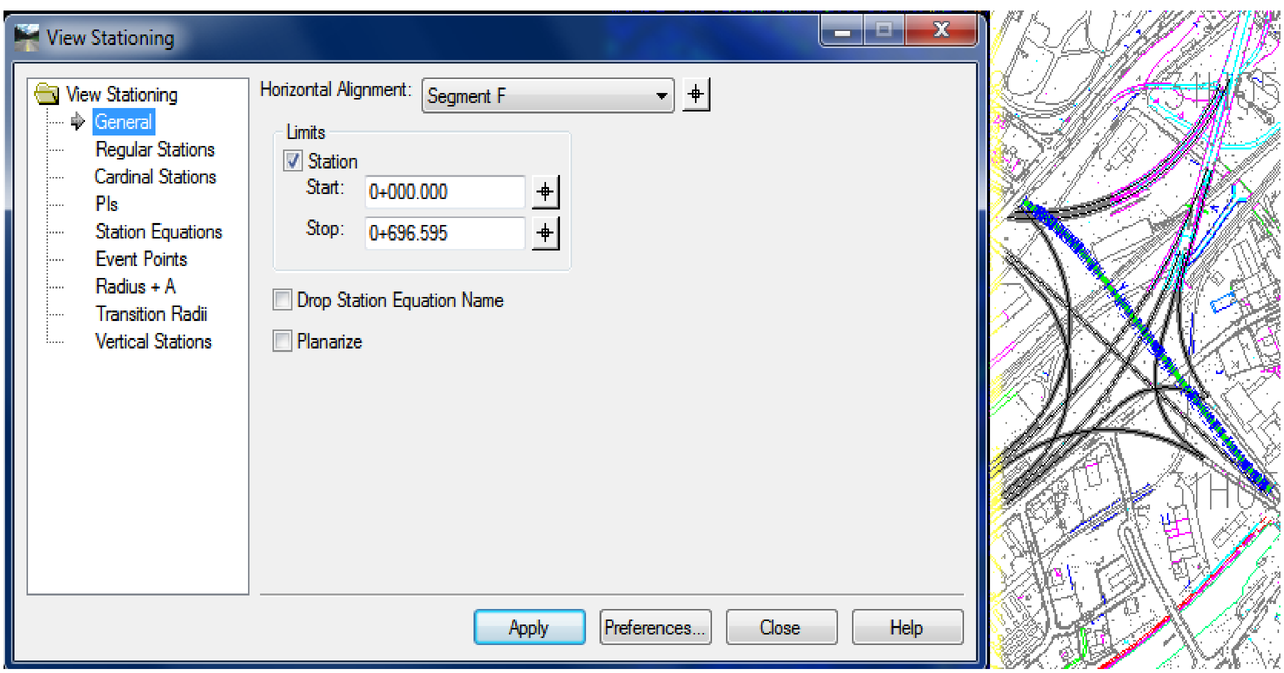

Figure A.6 Stationing horizontal alignment in InRoads

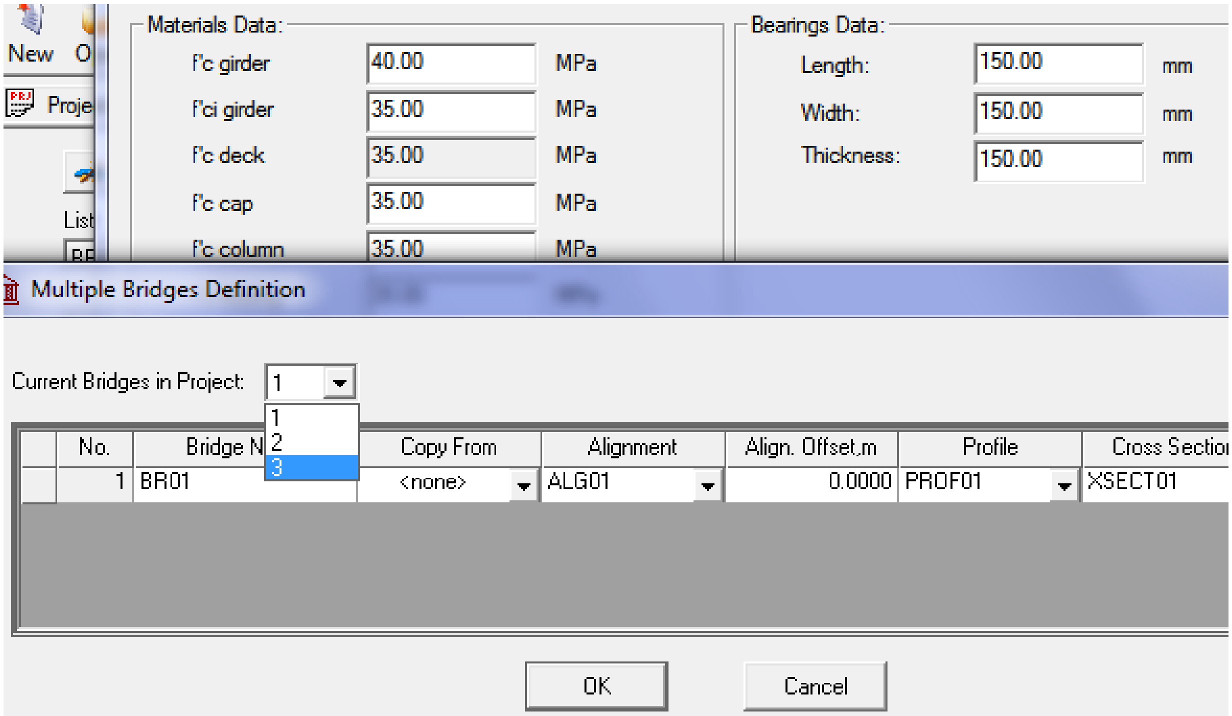

Figure A.7 Limited number of bridges in a project file, LEAP Bridge

APPENDIX B: Part of an XML File of a Bridge Model Created in "LEAP Bridge" Software


```
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    <Health>Healthy</Health>
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  - <XSectionList>
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      <Health>Healthy</Health>
      <Name/>
      <PgmGen>true</PgmGen>
    - <XSecVarItem>
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        <Name>XSecVar3172154</Name>
        <XSecRefID>614</XSecRefID>
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    <SectionMember/>
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- <Girder>
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    - <XSecVarItem>
        <ObjectID>668</ObjectID>
```

APPENDIX C: List of Publications

- Doriani, A., Mawlana, M., & Hammad, A. (2013). Simulation-Based 4D Modeling for Planning and Scheduling of Elevated Urban Highway Reconstruction Projects. *TRB 2013,* Washington, U.S. (submitted)
- Hammad, A., Vahdatikhaki, F., Cheng, Z., Mawlana, M., Doriani, A. (2012). Towards the Smart Construction Site: Improving Productivity and Safety of Construction Projects Using Multi-Agent Systems, Real-Time Simulation and Automated Machine Control. *Winter Simulation Conference 2012*, Berlin, Germany.
- Mawlana, M., Hammad, A., Doriani, A., & Setayeshgar, S. (2012). Discrete event simulation and 4D modelling for elevated highway reconstruction projects. *ICCCBE 2012,* Moscow, Russia.
- Hammad, A., Mawlana, M., Doriani, A., & Chedore, D. (2012). Simulation-Based 4D Modeling of Urban Highway Reconstruction Planning. *TRB 2012,* Washington, U.S.