EVALUATION OF LINEAR-SCHEDULING-BASED 4D MODELING APPROACHES

by

Amir Mohammad Tangestani Zadeh

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Abstract

Project teams face increasing pressure to deliver projects as quickly as possible. To satisfy these demands, contractors must explore various construction strategies to meet delivery dates. Using existing tools for large-scale horizontal and vertical projects characterized by significant repetition of components, the lack of ease with which alternative strategies can be formulated and evaluated precludes meaningful exploration.

To address this problem, an approach has been developed at UBC that leverages a generalized implementation of linear scheduling coordinated with a 3D building information model to produce 4D images. This approach enables a more generic mapping mechanism between product and process models that works at multiple levels of detail.

In this thesis, we compare this research-based approach with a commercial 4D platform that also employs linear scheduling concept to formulate its process model. This evaluation is based on a detailed case study of an actual high-rise construction project and it compares the development, functionality, and flexibility of the two approaches based on the features required of a 4D modeling environment with linear scheduling capabilities which facilitates the speedy formulation and evaluation of alternative construction strategies and which provides insightful visual feedback.

Preface

The author of this thesis, Amir Mohammad Tangestani Zadeh, was responsible for substantial contributions to the content and writing of the co-authored manuscript presented in Chapter 2. He played a lead role in writing this manuscript. The analysis performed on each of the systems, as well as the whole discussion on how the two examined systems compare with each other was done by him.

Some parts of the analysis and information used in the above-mentioned chapters was based on previous research conducted by the co-authors of the thesis: Dr. Alan Russell (professor, Dept. of Civil Engineering, University of British Columbia, and Chair, Computer Integrated Design and Construction), Dr. Sheryl Staub-French (associate professor, Dept. of Civil Engineering, University of British Columbia), and Ngoc Tran (research assistant, Dept. of Civil Engineering, University of British Columbia).

The co-authors participated in the development and drafting of ideas and were equal partners with the thesis author in the review and revision of the manuscript.

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The author wishes to express his gratitude to his supervisors, Prof. Dr. Sheryl Staub-French for her supervision, guidance and motivation throughout this research, and Prof. Dr. Alan Russell without whose knowledge and assistance this study would not have been possible.

The author would also like to convey his regards and blessings to all of those who supported him in any respect during the completion of the project, especially Helia Amiri and Behzad Pilehchian who kindly read the thesis and provided the author with priceless comments.

The author wishes to express his love and gratitude to his beloved parents for their understanding and endless love, through the duration of his studies.

To my Rezvaneh…

Chapter 1: Thesis Overview

1.1 Introduction

On time and within budget delivery of projects is becoming more and more critical to the existence of teams involved in the construction industry. The need to assess alternative strategies both prior to construction (trying to meet project objectives in the most efficient way while accounting for any hard constraints including regulatory ones) and during construction (coping with changes in conditions) is of vital importance to contractors. Having access to tools and techniques by which formulation and exploration of various construction scenarios are made easy is an important asset for any contractor to satisfy project needs and to meet delivery dates. An example of this situation would be the execution phase of a project, where formulation and evaluation of recovery schedules become important. Contractors are forced to modify their current construction strategies from time to time, in order to cope with unforeseen circumstances imposed on projects. Using existing tools for large-scale horizontal and vertical projects characterized by significant repetition of components, the lack of ease with which alternative strategies can be formulated and evaluated precludes meaningful exploration.

Using 4D modeling as a response to the need for formulating, evaluating and comparing alternative construction scenarios has faced stakeholders with challenges such as: how best to formulate the construction scenario at hand in the first place, or how best to reflect the changes made to sequence and duration of the tasks in the 4D model. In order to improve current 4D approaches to assist with the formulation and evaluation of alternative construction strategies, the features corresponding to these challenges need to be identified and addressed.

In this research, these features were identified. Based on the identified features, and by making use of an actual case study, two linear-scheduling-based 4D approaches were evaluated and compared against each other. Strengths and weaknesses of each approach are discussed and the areas to be focused on in future research are determined.

1.2 Literature review

There has been very little research to date on the integration of 4D and linear scheduling. A few efforts have looked at combining 4D with line-of-balance (LOB) representations. Jongeling and Olofsson [1], explored the benefits of combining 4D with line-of-balance (LOB) techniques on a project in Sweden. They found that 4D helped to identify workflow issues that were not evident in the LOB charts. Based on these results, they propose a process model for the planning of work flow in construction that includes model-based methods for cost estimation, production planning and simulation. Akbas [2], developed a LOB diagram style interface as part of a 4D application. The LOB interface aids the definition of crew sequences, their mobilization date and production capacity. This approach also supports the generation of LOB charts for a given 4D status. However, these approaches focus more on the presentation of LOB charts rather than the integration of linear scheduling and 4D. Some research efforts, [3],[4],[5],[6],[7], have focused on 4D modeling as a communication tool to visualize the construction process, and how it could provide construction planners with the opportunity to assess the constructability of a proposed design and construction plan. With respect to evaluation of construction scenarios and how CAD tools can assist decision makers, Fischer [8],[9],[10],[11],[12], has conducted significant research and case studies. Russell [13],[14],[15],[16],[17],[18],[19], has done extensive research on the visualization of construction scenarios, as well as application of linear scheduling methods in construction projects using a research tool called Repcon. Work by other authors in this area includes: [20],[21],[22],[23],[24],[25]. However, very little work has been done to date by others on exploiting the combined benefits of linear scheduling and 4D CAD to formulate and evaluate alternative construction scenarios.

With reference to the previous research conducted by Russell and Staub-French [26],[27], a 4D modeling approach has been developed that leverages a generalized implementation of linear scheduling coordinated with a 3D building information model to produce 4D images. This approach enables a more generic mapping mechanism between product and process models that works at multiple levels of detail.

The concept of "strategy", has been discussed in several papers including [6],[26],[27]. Russell [15], has defined "strategy" as "plan of attack" which consists of: sequencing, methods, resource levels, etc. Based on this definition and with respect to the thesis, an important point to mention here is that in the context of this research, a construction "strategy" is different from a construction "scenario". A "scenario" consists of one or more "strategies". By using the term "scenario" we mean the whole storyline that corresponds to a construction schedule in general (e.g. the base scenario in this research refers to the base schedule developed for actual construction of the building). But a "strategy" is the specific method, sequencing, or resource level used in a "scenario" (the same definition from [15] was used - e.g. the recovery strategy in this research refers to the methods of tower enclosure system installation).

1.3 Research objectives

The specific objectives of this research are to share some of the insights generated to date with respect to use of a commercial platform (Vico Software) that “does it all”, and comparing that to the current state of a research approach (Repcon-Revit), the goal of which is to provide enhanced modeling capability and enhanced flexibility. The effort will be directed toward contributing to the development of a flexible tool kit. Specific objectives of this research relate to:

1) Exploring the steps involved in formulating a construction scenario, and analyzing the challenges/constraints encountered in each of the 4D approaches (Vico Software vs. Repcon-Revit).

2) Exploring the steps involved in reflecting the modifications made to the construction scenario at hand, and analyzing the challenges/constraints encountered in each of the 4D approaches.

3) Identifying the features required of a 4D environment by which alternative construction scenarios could be formulated and evaluated easily.

4) Comparing the two approaches with respect to the required 4D environment features identified in (3), assessing the strengths and weaknesses of each of the approaches, and proposing the areas where future work and research could be focused on.

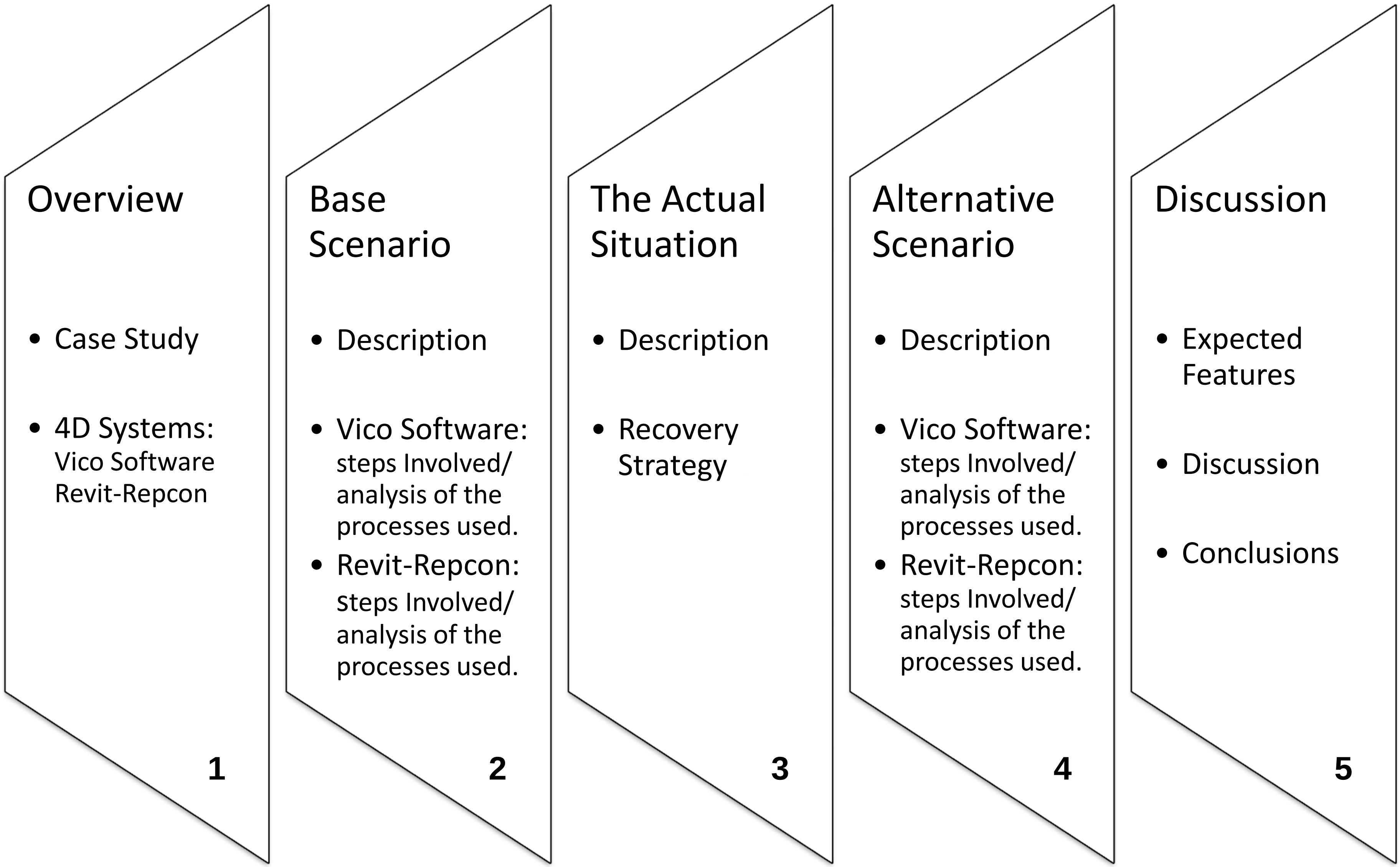


Table 1.1 Research methodology, illustrating the storyline of the research

1.4 Research methodology

The methodology employed in pursuit of the research objectives is summarized in Table 1.1 and elaborated upon as follows:

1.4.1 Describing the case study

The Hotel Georgia located in Downtown Vancouver was selected as the case study to be examined for this research. The project consists of three sections which are: existing hotel, hotel extension, and a tower. The tower section of the project provides the focus for developing the alternative construction scenarios examined.

1.4.2 Describing the 4D approaches examined

The following two approaches were examined:

a) Vico Software 4D approach (hereafter called "Vico Software system"), which consists of several modules such as Constructor for 3D modeling, Control for linear scheduling, and 5D Presenter for visualizing the 4D model.

b) Repcon-Revit 4D approach (hereafter called "Repcon-Revit system"), which is a research based 4D approach and generates 4D snapshots by mapping the product and process models using an intermediary module.

1.4.3 Base construction scenario

The starting point is the development of a base construction scenario that reflects the actual construction schedule of the building when it was started.

1.4.4 Formulation of the base scenario

Describing the steps involved in formulating the base scenario for each of the systems examined, and discussing the challenges faced separately for each system.

1.4.5 Delay in tower enclosure procurement

Describing an actual situation that occurred (delay in fabrication of enclosure, followed by the recession) during the construction phase, and which made the exploration of alternative construction scenarios essential.

1.4.6 Alternative construction scenario

Developing several alternative construction scenarios to cope with the actual situation encountered, and focusing on one alternative scenario to be examined in the two 4D systems. For the purpose of the alternative scenario selected, a "recovery strategy" was introduced to the base scenario at hand. The recovery strategy corresponded to the number of crews working on the enclosure, and the sequence of completing the enclosure installation at each level of the tower (level 14 and beyond), so that by accelerating the installation of enclosure, the project could be brought back on track. The recovery strategy examined consists of a number of components which need to be considered separately and which include: construction method; granularity of activity definition; activity sequencing; granularity of product model definition; resource allocation (crewing); number of work faces (zoning); temporary facilities; material handling; definition of the work week; and, onsite vs offsite production of components.

1.4.7 Formulation of the alternative scenario

Describing the steps involved in formulating the alternative scenario by making changes to the base scenario at hand in each of the systems examined, and discussing the challenges faced separately for each system.

1.4.8 4D environment features

Describing the features required of a 4D environment by which alternative construction scenarios could be formulated and evaluated easily. Based on the desired functions, the features are categorized in 4 groups: process model; product model; mapping; and, visualization. With respect to each of these functions, the features relate to; formulate/add/remove/modify/manage components; defining/ redefining zoning; and, the level of automation provided.

1.4.9 Discussion

Comparing the two systems with respect to the required 4D environment features identified in (8) in the context of the case study at hand. With respect to formulation of the current construction scenario (the base scenario), the features identified for examination include: linear schedule formulation capabilities; 3D model formulation capabilities; link establishment capabilities (between tasks from the linear schedule and CAD components from the 3D model); zoning capabilities; degree of automation allowed in setting up the schedule; 3D model and links; format of the project breakdown structure both on the schedule as well as the 3D model side; and, finally the visualization tools and capabilities provided by the 4D environment. With respect to formulation of the alternative construction scenario, the features identified for examination include: linear schedule modification capabilities; 3D model modification capabilities; and, links management capabilities (add/remove/modify the links between tasks from the schedule and CAD components from the 3D model).

1.4.10 Conclusions

Proposing the areas where the future works and research could be focused on with respect to developing a 4D environment with linear scheduling capabilities that facilitates the formulation and evaluation of alternative construction scenarios.

1.5 Scope and context

Four points of importance to consider regarding the scope and the context of the research conducted in this thesis are:

a) The context is large-scale linear projects (high-rise buildings, bridges, guideways, etc.), with the particular focus in this thesis being on vertical construction;

b) The scope of the research with respect to formulation of the alternative scenario, covers the changes made to the construction methods and strategies used. The design is taken as fixed. Moreover, in formulating the base scenario, the challenges faced and discussed relate to a multi-facility project (there are three facilities in the project to model), which adds more complexity to the formulation of the base scenario. However, in formulating the alternative scenario, attention was focused on a single facility project, where the changes in construction strategies happen on one of the three facilities present in the project. That having been said, the ultimate goal of this research would be the assessment of design changes in combination with construction strategies for multi-facility projects.

c) The case study used for the purpose of this research was examined in full scale. An important factor to consider when evaluating 4D modeling tools is to reflect and deal with projects at full scale. The scale of actual projects constitutes part of the challenge of formulation and making changes to a 4D model.

d) With respect to the Vico Software approach, many of the constraints identified in the process, arose from the fact that the 3D model was not formulated from scratch in the Vico system. This was done purposely, but it is also believed that if the 3D model was formulated from scratch in this system, many of the constraints would have not been there.

1.6 The manuscript overview

This thesis consists of an introduction chapter which summarizes the storyline followed in the research conducted, and a conclusion chapter which outlines the results. Chapter 2 constitutes the main body of the thesis and focuses on the specific contributions. In this chapter, the two 4D approaches are introduced and applied to the base and alternative construction scenarios at hand. Then, the two 4D approaches are compared based on the features required of a 4D environment. Appendices A and B illustrate the 4D snapshots generated for each of the two 4D systems examined.

Chapter 2: Evaluation of Linear-Scheduling-Based 4D Modeling Approaches

2.1 Introduction

Project teams face increasing pressure to deliver projects as quickly as possible. To satisfy these demands, contractors must explore various construction strategies to meet delivery dates. In the execution phase of a project, evaluation of recovery schedules would be a challenge when contractors are forced to modify their current strategies in order to cope with the circumstances imposed on the project. Using existing tools for large scale horizontal and vertical projects characterized by significant repetition of components, the lack of ease with which alternative strategies can be formulated and evaluated precludes meaningful exploration.

Using 4D modeling as a response to the existing demand of formulating, evaluating and comparing construction scenarios has faced stakeholders with essential limits (e.g. how best to reflect changes made to the sequence, duration, resource usage, etc. in a 4D model). In order to improve current 4D approaches to assist with the formulation and evaluation of alternative construction strategies, the features corresponding to these challenges need to be identified and addressed.

In this research, these features were identified. Based on the identified features, and by making use of an actual case study, two linear-scheduling-based 4D approaches were evaluated and compared against each other. Strengths and weaknesses of each approach are discussed and the areas to be focused on in future research are determined.

There has been very little research to date on the integration of 4D and linear scheduling. A few efforts have looked at combining 4D with line-of-balance (LOB) representations. For example, Jongeling and Olofsson [1] explore the benefits of combining 4D with line-of-balance (LOB) techniques on a project in Sweden. They found that 4D helped to identify work flow issues that were not evident in the LOB charts. Based on these results, they propose a process model for the planning of work flow in construction that includes model-based methods for cost estimation, production planning and simulation. Akbas [2] developed a LOB diagram style interface as part of a 4D application. The LOB interface aids the definition of crew sequences, their mobilization date and the production capacity. This approach also supports the generation of LOB charts for a given 4D status. However, these approaches focus more on the presentation of LOB charts rather than the integration of linear scheduling and 4D. Some research effort have focused on 4D modeling as a communication tool to visualize the construction process, and how it could provide construction planners with the opportunity to assess the constructability of a proposed design and construction plan [3],[4],[5],[6],[7]. With respect to evaluation of construction scenarios and how CAD tools can assist the decision makers in this area, Fischer [8],[9],[10],[11],[12] has conducted significant research and case studies. Russell [13],[14],[15],[16],[17],[18],[19] has conducted extensive research on visualization of construction scenarios, as well as application of linear scheduling methods in construction projects, based on which he has developed Repcon, a location-based linear scheduling software at the UBC. Some other works in this area include: [20],[21],[22],[23],[24],[25].

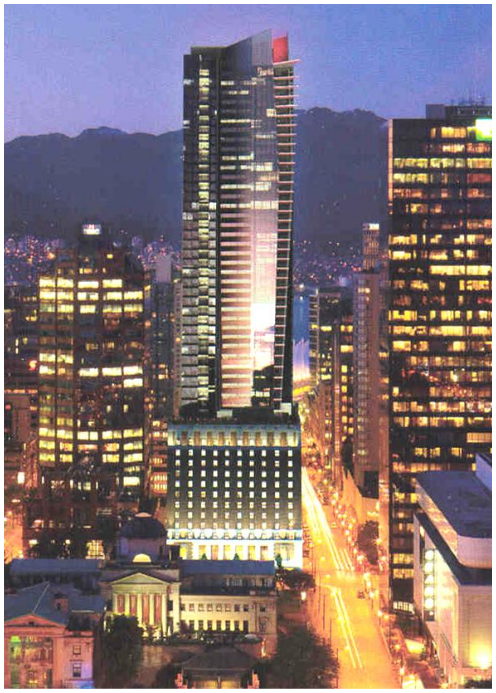
The specific objectives of this research are to share some of the insights generated to date with respect to use of a commercial platform that “does it all”, and comparing that to the current state of a research approach the goal of which is to provide enhanced modeling capability and enhanced flexibility. This evaluation is based on a detailed case study of an actual high-rise construction project and it compares the development, functionality, and flexibility of these tools. Findings relate to the features required of a 4D modeling environment with linear scheduling capabilities which facilitates the speedy formulation and evaluation of alternative construction strategies and which provides insightful visual feedback.

The methodology used to address the research objectives involves: 1) Description of the case study that corresponds to an actual project; 2) Description of the tools used; 3) Formulation of the base scenario and discussion of the challenges faced in each of the 4D approaches used; 4) Treating an actual situation that occurred, by applying one schedule recovery strategy to the base scenario; 5) Formulation of the alternative scenario and discussion of the challenges faced in each of the 4D approaches used; 6) Identifying the features required of a 4D environment by which alternative scenarios could be formulated and evaluated easily; and, 7) Comparing the two approaches with respect to the required 4D environment features identified in (6).

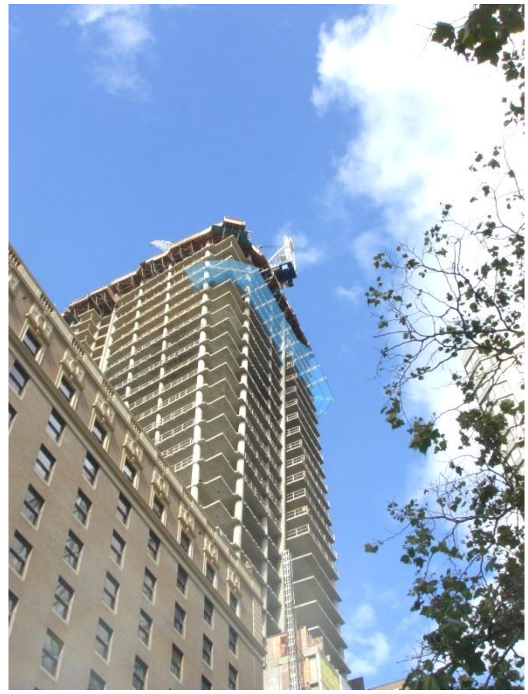
2.2 Overview of case study

The Hotel Georgia project is located in downtown Vancouver. The project is comprised of 3 sections: existing hotel, hotel extension (hereafter called "infill"), and a tower. The scope of the project includes: 1) Renovation of the existing hotel, 2) Construction of the infill structure, and 3) Construction of a mixed-use tower for commercial and residential purposes, 4) Construction of an 8-storey parkade under the area of the infill and the tower.

The tower is a 49-storey building. Levels 1-12 are for commercial use, and levels 14-49 are for residential use. Many constraints needed to be considered in the course of the project. A tight and congested site (see Figure 2.1a for some of the surrounding structures), limited material storage area, restricted street access, noise by-laws, labor shortages, delay in procurement of materials, and the fact that the project is a combination of rehab and new construction, are some of these constraints. In this section, the storyline of the project with respect to the case study at hand is described.



(a)



(b)

Figure 2.1 Case study project: (a) Architectural rendering of finished project and, (b) Project status of September 2010 showing delayed start of exterior enclosure.

2.2.1 The base scenario

The base construction scenario (hereafter called "Base Scenario") was drafted during the very early phases of the project (the end of 2008). At that time, renovation and finishing works of the existing hotel were critical for the project. Also the tower consisting of heavy superstructure construction was required to be completed up to level 12 in the first phase of the project. In the course of the project several major changes occurred. However, the “base scenario” which is represented in this research is sufficient to show superstructure construction of the actual project as well as installation of the outer skin of the building. The lag between actual construction of the superstructure compared to our base scenario - which is an early schedule - is approximately 3 months.

The focus of the base scenario examined is mainly on the sequence of tasks needed to build and form the exterior skin of the tower (hereafter called “enclosure”), and how it follows the sequence of tasks involved in building the tower’s superstructure.

2.2.2 Delay in procurement of enclosure followed by the recession

The project was initially planned to be ready for the 2010 Olympics. However, complications in site preparation, excavation, and shoring made that very difficult to achieve. The 2010 Olympics deadline for completion of the hotel and the infill was abandoned due to the global financial crisis which affected the financing of the project, resulting in a cash flow constraint that slowed the work. In addition, the decision to source the enclosure system from China, with its attendant fabrication and shipping problems, became a significant source of difficulty. Also, finishing work of the hotel renovation was delayed to the middle of May 2009 so that infill and renovation work could be finished together. The hotel and residential levels of the tower were scheduled to be finished by September 2010 and June 2011 respectively. These completion dates were extended considerably given the difficulties encountered with the enclosure system (see Figure 2.1b). Recently, with a pickup in the market and financing in place, timely delivery has become more urgent

2.2.3 Alternative scenario

In order to make up time in relation to the base schedule and to minimize the consequences of the unforeseen circumstances imposed on the project, alternative construction scenarios had to be formulated assessed. The ease with which these tasks could be pursued is of critical importance to the project management team in terms of making informed decisions regarding the workability and relative effectiveness of the strategies available to them. In this thesis we focus on the challenges involved in formulating and evaluating alternative scenarios and how each of the two approaches (commercial vs.research) responds to the need to formulate and evaluate different construction scenarios.

To catch-up with the base scenario and to reduce the consequences of the delay in procurement of the tower's enclosure system and follow up work for the level 14 and above, several alternative schedules were suggested. We chose one of these for formulation and evaluation in both Vico Software and Repcon-Revit systems. The main strategy introduced to the alternative schedule to accelerate the installation of enclosure, called the "recovery strategy", corresponds to the number of crews working on the enclosure and the sequence by which they complete installation of the curtain wall on each floor.

2.3 Overview of tools used and what is involved

In this section the 4D systems used for formulating and applying changes to the base construction scenario are discussed. A brief overview of the internal processes that each of the systems uses in its approach toward linear-scheduling-based 4D modeling is also presented.

At the time of writing this thesis, Vico Software was the only commercial 4D platform available. It enables the integration of a linear schedule and a 3D model in order to generate a 4D model. The 2009 version of Vico Software was used to formulate the construction scenarios described in this research. This was the latest educational version of Vico Software available at the time of conducting the research described. It is believed that the analysis conducted on the version of Vico Software used herein, is applicable to at least the next version of Vico Software. This is because the modules discussed herein remained almost unchanged in the next version. With respect to the next version of the software, Vico changed its focus to development of the Vico Office Suite product which includes a new series of Vico modules.

Vico Software is comprised of several modules including: Vico Constructor (hereafter called "Constructor") for building the 3D model and managing the process of mapping 3D components with the schedule tasks, Vico Control (hereafter called "Control") which is a linear scheduling application to formulate the schedule with, Vico 5D Presenter (hereafter called "5D Presenter") by which the user can view, represent, and manage the final 4D model, and Vico Estimator (hereafter called "Estimator"). Figure 2.2 illustrates the flow of information between different modules of Vico Software system. The process of using the Vico Software system starts with formulating the 3D model in Constructor. The schedule tasks are also defined in Constructor, and the mapping between the tasks and 3D components is made possible by means of Recipes. A "Recipe" is an information package which includes the Methods by which a building component will be built. By assigning Recipes to 3D components, and mapping the defined tasks with their corresponding Methods/components, the project is ready to be sent to Control for scheduling. After scheduling is done in Control, the time data is brought back to Constructor and attached to the 3D components. The final step is to define the visualization options of the 4D model in Constructor, and send the project to 5D Presenter in order to visualize the 4D model (see section 2.4.2.1 for a detailed description of the steps involved).

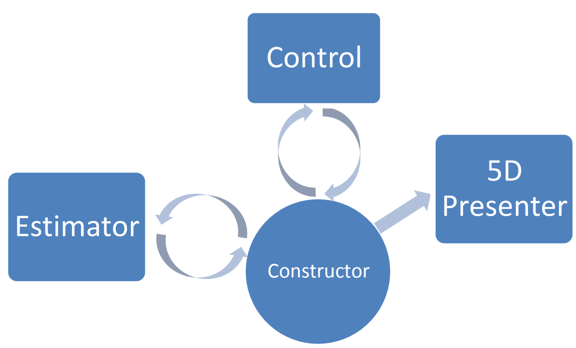


Figure 2.2 Flow of information between different modules of Vico Software system.

The Repcon-Revit system is the research-based approach studied in this thesis. By examining this 4D system, we seek to examine the challenges that exist with formulating and reformulating strategies, which is not a strength of current technologies but which this research system seeks to address. The two primary tools used in this approach are: Autodesk's Revit as the 3D modeling module, and

Repcon as the linear scheduling module. This prototype construction management system treats generalized CPM including linear or time-space scheduling, true hierarchical scheduling, and a multi-view representation of a project, including a product view (referred to as the physical component breakdown structure (PCBS)). An association between PCBS components (product view) and schedule activities (process view) can be mapped onto the CAD product model. The linkage between the two tools is by way of a Microsoft Access database application which allows mappings to be made between the product model objects in Revit and the product view in Repcon. Figure 2.3 illustrates the flow of information between different modules of Repcon-Revit system. Use of the Repcon-Revit system starts by formulating product and process views of the scheduling system in Repcon. The next step is to formulate the product model on the Revit side. Then a mapping is made between the product and process models using an intermediary module, to create an integrated CAD-PCBS model. The final step is to generate 4D snapshots (see section 2.4.3.1 for a detailed description of the steps involved). Figure 2.4 shows the main steps involved in using each of the two 4D approaches.

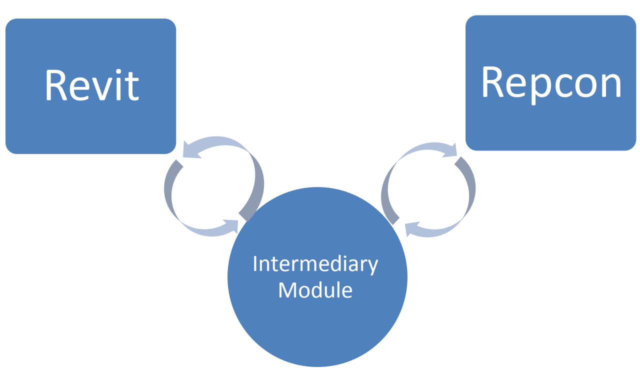


Figure 2.3 Flow of information between different modules of Repcon-Revit system.

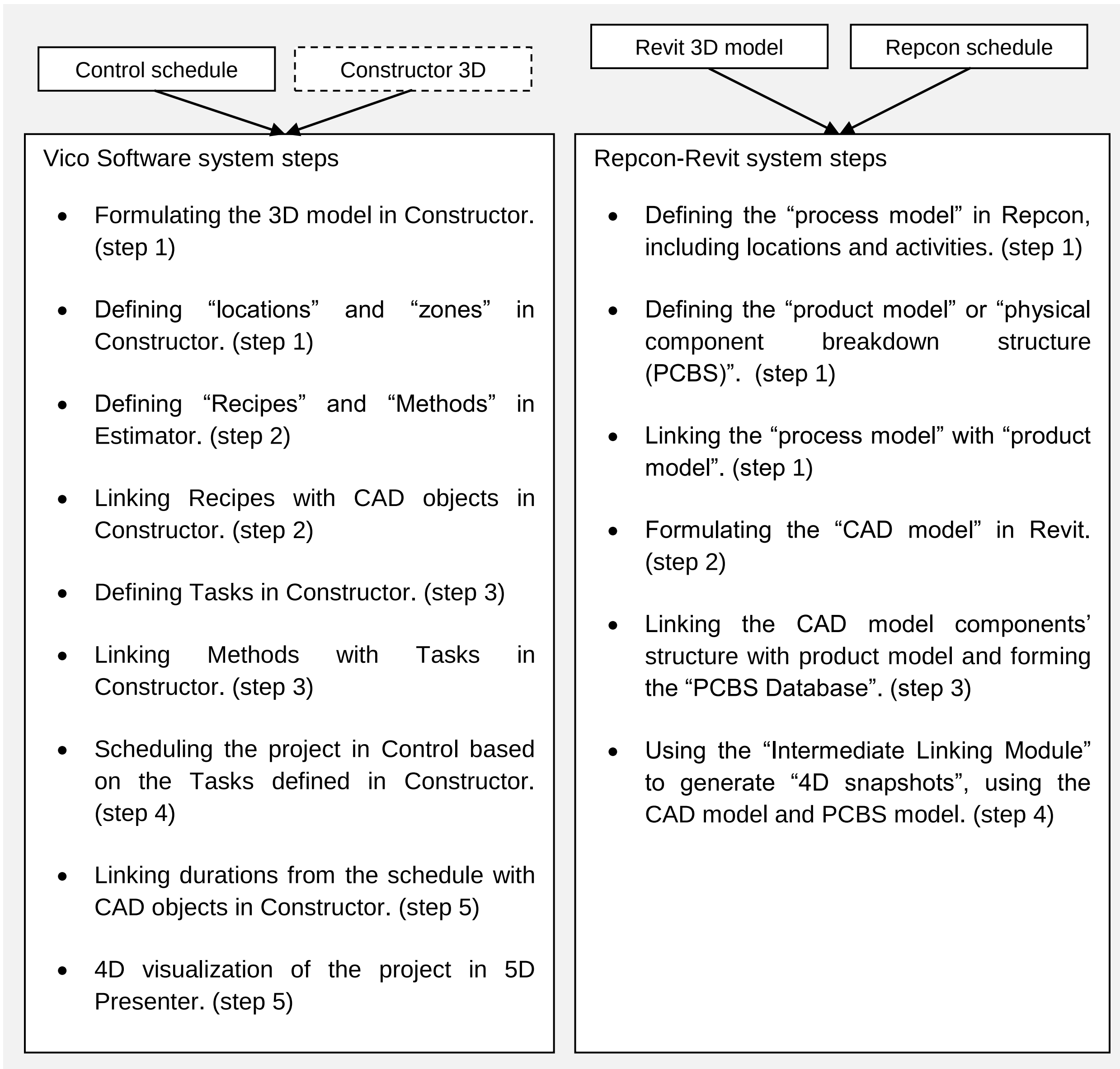


Figure 2.4 Side-by-side lay out of the processes taking place in the two approaches. The steps mentioned in the table correspond to sections 2.4.2.1 and 2.4.3.1.

In this thesis, the two terms: "task" and "activity" will be used interchangeably to refer to schedule activities. However, "task" will be used more frequently with respect to the processes relating to the Vico Software system, as "task" is the terminology used in this software to describe schedule activities.

The work described herein relates to the application of these two approaches to explore 4D modeling issues associated with providing a visualization environment that allows construction professionals to search for and evaluate alternative construction scenarios to meet project requirements.

2.4 Creation of “base scenario”

2.4.1 Introduction

With respect to the enclosure work, a single strategy was originally planned. The strategy corresponds to a floor by floor installation of the enclosure panels with some overlap (saw-tooth pattern, see Figure 2.5), and a constant production rate all the way up. The enclosure work "shadowed" the slab re-shoring removal activity and could not cross re-shoring due to material handling issues. Figure 2.5 shows a linear scheduling representation of the base schedule in both systems. In each of the diagrams, the left-hand side line represents the sequence of tasks involved in building the tower’s superstructure and the right-hand side line represents the sequence of tasks involved in building the enclosure of the tower.

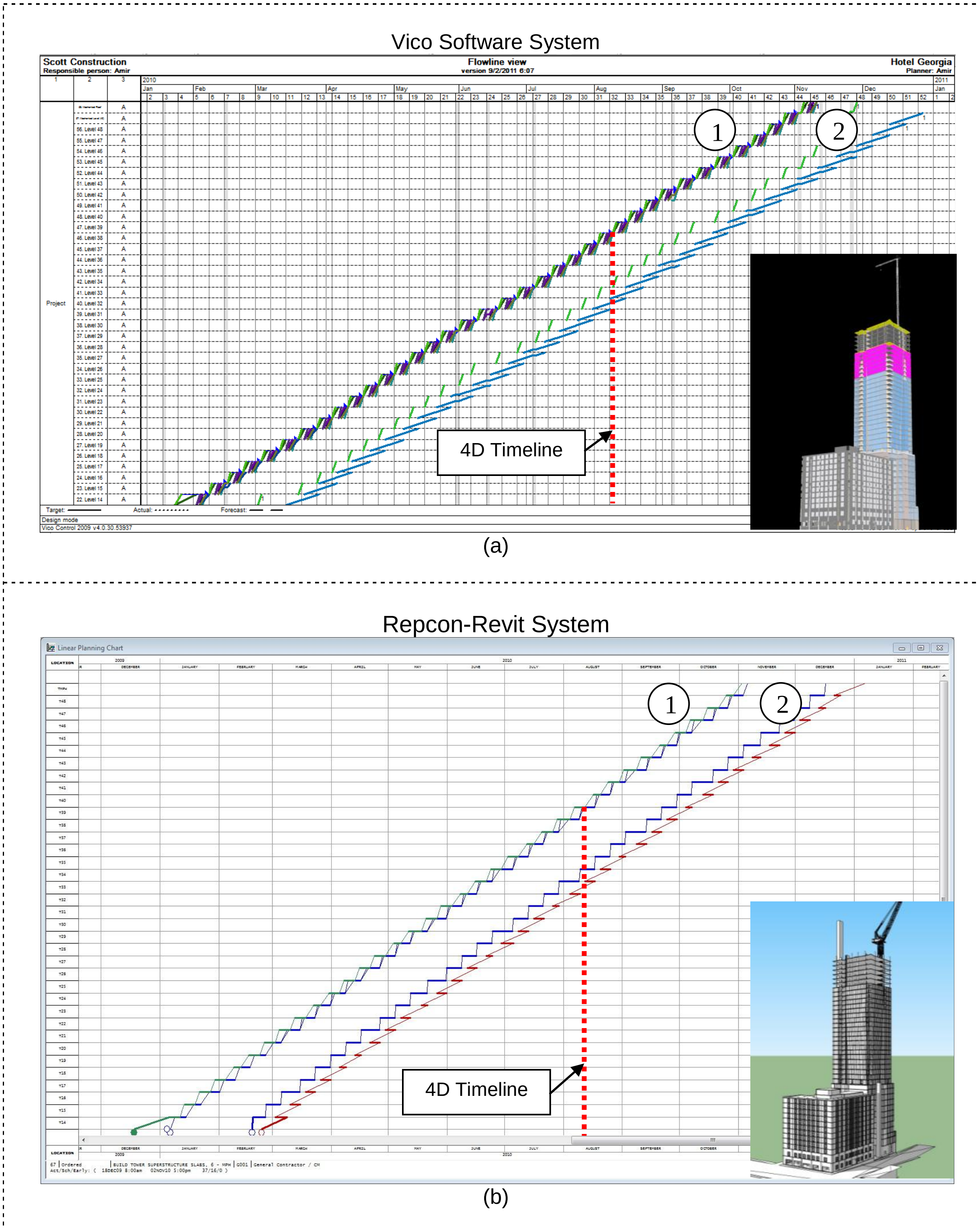


Figure 2.5 The linear scheduling representation of the base scenario in: (a) Vico Software system and, (b) Repcon-Revit system. Line 1 represents tower's superstructure and line 2 represents tower's enclosure. 4D snapshots of the timeline specified (August 2010) are also shown.

For the Repcon-Revit system, the 3D model was built from scratch using Revit Architecture. The schedule was originally developed in SureTrak and was based on the reality as seen by the construction manager of the project as of that time. Using the SureTrak schedule as the source of information, the project was again formulated in Repcon.

For research purposes and in order to consider the actual challenges of projects where information is collected/provided from different sources (e.g. the 3D model is created by another stakeholder and cannot be used directly in the 4D modeling system at hand), we chose to use the 3D model previously created in Revit. Therefore, for the Vico Software system, the starting point of the 3D model was the Revit model. The IFC conversion method was employed to bring the Revit model into Vico Constructor. Table 2.1 illustrates the base strategy and the sequence to be followed in installation of the enclosure for each of the scenarios (base scenario vs. alternative scenario).

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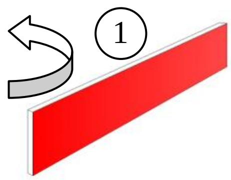
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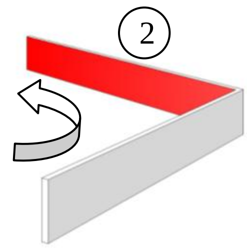
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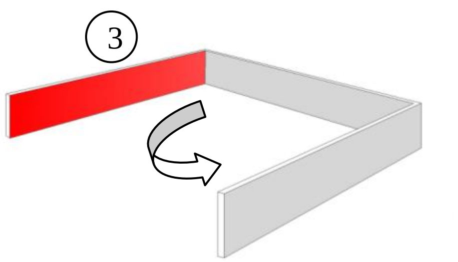
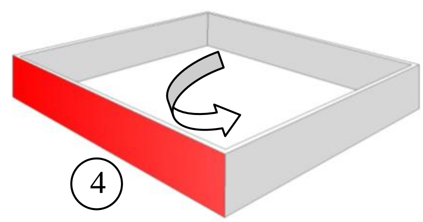

enclosure panel No. 3</td><td colspan="2">4

enclosure panel No. 4</td></tr>
<tr><td colspan="4">Steps involved in formulating the base strategy for installing the enclosure.</td></tr>
<tr><td colspan="2">Vico Software</td><td colspan="2">Repcon-Revit</td></tr>
<tr><td>Product model:</td><td>Defining and assigning the same Recipe to all the sides.</td><td>Product model:</td><td>One Revit Family Type will be defined and assigned to all the sides.</td></tr>
<tr><td>Process model:</td><td>One task needs to be defined and mapped to the 3D components.</td><td>Process model:</td><td>One task needs to be defined and mapped to the 3D components.</td></tr>
</table>

Table 2.1 Illustration of the base strategy followed for installation of the tower enclosure. The main steps involved in formulating the product and process models in each system are also listed.

As already mentioned, an important point to restate here is that many of the challenges faced in formulation and reformulation of the construction scenarios with the Vico Software system, were caused due to the IFC conversion method used. We chose this method to add to the breadth of the analysis conducted on this 4D system. However, it is believed that if the 3D model was formulated from scratch using the Vico Software system, many of the challenges faced regarding the formulation of the 3D model would not have existed (for example the difficulties encountered with curtain wall components). The schedule used in the Vico Software system was formulated from scratch in Vico Control, which is also based on the schedule previously developed using SureTrak and Repcon.

For each system, a description of the main steps involved in formulating the 4D model is given, followed by an analysis of the system. The base scenario was formulated in each of the two systems in order to evaluate their responsiveness with respect to the main 4D modeling features required. These include: formulating the schedule; creating the 3D model; and, establishing links, as well as the attributes which are unique to each of the systems, such as: internal processes; working with different product models; level of automation; zoning capabilities; and, project breakdown structure.

2.4.2 Vico Software system

To bring the 3D model from Revit into Constructor, we used IFC as intermediary format file, which resulted in an almost identical 3D model in Constructor in terms of the geometry and positioning of the components. However, a considerable amount of the component intelligence was lost, as the version of the Constructor we used in this research was not capable of recognizing curtain wall components. In addition, many other components lost their intelligence due to the method of conversion used. The IFC output file from Revit was not completely compatible with Constructor. Nevertheless, this was the most reliable method of conversion to preserve the data transferred between the two applications.

Due to the difference in system approaches for formulating the linear schedule, (Control vs. Repcon), the resulting schedules for the base scenario are not completely identical in the two systems. However, they follow the same overall rationale in terms of the sequence of the tasks, relationships established between the activities, as well as the durations and milestones planned for the project. There is a tolerance of 1 week in the start/finish dates of activities in Vico Control when compared against the schedule activities from the Repcon-Revit system.

The intuitive and flexible tools and techniques that Constructor provides, makes it possible to define horizontal zones with custom methods of assigning components to the defined zones. By using the WBS Manager palette and having the capability of defining several alternative sets of locations and zones, it is possible to investigate and compare different construction scenarios all in one place (Constructor) with relative ease.

Figure 2.6 shows the overall approach and the steps used by the Vico Software system to formulate a 4D model. In the following section of the thesis we elaborate more on these steps. Figure 2.7 shows an overview of the flow of information in the Vico Software system, and where each of the modules enters the 4D modeling process.

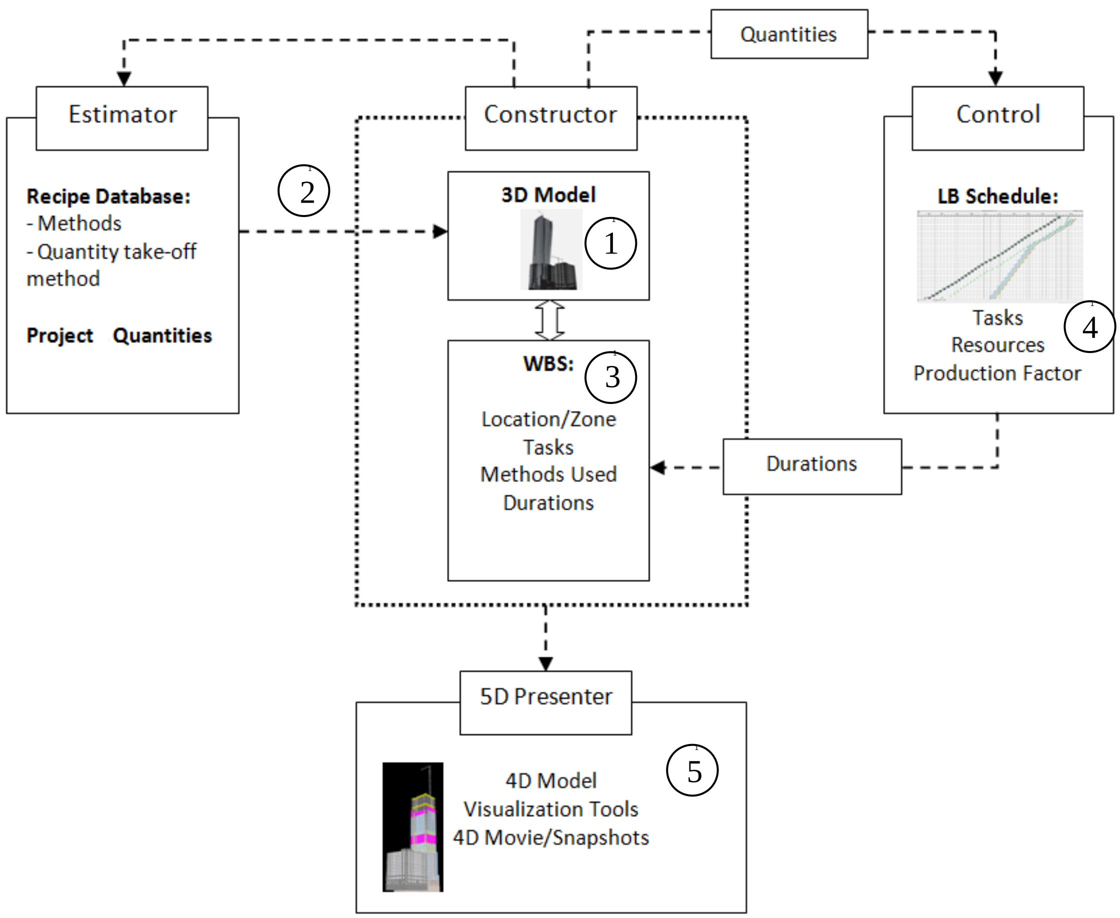


Figure 2.6 Approach for integrating 3D/4D and linear scheduling in the Vico Software system. The numbers in the figure correspond to the steps involved in formulating a 4D model in this approach. (see section 2.4.2.1)

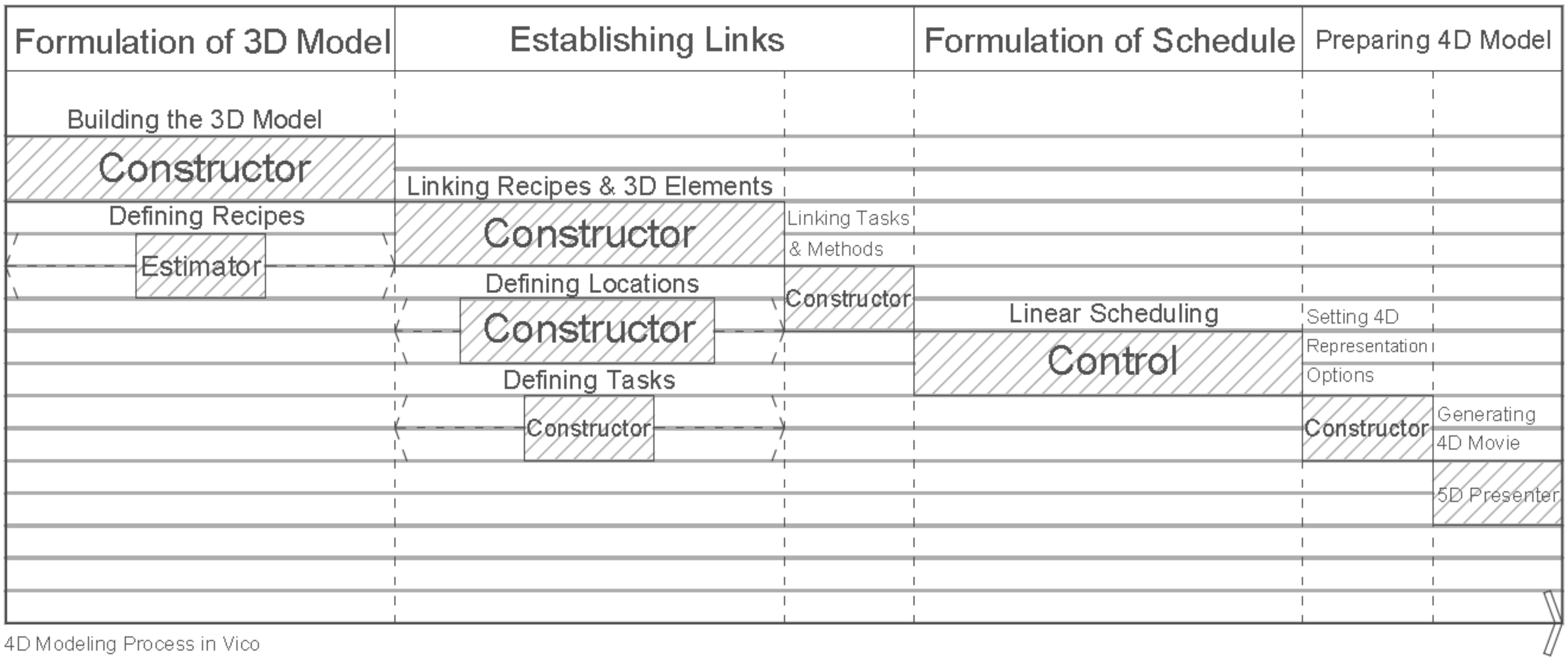


Figure 2.7 An overview of the 4D Modeling process using Vico's modules.

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2.4.2.1 Steps involved in formulating 4D model in Vico Software system.

The method Vico Software uses in order to generate a 4D model is an integrated approach that uses several modules: Constructor; Control; Estimator; and, 5D Presenter (see Figure 2.7). This method minimizes the need for manual input. The linkage of 3D components with schedule tasks is by means of assigned Recipes, Methods and an internal mapping process. This approach enables users to explore a variety of construction scenarios by means of tools such as WBS Manager Palette and Recipe Link Checker and intuitive methods by which the users can define locations and zones.

Using an .xml file format for transferring time data between different modules of Vico, while limiting us in making further changes to the schedule to some extent, adds unique capabilities to the whole system specifically when the 4D model has to be updated with new values of time data. These features are discussed in more detail in the coming sections of the thesis.

2.4.2.1.1 Step 1: formulation of 3D model in Vico Constructor

The 4D modeling process using Vico starts with the creation of the 3D model using the Vico Constructor module. This is where the level of detail for the project is defined and later during the scheduling process using Vico Control, the schedule basically follows the same level of detail. Constructor is also where the WBS (Work Breakdown Structure) of the project is established using tools by which the user can define location sets and their corresponding zones. For this project, and in terms of zoning, we mostly used the Boundary Filter tool to define the required horizontal zones and to represent phases in the construction sequence. This provided us with a unique functionality that avoids element splitting operations. When multi-spanning model elements (e.g. slabs, walls) are located in more than one construction zone, Constructor automatically calculates the quantities for those elements in each of the zones without splitting any operations (non-destructive element splitting is shown in Figure 2.8). Figure 2.9 shows the WBS Palette where several zoning methods are provided to define new or modify existing zones.

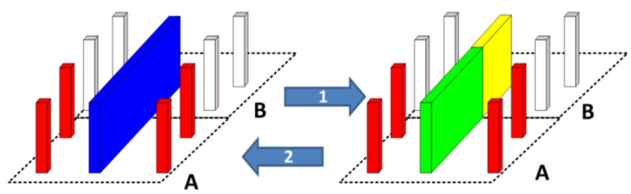


Figure 2.8 Non-destructive element splitting [28]

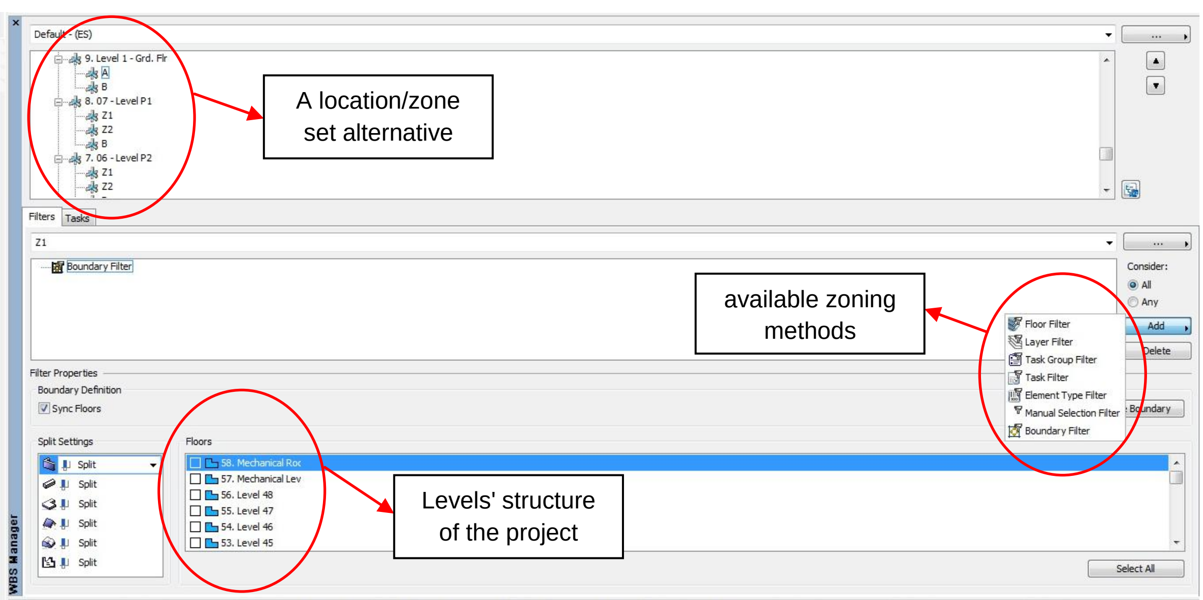


Figure 2.9 WBS Palette in Constructor provides users with several zoning methods.

2.4.2.1.2 Step 2: formulation of Recipes and linking them to 3D elements.

Recipe is the element level information package, and can be assigned to 3D model elements. One element in the model can only have one Recipe [28]. In Vico, by linking Recipes to 3D components we will assign Methods and Resources to those elements. The Method is an information package that contains activity or trade specific cost data and is included in the Recipe. How much of a Method is needed for one unit of Recipe is defined as a Consumption “Method of Recipe”. Each Method contains Resource, and the amount of a Resource needed for one unit of Method is defined in a Consumption “Resource of Method” (see Figure 2.10 and Figure 2.11) [28].

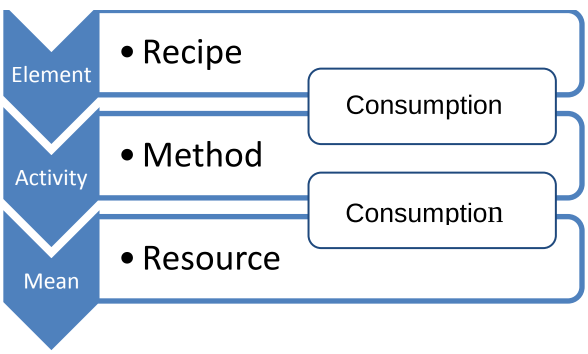


Figure 2.10 Recipe data structure [28].

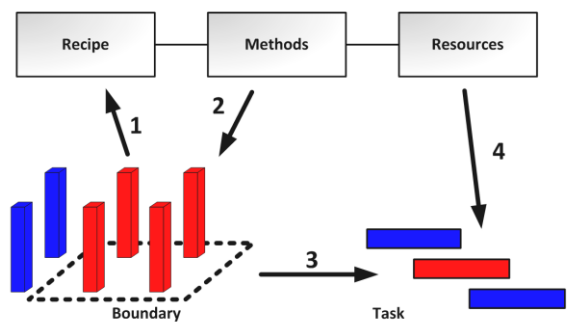


Figure 2.11 Vico’s scheduling integration concept [28].

By means of Estimator, we can create a new Recipe or modify an already existing Recipe in a way that it reflects the definition of the building components we are looking for. This definition will be based on the level of detail, resources to be used and the Quantity Data Type required for that type of building component (e.g. wall, door, etc.). Table 2.2 shows an example of a Recipe called "RC Wall", which is defined to be assigned to Reinforced Concrete Wall components from 3D model. By assigning this Recipe to its corresponding components, an information package which contains the methods of construction, units, consumption rate (which is a quantity unit of measure - by using the quantities obtained from here and attaching the production rates to them, activity durations are derived and used in Control), and quantity data type will be linked to those components.

Recipe	Component	Method	Unit	Consumption	Quantity Data Type
RC Wall	Reinforced Concrete Wall	Formworking	m2/m2	2.00	Gross Surface Area
		Reinforcing	tonne/m2	0.05	Gross Volume
		Concrete Pouring	m3/m2	0.30	Gross Volume
		Finishing	m2/m2	1.00	Gross Surface Area

Table 2.2 An example of the information captured in a Recipe: RC Wall

Recipe Link Checker has made the process of linking 3D elements and Recipes/Methods easy by providing a palette by which the user can manage all of the already established links or define new links as needed (see Figure 2.12). Constructor loads the Recipe database from Estimator, where users can define new or modify the pre-defined Recipes and Methods. For the purpose of the case study at hand, and in order to evaluate the constraints of the Vico Software system, all of the Recipes used were newly defined.

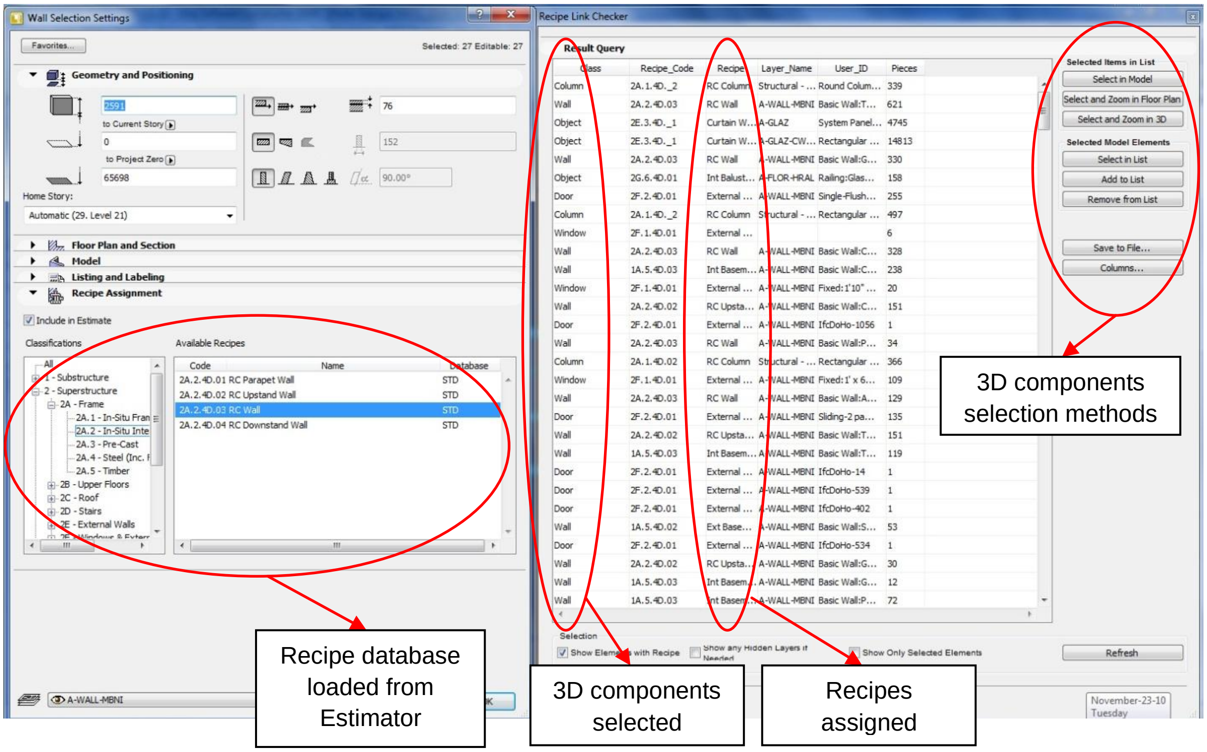


Figure 2.12 The process of linking Recipes/Methods with 3D components. The left-hand side is the component settings palette. The right-hand side is the Recipe Link Checker Palette.

2.4.2.1.3 Step 3: mapping Methods and Tasks (3D components and activities)

After linking Recipes and 3D elements using the Recipe Link Checker, by selecting any of the locations from the WBS Manager list of locations, the Tasks tab of the WBS Manager palette will show us a list of all of the Methods which are being used at that location and are ready to be mapped to their corresponding activities in Vico Constructor. Therefore the next step in the process is to define the list of Tasks to be used in the schedule using the Schedule Task Manager Palette. Here we add the list of the Tasks to one side of the palette and see an automatically generated list of all of the Methods used in the project on the other side. By selecting a task and assigning its corresponding Methods to it, we have mapped that task to its corresponding 3D elements.

Figure 2.13 shows the Schedule Task Manager Palette, where the process of mapping tasks and Methods (or in other words, the process of mapping schedule activities and 3D components) happens. As an example, by selecting and linking the Task "Reinforce Parkade Columns" from the left-hand list, and the Method "RC Column Reinforcement" from the right-hand list, the 3D components corresponding to this Method will be linked to the Task used.

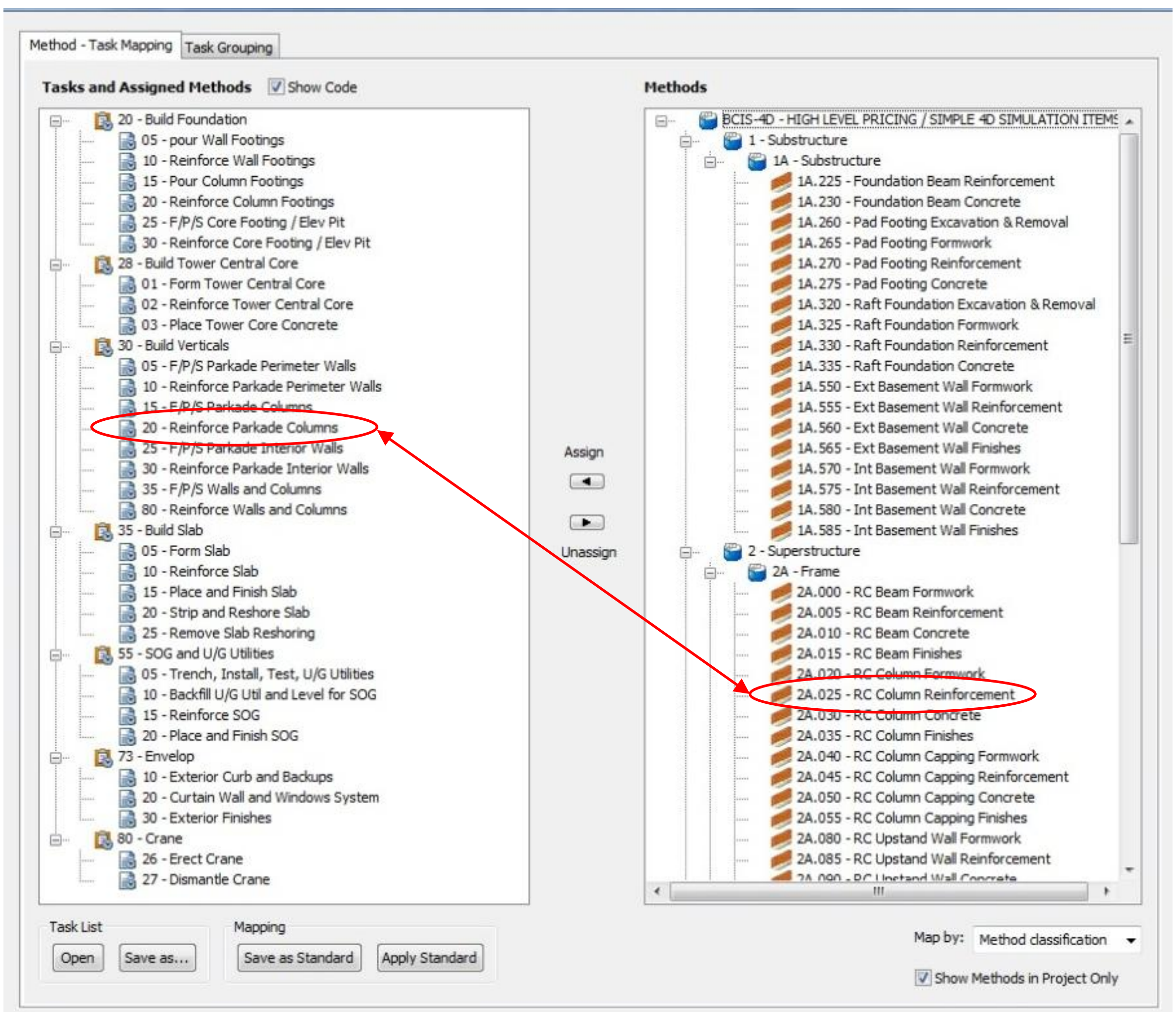


Figure 2.13 Schedule Task Manager Palette in Vico Software system, helps to link tasks and Methods

2.4.2.1.4 Step 4: perform linear scheduling

After mapping Methods and Tasks, the project is ready to be sent to Vico Control for scheduling. Control is a linear scheduling application which enables the user to obtain the required data including location definitions and a list of activities from Constructor in the form of a .xml file (phase 1 from Figure 2.14). By importing this data into Control, we have enough information to start the scheduling process in Control (which includes adjusting durations and assigning relationships to the tasks).

Figure 2.14 Constructor's two-phase connection with Control [28].

In order to work with the tasks that are being used in more than one zone of a location separately, we first need to split the task into its corresponding zones. Using the Quantity Data Type (defined in Estimator), and the required resources defined in the assigned Methods (defined in Estimator), and by means of automatic quantity take off (in Constructor), as well as the attached productivity rates (in Control), Control automatically calculates durations for all of the activities. The automatically-generated durations could be changed manually later during the process by changing the Productivity Rates factor. Figure 2.15 shows the filtered linear scheduling chart of the base scenario at hand formulated in the Vico system. The linear scheduling chart has been filtered heavily to help ensure readability.

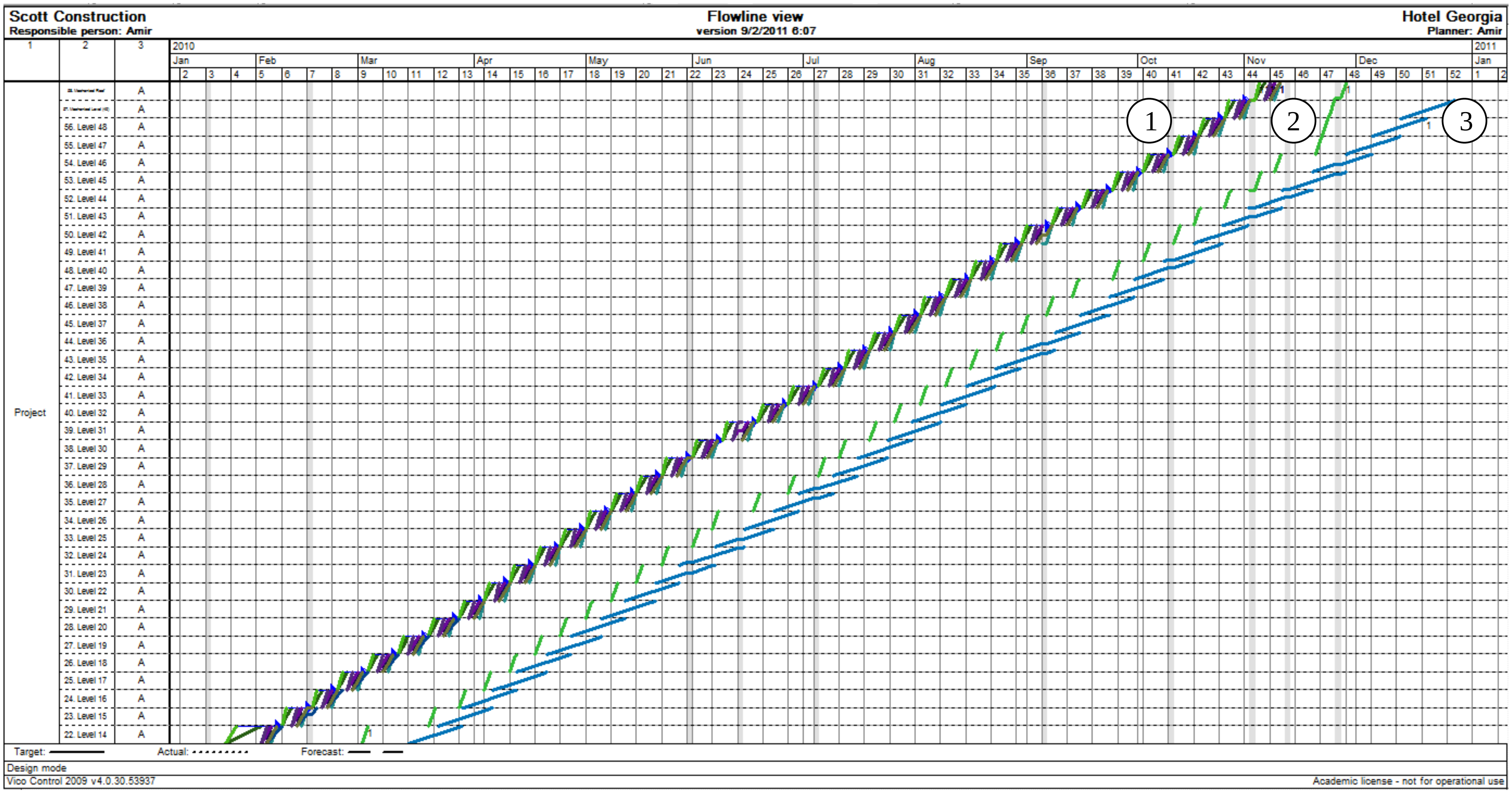


Figure 2.15 Filtered linear scheduling chart for the base scenario formulated in Vico Control: 1) Superstructure (14-48), including: Core, Verticals, and Slabs, 2) Removal of slab re-shoring (14-48), and 3) Curtain wall/enclosure installation (14-48). The linear scheduling chart has been filtered heavily to help ensure readability.

2.4.2.1.5 Step 5: create 4D snapshot / animation

When the scheduling process is finished in Control, it is time to bring the time data back into Constructor using .xml file format (phase 2 from Figure 2.14). In doing so, all the corresponding 3D components in Constructor are assigned a time tag including start/finish date and duration. The final step in the 4D modeling process is to set the 4D representation options in Constructor and publish the 4D model of the project. The final 4D model consists of the schedule formulated in Control, and the 3D model and mapping set up in Constructor.

Using the Vico 5D Presenter module, we can easily navigate through the 4D model, set the camera position and manage the playback of the 4D animation, as well as the ability to get snapshots and adjust the transparency of the not-in-progress 3D components to get a better view of internal works (see Figure 2.16). Shown in Appendix A are snapshots of the 4D representation of the base scenario using the Vico 5D Presenter module.

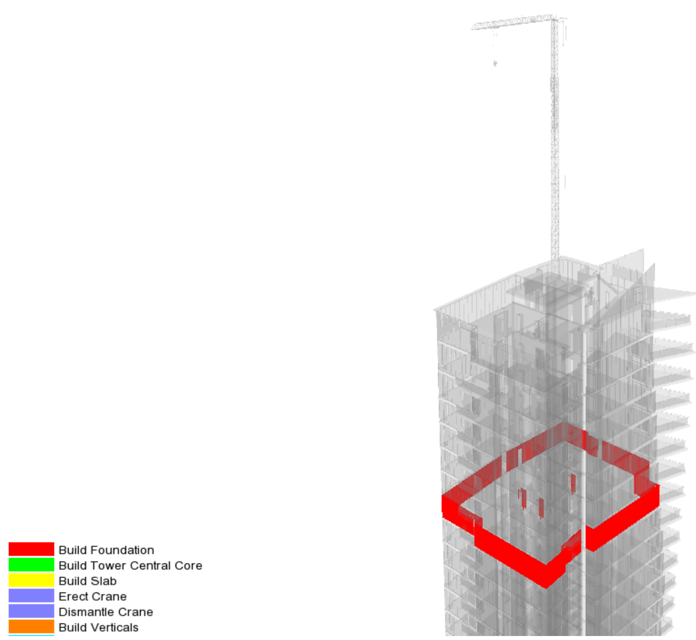


Figure 2.16 Transparency adjustment of the not-under-progress 3D components in Vico Software.

2.4.2.2 Analysis of the constraints and challenges faced in formulating the "base scenario" with Vico Software system

2.4.2.2.1 The method of conversion used

Using the IFC file format to transfer the 3D model from Revit into Vico Constructor resulted in some inconsistencies:

- Some loss in the intelligence of the BIM components. As an example, the version of Constructor we used did not recognize the curtain wall components, which means that the entire curtain wall transferred from Revit into Constructor was converted into thousands of non-intelligent geometric objects, which resulted in a very sizeable 3D model file. As a result, the model was too slow to navigate through, making it cumbersome to manage the non-intelligent objects inside the 3D model (e.g. selecting them) and establish links with them. The Recipe Link Checker tool in Constructor made it much easier to manage even a big number of non-intelligent objects by recognizing them based on common attributes and performing batch functions on them.
- Due to losing some of the intelligence in the model, we had to reassign some of the attributes back to the components:
    - The definition of the predefined locations of the 3D model got changed in Constructor. As a result, some components got lost in the model as the location tag assigned to them was no longer valid. To address this issue we had to hide all of the components with correct location tags and then select the incorrect ones level by level and change their location tags.

- Some of the basic information such as the assigned materials needed to be reassigned to the components.
- Finally some elements such as the parkade ramps had to be completely remodeled in the Constructor as they lost their geometry information in the imported model.

2.4.2.2.2 Zoning

- The floor plans of the building are different from level to level which means part of the process of zoning for each level had to be performed manually.
- Due to some inconsistencies which were mainly caused by the IFC conversion method used, not all of the components within a zone boundary were assigned to that zone. For those components, the whole process of selecting and assigning to the corresponding zone had to be done manually.
- In Constructor, the vertical locations are based on the level structure of the project as defined in the very early steps of the modeling process. The level structure of the project is defined based on the height and elevation assigned to each storey of the building. The issue here is that only one level structure per project can be defined in Constructor, even if there is more than one building in the same model (where more than one level structure would be needed). Let us assume there are two buildings in our model: building #1 and building #2 (the Tower and the Infill in reference to the case study), with different definitions of height and elevation for each level structure. The level structure in Constructor will be set up based on the level structure of the building which was modeled first (e.g. the building #1). Thus, the other

building (building #2) has to follow the same level structure configuration. This will cause some inconsistencies in managing the model, such as:

- Components of building #2, which may be positioned in between the defined levels of building #1, might be moved either to the upper or to the lower level. This will bring up the need for manually checking the components of building #2 to see if all the components are correctly positioned within the defined level structure of building #1.
- Constructor essentially uses the same level structure of building #1 to create the vertical locations required for building #2 for use in the linear scheduling process. There are 2 solutions to get the most out of this structure and use it for building #2 in a practical way: 1) define a separate horizontal zone for each level of building #2 within building #1's structure of locations, or 2) define a whole new set of vertical locations for building #2. The latter solution is quite a tedious process.

2.4.2.2.3 Defining and assigning Recipes and Methods (establishing links)

- In Vico Estimator, the Recipes are defined based on the type of element they are assigned to. As a result, a specific quantity take-off method is defined and assigned to each element type (e.g. m2 for wall surface or m3 for the amount of concrete in slab). The user cannot assign a Recipe which for example is defined for a wall, to a slab. For the components which were converted as non-intelligent geometric objects into the 3D model (e.g. curtain wall), even though we had to define a specific Recipe which matched the specifications of those components, the quantity take-off method for those components had to be set as “number” of elements found in the corresponding zone. This limited us in getting required quantity data for those component types.

- As discussed in further detail later in the thesis, in order to address some of the issues concerned with the level of detail used in the 3D model as well as the schedule, more than one Recipe may be needed to be assigned to a single component type, depending on the location of the components and the level of detail needed in that location.

2.4.2.2.4 Linear scheduling capabilities

- Control uses the quantity take-off information provided by Constructor. By assigning a production rate to each of the Methods used in the Recipes, it automatically calculates the duration for the corresponding tasks. Since many of the elements lost their intelligence while bringing them into Constructor, the quantity take off method assigned to them was not as useful as it was for the intelligent components, as it reflects irrelevant or sometimes misleading information. As a result the calculated durations for those components were not correct, which meant that the durations had to be manually input by adjusting the production rates (durations cannot be assigned directly to the activities in Vico).
- In Control, no further modifications could be made to finish-to-start internal logic relationships established by Control between the instances of the same task in different locations of the project. This caused some limits in terms of the relationships and lags that needed to be established (for example no negative or positive lagging could be imposed directly to the logic

relationships of instances of the same task in different locations of the project - see section 2.7.2.4 for further discussion).

- For some components, we needed multiple levels of detail in terms of the assigned tasks depending on the location of those components. For example, for the parkade levels, we have two sets of tasks that correspond to the wall components, (interior and perimeter wall - excluding core walls), and one set of tasks which corresponds to the columns at those levels. However, for the rest of the levels (the tower), all three sets of tasks have been collected into a single set of tasks named "walls and columns". The issue here is that based on how many sets of tasks for the same component type are needed and scheduled, and based on the level of detail to be used in the schedule at each location, we need to define and use an appropriate set of Recipes to be linked to those components. Correspondingly, we need to define the zones in a way that addresses our needs in terms of the above-mentioned concerns. This is something that has to be considered prior to the scheduling phase and needs to be foreseen, which is not that easy to do in some cases.

2.4.3 Repcon-Revit system

The genesis of the Repcon-Revit approach is to try and address problems encountered in being able to quickly formulate, implement, and assess proposed construction strategies. Repcon-Revit system's approach is unique in that it leverages a generalized implementation of CPM that includes linear scheduling coordinated with a 3D CAD model to produce 4D CAD images. This approach enables a more generic mapping mechanism between product and process models that works at multiple levels of detail. This type of linking mechanism minimizes the number of links that need to be made, and eliminates the need to manually re-link CAD objects and activities as the design and schedule changes. Therefore, with linear scheduling and the ease with which 4D snapshots can be generated, it is now possible to explore a variety of construction strategies relatively quickly [27].

The 3D model was built in Autodesk Revit based on 2D drawings obtained from the architect for the case study project, and it contains more than 36,000 individual objects. Figure 2.17 illustrates the four main steps involved in interfacing the 3D model with the scheduling system to allow a two-way flow of information to calculate quantities used for scheduling and productivity analysis, check product and process model consistency, and create a 4D simulation for the base scenario at hand [26],[27].

Here we summarize the key elements of the Repcon-Revit system approach [27]. The details and challenges associated with each step are described in Staub-French et al. [26]. For the sections 2.4.3.1 and 2.4.3.2, as well as other sections which related to the processes taking place in Repcon-Revit system, direct use has been made of some of the material of these references. The actual 3D modeling module used in [26] and [27] was ADT (Autodesk Architectural Desktop). However, in this thesis ADT was replaced by Revit, and all the material used was revised correspondingly.

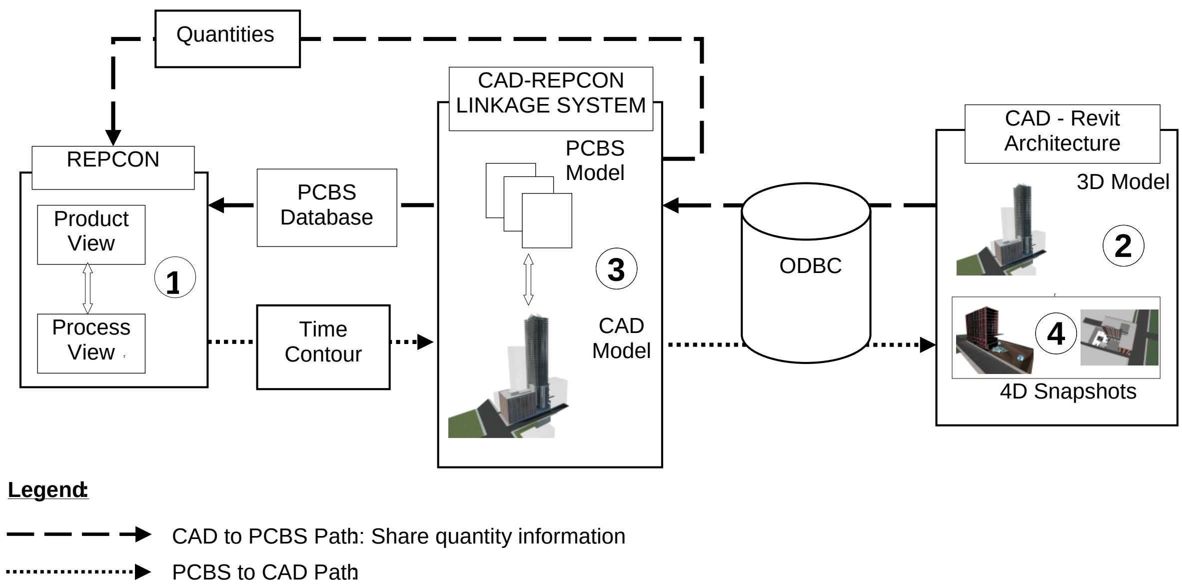


Figure 2.17 Approach for integrating 3D/4D and linear scheduling in the Repcon-Revit system. The numbers in the figure correspond to the steps involved in formulating a 4D model in this approach. (see section 2.4.3.1**)**

2.4.3.1 Steps involved in formulating 4D model in Repcon-Revit system

2.4.3.1.1 Step 1: formulation of scheduling system product and process views and coordination with CAD

This step involves the formulation of the project product (PCBS) and process views (see Figure 2.18) in the scheduling system in terms of hierarchically structured components, component attribute definitions and attribute values. Schedulers define the product view in terms of locations, physical components, component attribute definitions, and as-planned and as-built attribute values as a function of location. It is this breakdown that must be coordinated with and communicated to the CAD system, in the form of a PCBS database. With respect to the process model, input from the scheduler includes the locations at which work is to be performed and the sequence in which locations are to be worked, production rates at each location (this is where quantity information for PCBS component attributes fed back from the CAD model comes into play), and logic linking the activities as well as other date constraints. Other scheduler input deals with linking the product and process views. Output from the process consists of Time Contour information given the mapping between the product and process views, and a progress date or series of progress dates specified by the user. Specifically, given the breakdown of activity work on a location by location basis, the corresponding physical components are flagged as either being completed (value of 1), or not yet started (value of 0) as of a specific progress date. Current work as a follow-up to this thesis work is directed at showing work in progress using color and all date scenarios (early, late, scheduled and actual are being supported). Figure 2.19 shows the filtered linear scheduling chart of the base scenario at hand formulated in the Repcon-Revit system. The linear scheduling chart has been filtered heavily to help ensure readability.

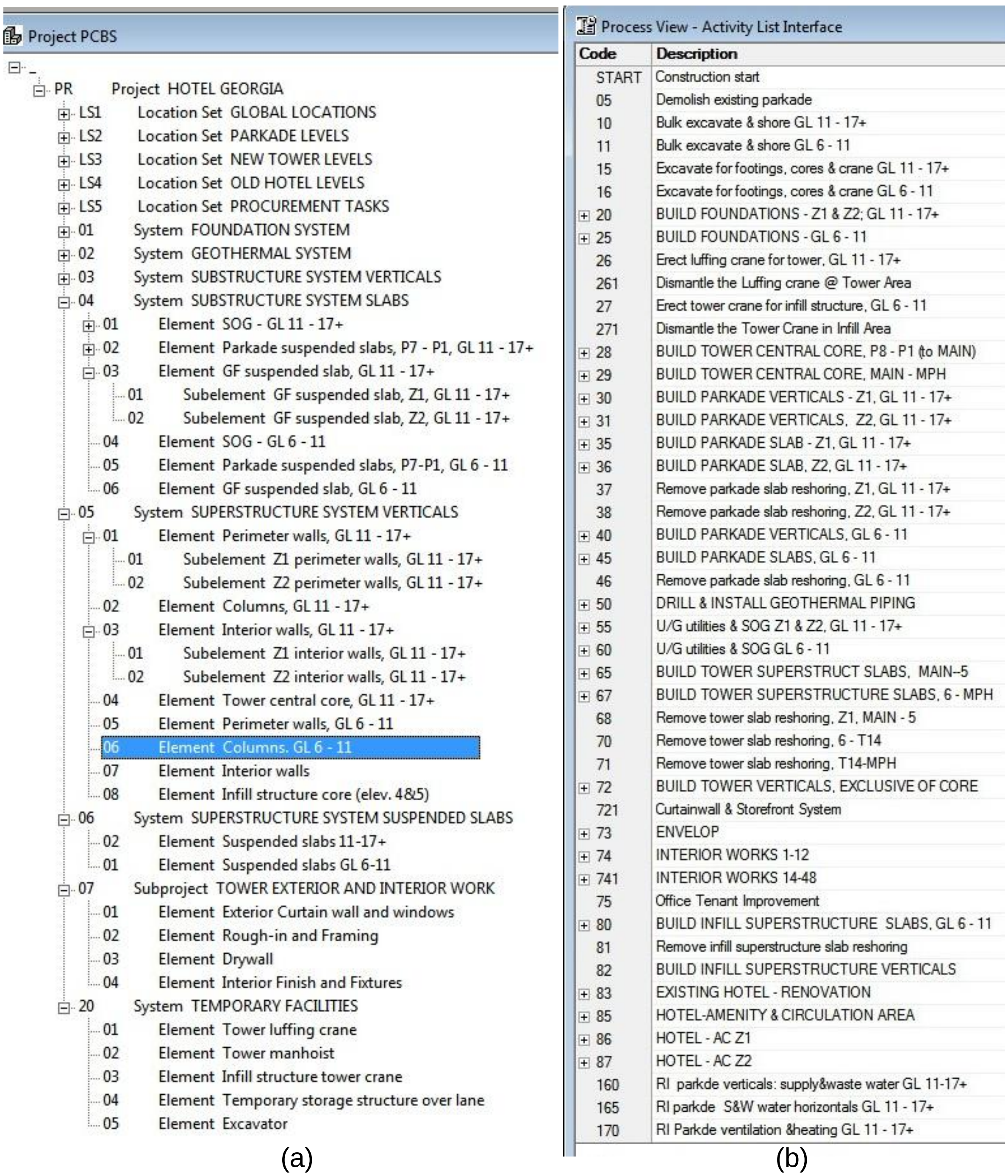


Figure 2.18 (a) Repcon scheduling system product model - the physical component breakdown structure (PCBS). (b) Scoping of the project in Repcon in terms of activity planning structures

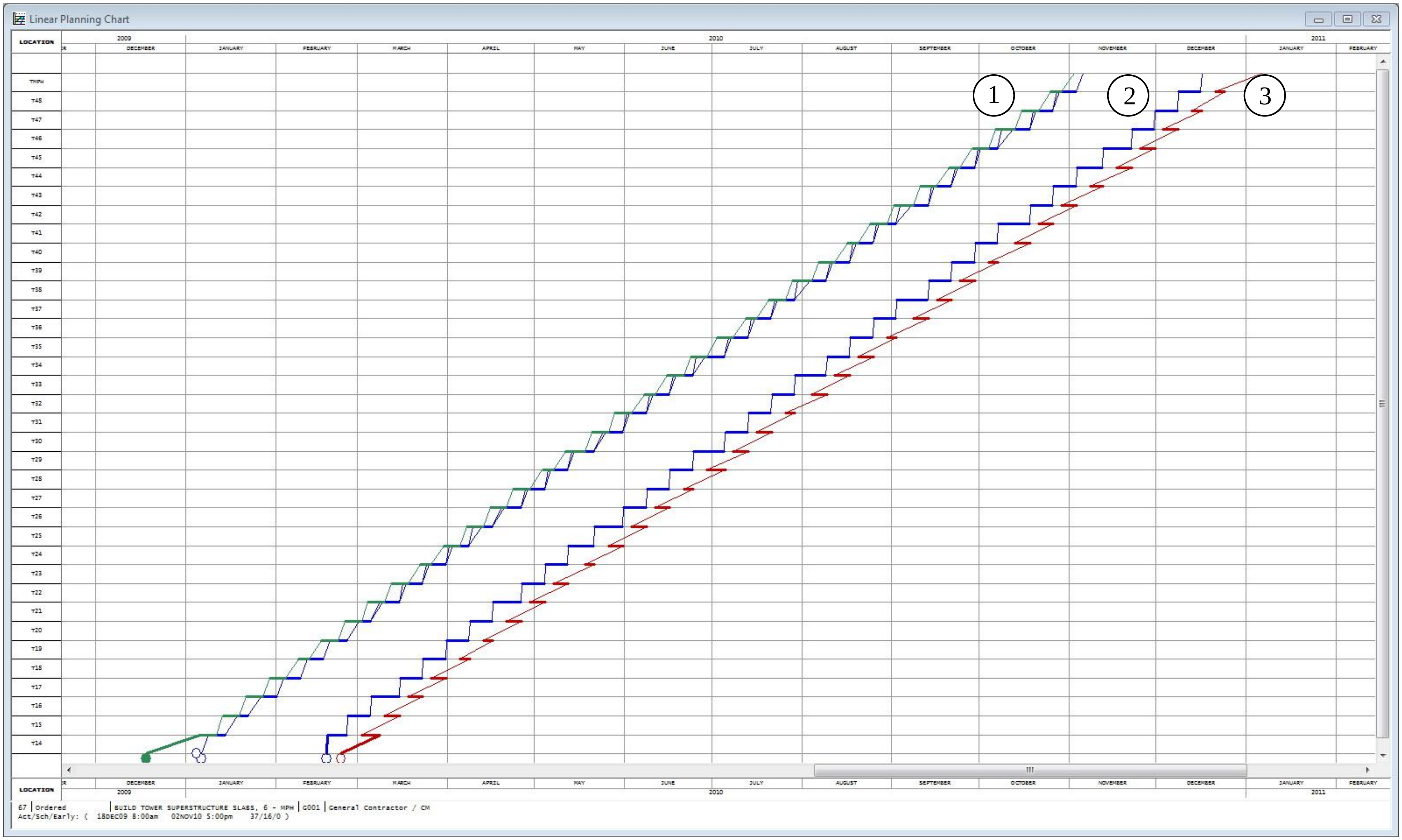


Figure 2.19 Filtered linear scheduling chart for the base scenario formulated in Repcon: 1) Superstructure (14-48), including: Core, Verticals, and Slabs, 2) Removal of slab re-shoring (14-48), and 3) Curtain wall/enclosure installation (14-48). The linear scheduling chart has been filtered heavily to help ensure readability.

2.4.3.1.2 Step 2: formulation of 3D model in Revit

This step involves the creation of the 3D model, preferably in a way that is consistent with the PCBS. Of particular importance in creating the 3D model is the way objects are defined (Family Types in Revit) and locations are specified (Levels in Revit). In the Repcon-Revit environment, the Level ID in CAD corresponds to the scheduling system Location Code. In addition, users specify the component attributes required for the scheduling system so that they can be properly set up and included in the model. For example, the Concrete Core wall requires properties for the Formwork Area, which can be derived by summing the two CAD properties Area-LeftNet and Area-RightNet. This quantity information is transferred to the scheduling system in the next step.

2.4.3.1.3 Step 3: create integrated CAD-PCBS model

This step deals with the mapping of Revit objects to PCBS objects to create an integrated model. The main processes carried out in this step relate to the aggregation of Revit objects across family types and locations, the creation of linkages between PCBS components and CAD Types, and the assignment of attribute values to PCBS components. This step involves a two-way flow of information: 1) the CAD to PCBS path, and 2) the PCBS to CAD path (see Figure 2.17). In the CAD to PCBS path, a single database is created that contains all CAD and PCBS objects, and quantity information is transferred from CAD objects to PCBS components. The result of this step is a single database that contains all objects for one project. In the PCBS to CAD path, process information for PCBS components is used to generate 4D Snapshots. The input is the Time Contour showing the completion of PCBS components over time. The output consists of a set of filtered CAD objects for creating 4D snapshots.

2.4.3.1.4 Step 4: create 4D snapshots

In this step, the linkages between PCBS and CAD objects are combined with the Time Contour generated from Repcon to create 4D visualizations in Revit. The key input to this step is the filtered CAD objects, which correspond to the CAD objects that are associated with completed construction activities. The internal processes in this step deal with identifying those CAD objects that correspond to completed construction activities for the different locations and making them visible in CAD. The output of this step is a 4D snapshot (or a series of 4D snapshots) at each progress date generated from the scheduling system that graphically highlights the completed construction activities in the 3D model. Shown in Appendix B are snapshots of the 4D representation of base scenario using the Repcon-Revit system.

2.4.3.2 Analysis of the constraints and challenges faced in formulating the "base scenario" with Repcon-Revit system

Selected aspects of this approach are directed at formulating a dynamic visualization environment that links 3D CAD and a generalized implementation of CPM which embraces linear planning to create custom 4D images. The ability to represent dual product models on the CAD and scheduling sides is central to this approach. It enables a more general way of linking product and process models. Essentially it enables objects to be linked at the class level rather than the instance level and through the different product models rather than linking CAD objects and activities directly. This type of linking mechanism resolves many of the difficulties associated with linking/re-linking product and process models, which often limits the availability of these models in practice. These efficiencies are necessary for treating issues of scale, and for developing operations-level 4D models, enabling the exploration of multiple construction strategies. It also provides considerable power in that the completeness and consistency of each of the product models can now be easily validated [27].

Following is a list of challenges faced in the process of formulating the 4D model in the Repcon-Revit system:

2.4.3.2.1 Work breakdown structure

- The breadth of detail captured in the PCBS is not usually reflected in the components of a CAD model (e.g. temporary facilities like scaffolding, etc.), which results in many-to-one relationships being established between PCBS components and CAD elements. The point is that in PCBS, the focus is on groups of similar components, and not the individual instances (e.g. all columns of a certain type at a given location as opposed to each individual column at a location.).

- Since different naming conventions are used on the CAD and scheduling sides, the mapping process needs manual input.
- The CAD side structure of the project needs to be defined level by level.

2.4.3.2.2 Zoning

- Users need to coordinate the definition of levels so that they are identical to the locations specified in the PCBS. In the Repcon-Revit system, the Level ID in CAD corresponds to the Location Code in Repcon.

2.4.3.2.3 Establishing links - creating an integrated CAD-PCBS model

- The differences between the product model representations, and the omissions or gaps in the different product views may pose challenges for the process of integrating product models. Tension exists in terms of the degree of flexibility permitted, the user input required, and the degree of automation provided. This tension is most evident when dealing with the different types of mappings between CAD and Repcon.
- The variability in design details as represented by family types and the variability in levels of detail on the scheduling side make it challenging to automate the mapping process without overly constraining the user. The Family Types names are also critical for mapping CAD objects to PCBS components.

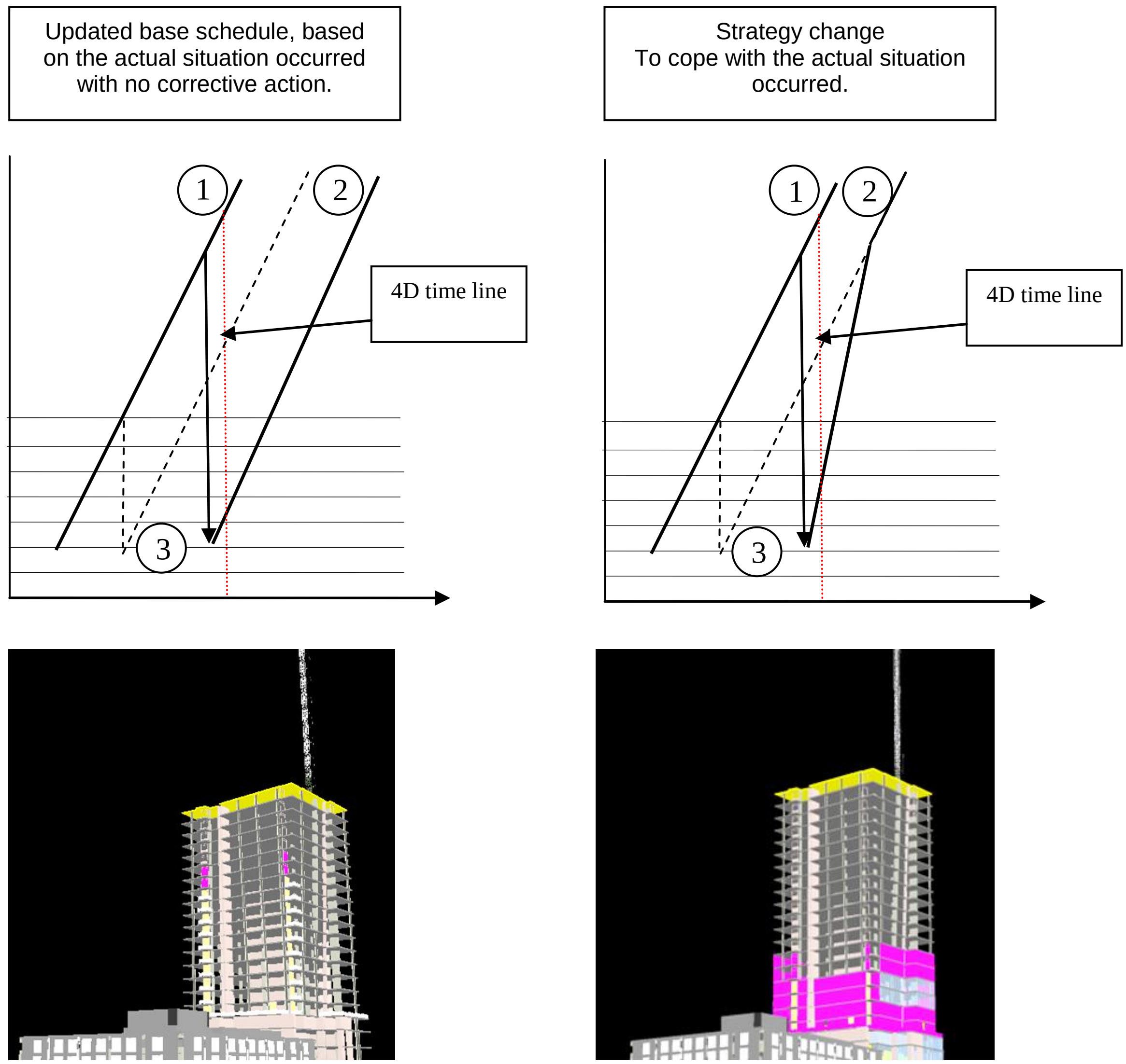
2.4.3.2.4 4D visualization

- Work in progress is not shown in the generated snapshots. This issue becomes more significant especially when a PCBS component represents a collection of CAD objects. As noted previously, follow-up work to the thesis is addressing this issue.

2.5 An actual situation occurred: delay in procurement of enclosure

Offshore fabrication of enclosure elements and their shipping resulted in a significant delay in the procurement process for the enclosure and curtain wall of the tower for the level 14 and above, delaying installation. Figure 2.20(a) shows a schematic linear scheduling diagram of the updated base scenario schedule, with no corrective action for the actual delay that happened in delivery of enclosure system.

In order to cope with this situation, an alternative scenario had to be introduced to the project to minimize the effects of the delay. The corrective actions (called "recovery strategy") to be applied to the updated base scenario and its reformulation to transform it into an alternative construction scenario, are the topics discussed in the coming section of the thesis. Figure 2.20(b) shows a schematic linear scheduling illustration of the corrective actions considered to make up for the time lost.



(a) (b)

Figure 2.20 4D rendering for time line shown, illustrating: (a) The impact of delay on physical progress with no corrective action, and (b) The strategy used on the enclosure system to recover the time lost. Line 1 represents tower's superstructure activity, line 2 represents the actual tower's enclosure activity, and line 3 represents the planned tower's enclosure activity.

2.6 Formulation of “alternative scenario”

2.6.1 Introduction

Several alternative scenarios were proposed in response to the need to address problem areas in the base scenario, from which one was selected and formulated in the two 4D systems examined. The main recovery strategy considered, corresponds to the number of crews working on the enclosure, and the sequence of completing the enclosure installation at each level of the tower (level 14 and beyond of the tower). The number of crews working on the tower enclosure was increased by a factor of 4, and the sequence of enclosure installation was changed in a way that curtain wall panels were divided into two sets (2 opposite facing side sets of enclosure panels), and were placed in 2 story lifts - instead of having one face at a time being installed sequentially (base scenario). This resulted in a factor of 4 in terms of production rate improvement. Table 2.3 illustrates the recovery strategy and the sequence to be followed in installation of the enclosure for each of the scenarios (base scenario vs. alternative scenario). By accelerating the process (by almost 4 times), the installation of the tower enclosure catches up with its predecessor activity (slab re-shoring removal - on Sep/Oct 2010), and from that point on and for the remaining levels, the strategy switches back to enclosure installation of only one level at a time with the original production rate used for the base scenario - one crew. For the strategy to be effective, all successor activities should also be accelerated. Using this recovery strategy, project deadlines based on the base scenario became achievable again. Figure 2.20(b) shows an overall linear schedule representation of the alternative scenario. The start date of enclosure was deferred, hence the actual activity was shifted to the right. However, by increasing the rate of production, the lost time has been regained.

The recovery strategy used to bring the project back on track, consists of several components which need to be considered and examined separately with respect to the consequences each might have on formulation of the process and product models of the 4D systems. The components of the recovery strategy stated above and that need to be addressed in the modeling process include: construction method; granularity of activity definition; activity sequencing; granularity of product model definition; resource allocation (crewing); number of work faces (zoning); temporary facilities; material handling; definition of work week; and, onsite vs. offsite production of components. With respect to the capabilities of the 4D systems as well as the scope of the research conducted, not all of these components were considered; several were pursued (singly or jointly) to formulate the alternative scenario for each of the 4D systems. Table 2.4 illustrates a list of the strategy components deployed in the recovery strategy, provides a definition for each, and discusses the impact that each of these components might have on the process and product models.

For each system, a description of internal processes involved in formulating the alternative scenario is stated, followed by an analysis of the system. The analysis includes the challenges faced and the limits the system has in addressing the 4D modeling requirements for the alternative scenario. The requirements relate to: Internal processes; level of automation; zoning; linear scheduling capabilities; establishing and managing links; and, project breakdown structure.

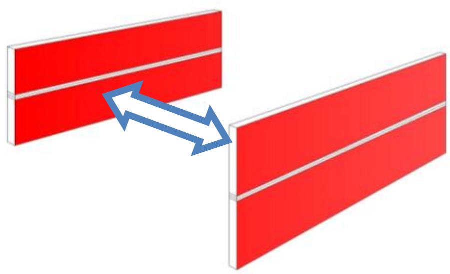
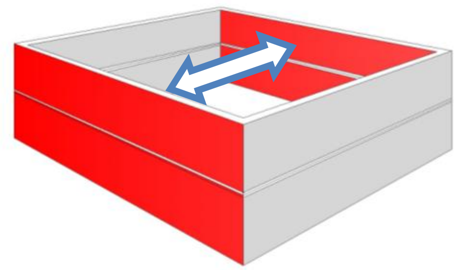
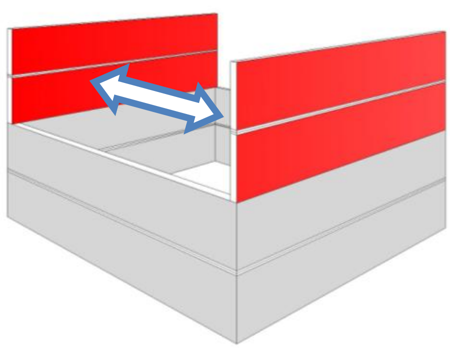
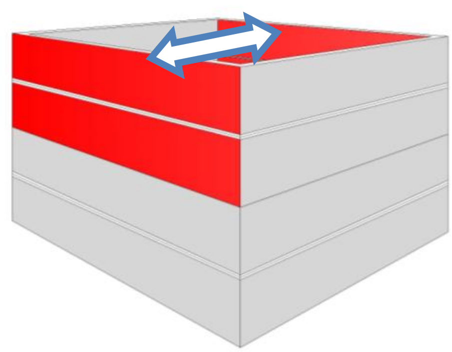
<table>
<tr><th colspan="4">The recovery strategy to be followed for installation of tower's enclosure. Red color shows the in progress components. In each step, 2 levels of opposite facing sides of tower's enclosure are being built at the time.</th></tr>
<tr><td colspan="2">1

enclosure panels from set 1</td><td colspan="2">2

enclosure panels from set 2</td></tr>
<tr><td colspan="2">3

enclosure panels from set 1</td><td colspan="2">4

enclosure panels from set 2</td></tr>
<tr><td colspan="4">Steps involved in formulating the recovery strategy for installing the enclosure.</td></tr>
<tr><td colspan="2">Vico Software</td><td colspan="2">Repcon-Revit</td></tr>
<tr><td>Product model:</td><td>+ Two Recipes need to be defined and assigned to the 2 sets of enclosure panels.</td><td>Product model:</td><td>+ Two Revit Family Types need to be defined and assigned to the 2 sets of enclosure panels.</td></tr>
<tr><td>Process model:</td><td>+ Two tasks need to be defined and mapped to the 3D components corresponding to the 2 sets of enclosure panels.
+ Each of the Two tasks has to be split into 2 sub-tasks in Control, to be accountable for the 2 levels at a time order of enclosure installation.</td><td>Process model:</td><td>+ The task corresponding to the enclosure installation, needs to be split into two, to account for the 2 sets of enclosure panels.
+ The internal sequence logic for each of the two tasks needs to be redefined in a way that reflects the 2 levels at a time order of enclosure installation.</td></tr>
</table>

Table 2.3 Illustration of the recovery strategy to be followed for installation of tower's enclosure. The main steps involved in formulating the product and process models in each system are also listed.

Strategy component	Definition	Relation to process modeling	Relation to product modeling	Pursued?
Construction method	Installation of 2 opposite facing sides' curtain wall panels in 7 working days for each level.	Durations, granularity, and sequence need to be determined.	Granularity and grouping of 3D components.	Yes.
Temporary facilities	In order to install the enclosure panels on a level, slab re-shoring for that level has to be already removed.	Brought in as an activity. Relationships had to be established.	---	Only in process model.
Materials handling	The procurement and storage of curtain wall panels. Slab re-shoring removal.	Brought in as an activity. Relationships had to be established.	---	Yes.
Granularity of activity definition	Number of activities to be defined to correspond to the product model component groups.	2 activities need to be defined to account for the 2 sets of panels.	Integration and mapping with the product model is of importance.	Yes.
Activity sequencing	Internal sequences as well as the successor/predecessor relationships need to be reorganized.	Internal sequence of each of the 2 defined activities needs to be reorganized to account for the 2 story lift order of installation.	Integration and mapping with the product model is of importance.	Yes.
Granularity of product model definition	3D component groupings need to reflect the sets.	Integration and mapping with the process model is of importance.	Enclosure's 3D components need to be grouped into 2 sets to correspond to the 2 activities defined.	Yes.
Resource allocation / crewing	How the resources are being allocated?	Number of crew was increased by 4 times.	---	Yes.
Number of work faces / zoning	Two opposite facing sides' enclosure and two levels at a time.	2 sets of activities to be defined in the schedule.	2 sets of enclosure panels to be grouped in 3D model.	Yes.
Definition of workweek	Workweek definition could be changed in a way that accelerates the construction.	---	---	No.
Onsite vs. offsite production of components	Prefabricated enclosure panels vs. onsite fabrication of enclosure panels.	Only installation of the panels is brought to the schedule as an activity (no fabrication).	---	Offsite production was assumed.

Table 2.4 The recovery strategy components deployed in the alternative scenario.

2.6.2 Vico Software system

2.6.2.1 Processes

For the purpose of this research and in order to identify more challenges to address, the alternative scenario was formulated in a 2 phase process:

- Extending the base scenario. This step includes bringing the interior works components that follow the installation of the enclosure system into the 3D model, as well as adding their corresponding tasks into the schedule. The tasks that were added to the base schedule include: rough-in and framing, drywall and painting, interior finishes and fixtures, and inspection and punch list. All of these tasks are due to be completed after the completion of enclosure. The resulting 4D model from this step will be called "extended base scenario" hereafter. The purpose of doing this was to be able to identify the ease or difficulty with which the Vico CAD model can be modified and linked back to the schedule. This item is not discussed for the Repcon-Revit system as modifying a Revit model and linking it back to the schedule is a relatively straight forward process.
- Applying the recovery strategy, and making changes to the “extended base scenario” in order to formulate the "alternative scenario". This step includes applying the required modifications to the methods used in the base scenario (see Table 2.3).

In Vico, if a Recipe is assigned to a group of components (e.g. columns all over the model), and some of those components (e.g. only the parkade columns), need to be modified (e.g. change the activities assigned to them, or modify the level of detail that corresponds to them in terms of any aggregation operation needed for those components), then a whole new Recipe needs to be defined and assigned to those components requiring modification. If this is not done, by modifying the already existing Recipes, all the components attached to them will get modified which is not what is intended. For example, if a new Method is going to be defined in an already used Recipe, then the new task which will be linked to that Method will be mapped to all the Recipe's corresponding components, even though it is only desired to link that new task to only a part of those components.

Figure 2.21 shows the filtered linear scheduling chart of the alternative scenario at hand formulated using the Vico Software system. The mixed strategy used is clearly illustrated, where enclosure installation (line 3) is accelerated until it catches up (at level 39) with the slab re-shoring removal (line 2), and then resumes with the original strategy of one level at a time for the remaining levels. The linear scheduling chart has been filtered heavily to help ensure readability. Shown in Appendix A are snapshots of the 4D representation of the alternative scenario using the Vico Software system.

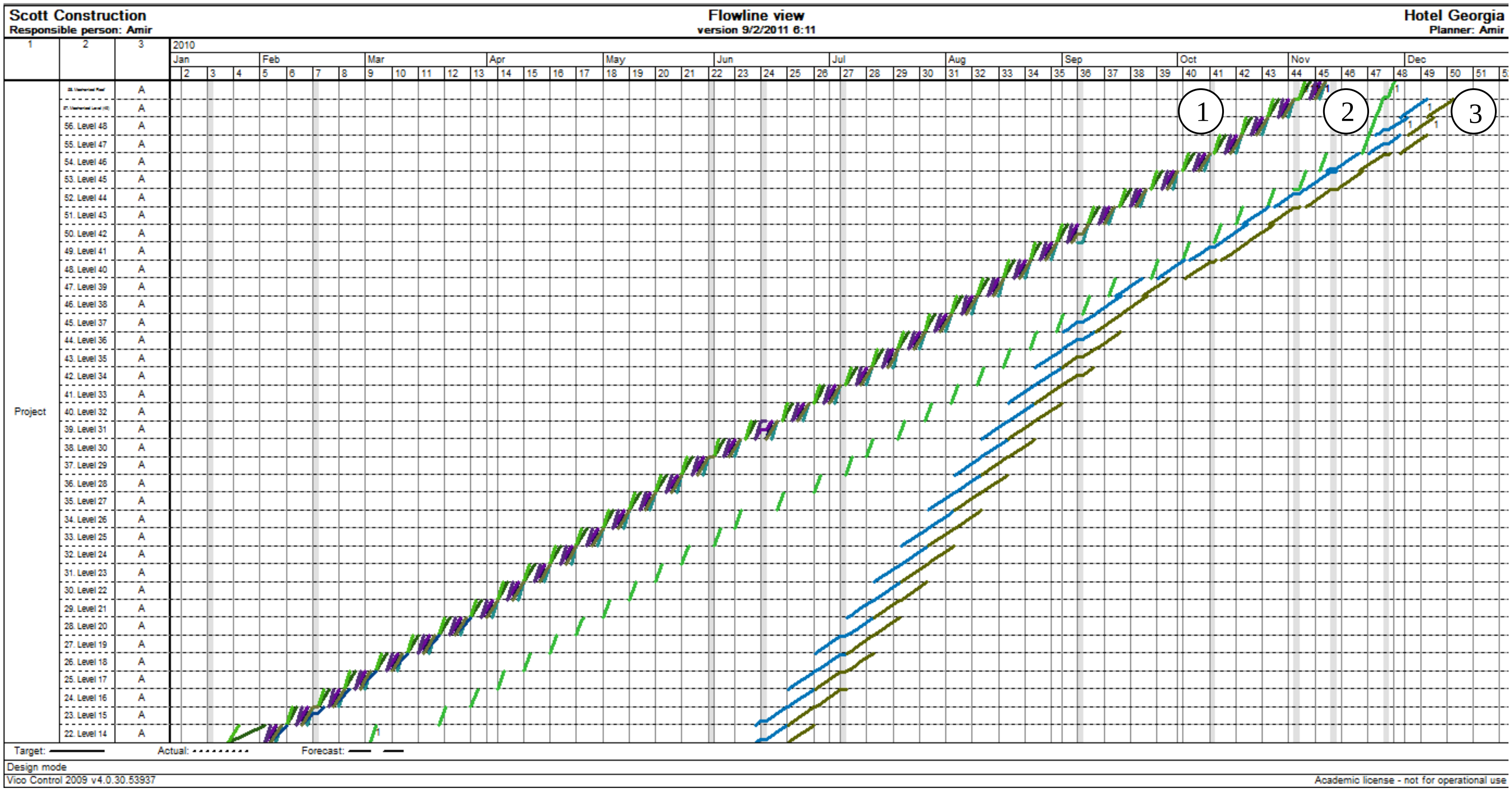


Figure 2.21 Filtered linear scheduling chart for the alternative scenario formulated in Vico Control: 1) Superstructure (14-48), including: Core, Verticals, and Slabs, 2) Removal of slab re-shoring (14-48), and 3) Curtain wall/enclosure installation (14-48). The linear scheduling chart has been filtered heavily to help ensure readability.

2.6.2.2 Analysis of the constraints and challenges faced in formulating the "extended base scenario" with Vico Software system

- Bringing in new 3D CAD objects: To include new 3D components, the user needs to know what exactly has to be brought into the already existing model, meaning that s/he has to clean up the model to be imported, in a way that no irrelevant or previously imported components remain in it. For this project and in order to bring in the Interior Works components, after filtering component types in Revit (the Revit model included the interior works) and exporting them to Constructor in an IFC format, the resulting model still had many unwanted elements within it. Recipe Link Checker Palette was the solution for detecting and managing all of the unwanted elements.
- Bringing in new activities: To deal with newly added activities like Interior Finishes which need to be linked to both existing walls and the newly brought-in internal partitions, not only do we need to define and assign a new Recipe to the new components, but we also need to modify the Recipes of the already existing components in a way that it addresses our needs regarding having relevant Methods linked to the new tasks.
- Flow of data between different modules: After bringing in the new 3D components and linking them to the newly defined tasks in Constructor, the new .xml export of the project needs to be saved on the previous original .xml file which was first used to build the schedule in Control, so that by updating the schedule in Control the added tasks are shown in the schedule and are

ready for scheduling. (The new .xml file cannot be imported directly into Control, as Control will ignore all the data related to the added tasks.)

2.6.2.3 Analysis of the constraints and challenges faced in formulating the "alternative scenario" with Vico Software system

In order to modify the “extended base scenario”, and apply the recovery strategy to it to form the alternative strategy where enclosure of opposite facing sides of each level gets built at the same time, we could choose between 2 possible approaches in Vico.

2.6.2.3.1 Approach number 1

Use new zones to differentiate between 2 sets of curtain wall components (see Table 2.3): In this method, by defining a new zone for each of the corresponding levels of the building (levels which are affected by the delay - level 14 and above), we can split and assign the curtain wall components between the already existing zone and the newly defined one (in each level), in a way that each set of opposite facing curtain wall panels is placed in one of these zones.

- The strength of this approach is that by using the WBS (work breakdown structure) Palette's capability of defining alternative location sets, the user can create and compare several zoning alternatives all in one place without having to remove or manipulate the already existing zoning structure.
- The weakness of this method is that it is too cumbersome to assign the required components to the newly defined zones. The curtain wall

components are made of thousands of smaller elements that need to be selected and assigned to the new zones defined (due to the IFC method of conversion used - see section 2.4.2.2). Another issue in using this method is that by defining a new zone for each of the corresponding levels, the resulting schedule in Control will also include the zones in its linear schedule diagram, which will make the schedule confusing and hard to read and understand. The reason is that the newly defined zones will show up on the vertical axis of the linear schedule (location axis of the chart), while corresponding to only a limited number of components in the model.

Due to the limits that this method has, we chose the second approach described below for formulating the alternative scenario.

2.6.2.3.2 Approach number 2

Use new Recipes to differentiate between 2 sets of curtain wall components: In this method, by defining and assigning new Recipes to the second set of curtain wall components at the corresponding levels of the building (levels which are affected by the delay - level 14 and above), we can differentiate between the 2 sets of curtain walls needed to schedule the alternative scenario.

- As mentioned for the first approach, one of the major issues faced here is selecting the corresponding curtain wall components, and assigning them a Recipe specifically defined for them. The newly defined Recipe has to have new Methods within it to be used to create new tasks.
- A new task has to be defined in Constructor (for the second set of curtain wall components), and then imported into Control by updating the xml structure of

the base scenario schedule originally used to formulate the schedule in Control.

- During the scheduling process which has to be performed on the newly defined task, as well as the predecessor and successor tasks of the modified activities, some of the issues faced while formulating the base scenario schedule in Control, occurred yet again (e.g. the issue with overlapping tasks, as Control doesn't let the location instances of an activity overlap, unless the task gets split manually).

2.6.3 Repcon-Revit system

2.6.3.1 Processes

In the Repcon-Revit system, the process of applying changes to the base scenario in order to generate the alternative scenario is straightforward and unsophisticated. By providing a more general way of linking the product models on both the CAD and scheduling sides, essentially we link objects at the class level rather than the instance level and through the different product models rather than linking CAD objects and activities directly. This type of linking mechanism minimizes the number of links that need to be made, and eliminates the need to manually re-link CAD objects and activities as the design and schedule change. This approach allows users to create links by using the semantics of the component classes in the PCBS on the scheduling side and in the family types on the CAD side to make general associations for classes of components [27]. As an example, in order to modify the sequence of tower's enclosure installation, we only need to make adjustments to the process model components which correspond to the enclosure panels - change the sequence of activities -, and no further linking is required, as the process and product models are already linked.

To apply the recovery strategy and in order to differentiate between the 2 sets of enclosure panels on the PCBS side (two sets of opposite facing sides - see Table 2.3), the user has to use a new Revit family type - either a predefined or a newly defined family type - to be assigned to the 2nd set of curtain walls. On the schedule side (process model view in Repcon), the task corresponding to the curtain wall installation could be split in two different ways in order to account for the 2 sets of curtain wall, as well as the 2 levels at a time recovery strategy approach:

1) To split the task into 4 sub-tasks accounting for 2 opposite facing sides sets of components, as well as the installation of 2 levels at a time for each of the sets,

2) To split the task into 2 sub-tasks accounting for 2 opposite facing sides sets of components, and then change the internal logic of the activity completion sequence in each of the sub-tasks to account for the 2 levels at a time order of installation.

With respect to the changes made to the 3D model as well as the process model view, the product model view of the project also needs to be modified correspondingly.

Figure 2.22 shows the filtered linear scheduling chart of the alternative scenario at hand formulated in Repcon-Revit system. The mixed strategy used is clearly illustrated, where enclosure installation (line 3) is accelerated until it catches up (at level 39) with the slab re-shoring removal (line 2), and then resumes with the original strategy of one level at a time for the remaining levels. The linear scheduling chart has been filtered heavily to help ensure readability. Shown in Appendix B are snapshots of the 4D representation of the alternative scenario using the Repcon-Revit system.

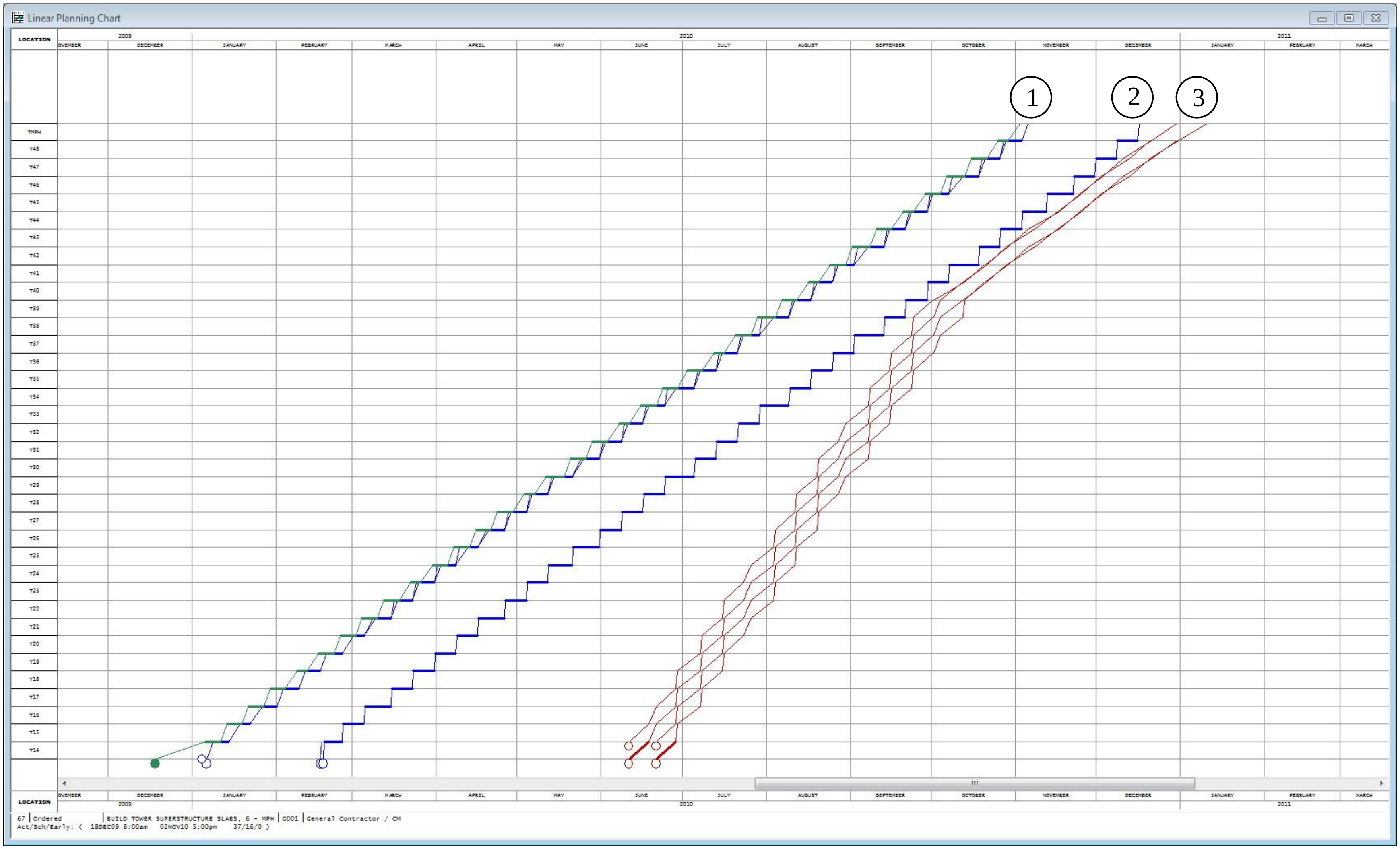


Figure 2.22 Filtered linear scheduling chart for the alternative scenario formulated in Repcon: 1) Superstructure (14-48), including: Core, Verticals, and Slabs, 2) Removal of slab re-shoring (14-48), and 3) Curtain wall/enclosure installation (14-48). The linear scheduling chart has been filtered heavily to help ensure readability.

2.6.3.2 Analysis of the constraints and challenges faced in formulating the "alternative scenario" with Repcon-Revit system

- Modifying CAD objects: If CAD objects have to be changed (e.g. new Revit family types have to be assigned to them), or new CAD objects need to be inserted into the 3D model, the change process can be cumbersome. It depends on whether or not the composition of objects used has to be changed (i.e. some variability in design can simply be handled by changing the properties of existing objects, without adding a new family type). In Revit, to change the composition of objects, you have to go into the family type properties to modify the object and its attributes before it can be populated. To add new objects, you need to create that object in the family editor environment and add any new properties, and then insert it into the project model.
- Modifying model views: Manual input was needed to modify the process and product model views as well as the 3D CAD object attributes.
- Modifying links: Links had to be established manually between the modified structures (product and process model views, and 3D model). Also, the relationships between the curtain wall tasks and their predecessors and successors had to be modified.

2.7 Discussion

In this chapter the responsiveness of each of the systems examined with respect to the main features expected from a linear-scheduling-based 4D modeling system is discussed. First, the features required of a 4D environment in order to be able to evaluate alternatives at any stage during the construction process (planning and execution) are introduced. Then, the features which correspond to the case study at hand as well as the base/alternative scenario discussed in this research, are examined and discussed.

2.7.1 Features required of a 4D environment

The features required of a 4D environment for formulation and evaluation of construction scenarios, can be categorized based on the main functions needed from such an environment, and include: features concerning the process model; features concerning the product model; features concerning the mapping process; and features concerning visualization capabilities. The following table (Table 2.5), lists the required features based on the desired functions.

Function	Feature
Process Model	• Tools and options available for formulating the process model (e.g. linear scheduling capabilities) • Tools and options available for making changes to an existing process model (e.g. add/remove/modify a component). • The level of manual input needed vs. automatic input methods. • Reflection of zoning and project breakdown structure in the process model.
Product Model	• Tools and options available for formulating the product model (e.g. 3D modeling capabilities) • Tools and options available for making changes to an existing product model (e.g. add/remove/modify a component). • The level of manual input needed vs. automatic input methods. • Reflection of zoning and project breakdown structure in the product model.
Mapping	• Establishing links between the process and product models. • Add/remove/modify links. • Managing links. • Manual mapping process vs. automatic mapping process.
Visualization	• Linear scheduling diagram representation options (e.g. color codes). • 3D model visualization options (e.g. navigation tools, materials, etc.). • 4D model visualization options (e.g. transparency adjustment).

Table 2.5 The features required of a 4D environment for formulation and evaluation of construction scenarios.

2.7.2 Discussion of the features corresponding to the case study at hand

Based on the storyline that this research follows, the features to be focused on can be categorized in two general groups: 1) features related to the formulation and creation of a 4D model (the base scenario in this research), 2) features related to application of changes to the already-formulated 4D model. With respect to the first group, the features include: zoning capabilities, formulation of linear schedule, and establishment of links. With respect to the second group, the features include: changing the schedule, changing the 3D model, and management of links. However, there are some features which cannot be categorized under these groups, but are critical for a 4D environment with linear scheduling capabilities. These features include: project breakdown structure format, degree of automation, and visualization tools and options.

In this chapter we compare the approaches of the two systems based on the above-mentioned features, and evaluate their responsiveness toward fulfilling the requirements of each feature.

2.7.2.1 General approach in formulating the project breakdown structure

Since the approach that each of the systems uses toward building the 4D model is different from the other, the final break-down structure of the project is different. To elaborate on this, in the Repcon-Revit system the project breakdown structure is formed based on the Product and Process Models and gets built in during the very early phases of the process, while the mapping between the schedule and CAD objects happens later. But in the Vico Software approach, the process model is basically embedded in the product model, as it is the product model which gets formulated first in the process, and then the process model is created based on the mapping that happens between the specified activities and the Methods defined in the product model. The next step is to modify and perform scheduling on the process model. These 2 different approaches result in a somewhat different structure for the project in each of the systems.

In order to get the closest break-down structure to Repcon-Revit's Product Model, in terms of the level of detail, as well as the tasks which correspond to the specified zones, we had to go through a 2-step process in Vico: The first step takes place in Constructor where zones and tasks are defined, and corresponding Methods have been assigned to the tasks. In this step, we can only adjust the level of detail needed for the defined activities. The second step is to bring the project into Vico Control and split each of the tasks into its corresponding zones.

By having two product models in the Repcon-Revit system, more input will be needed to set up the system, but once the links are established, no further re-linking is needed to reflect the changes in activities and/or 3D CAD objects (unless we subdivide the 3D components and/or activities.). In the Vico Software system, by having a single WBS (work breakdown structure) for the project, the management of the 4D model (e.g. managing the links, tracking the changes, etc.), is easy as all the required information can be found in the same WBS structure (including: locations, tasks, methods and quantities).

2.7.2.2 Degree of automation

As a general rule in the process of 4D modeling, the higher the level of automation is in generating the project model structures as well as establishing links between them, the less customization capabilities will be available to control those structures and links. Based on this argument, and with respect to the systems we are examining, the Repcon-Revit system uses much more scheduler/modeler input (less automation capabilities compared to Vico), but at the same time provides the user with a higher level of control over the functions and procedures. On the opposite side, most of the processes taking place in the Vico Software system are automatic, but at the same time this limits the user to have full control over all the functions and procedures.

An example of this would be the linking process of 3D components with tasks: in Vico, based on the Recipe assigned to a certain type of component (e.g. external walls), the Methods defined in that Recipe, and the tasks that those Methods are associated with, the breakdown structure for that type of component will be formulated. If the scheduler decides to add some more 3D instances to that type of component and wants to make sure that the new instances will also correspond to the same activities that the component type does, then s/he has to start from the Recipe level of the new instances and check if the Recipes assigned to them are either unique to those instances, or are the same as the Recipe used for the component type they are going to be a part of. After this step, the time data needs to be attached to the instances, for which a back and forth flow of information is needed between two of Vico’s modules (Constructor and Control). As you can see, the automation has made the process of change slightly complicated and several steps need to be taken in order to apply a change. But in order to attach more 3D instances to a set of tasks in the Repcon-Revit system, more manual input will be needed (selecting the instances, changing their attributes, and linking them with the product model), but the process is straight forward and has fewer complications.

2.7.2.3 Defining horizontal and vertical locations/zones

Even though that Vico Software system provides us with many intuitive methods of defining horizontal zones, it still lacks the capability to properly define vertical locations for several buildings we might have in the same model. As also discussed in the previous chapter (see 2.4.2.2), there is only one predefined set of levels inside Constructor which can only correspond to one of the buildings inside the model. This means that the other buildings which exist in the same model have to follow the same order of levels, in terms of height and elevation. The same level structure will be used to define the vertical locations needed for scheduling the project in Control. On the other hand, in the Repcon-Revit system, we have the capability to define as many level sets as we want, both in Revit to build the 3D model, and in Repcon to formulate the product and process model view structure.

In exploring different construction strategies, the extent of horizontal zoning may become a decision variable and the decision will depend on what the structural engineer will allow and where construction joints can be placed, and what is feasible from a construction strategy perspective [27]. In this regard, Vico Software has provided the user with several zoning methods from which the user can choose one or a combination to get the zoning structure s/he is looking for. But in the Repcon-Revit system, there are no separate zoning tools available, and the user has to use phasing methods or selection sets from Revit to define the zones needed. Moreover, Vico Software uses the "non-destructive element splitting" method for quantity take-off and visualization of the 4D model, while in the Repcon-Revit system, no such capability is provided (see section 2.4.2.1.1). Nevertheless, there is still need for more flexibility in terms of spatial zoning and related grouping of physical components in both systems.

2.7.2.4 Methods and tools available for formulating the linear schedule

Tools and techniques that each of the systems provides the users with for linear scheduling purposes are different in a way that there might be different solutions to the same problem in each system. Some examples of such solutions are as follows:

- Unlike Repcon, in Control, no relationship could be established between summary tasks, meaning that all the relationships have to be established between children level tasks.
- In Control, no negative or positive lag could be established between the instances of the same task in different locations of the project. In order to address the issue with negative lagging, (activities overlapping each other) we need to split the task and define new relationships between them in a way that they could be overlapped. For positive lagging, we could either define a dummy task and use it to impose the required lag on the tasks, or we could use the already lagged tasks and establish new relationships between them

and the tasks which need to be lagged. We used both of these solutions to address the issues concerned with lagging.

2.7.2.5 Establishing and managing links between tasks and 3D components

One of the strengths of Vico in organizing the structure of the project, as well as managing 3D components and the links established between them and their corresponding tasks, is providing the user with 2 manipulation palettes:

- WBS Manager, which helps to organize the Work Breakdown Structure or WBS of the project. WBS Manager is where the user can search through and have access to all the locations and zones defined, Tasks and Methods linked to 3D components, and the quantities which correspond to the amount of a 3D component specified to a certain Method within a specific zone, altogether in one place.
- Recipe Link Checker, which makes the process of selecting and managing components, as well as establishing links between components and Recipes so easy and almost automatic. By means of this tool, users can select 3D components based on common attributes and perform batch linking with Recipes. However, the linking between Recipes and Tasks has to be established manually and requires the Task list to be input manually in Constructor.

On the other hand, the Repcon-Revit system uses an intermediate linking module to manage the links established between the 3D CAD components and the product model view (called the physical component breakdown structure or PCBS) formulated in Repcon. The MS Access based application affects the user's ability to access all of the relevant CAD and schedule data. The issue in here is that MS Access does not fully support the hierarchical structure of the Repcon database [26].

2.7.2.6 Changing the 3D model

Changing the 3D model includes either the modifications to be made to the existing 3D CAD objects' attributes, or creating and inserting new 3D CAD objects into the 4D model. For the former scenario, the ease by which the user can change the CAD objects' attributes and preserve the already-established links is of importance. For the latter scenario, the process of creating new CAD objects and inserting them into the 4D model system by establishing new links, are the areas of interest to this research.

To create new CAD objects or modify the already existing CAD objects, each of the systems relies on the capabilities provided by its separate modeling module. The Revit module in the Repcon-Revit system and Constructor module in the Vico Software system provide the users with powerful tools and techniques to make the changes needed to the 3D model. Both systems follow similar internal processes to establish/preserve links between changed CAD objects and the schedule. In the Repcon-Revit system, if the attributes (e.g. new Revit family type) to be assigned to a CAD object have already been used and linked to the product model, then no further links are needed. But if the new attributes are unique to that CAD object, then new links need to be established with the product model. Similarly in the Vico Software system, as long as the Methods within a Recipe to be assigned to a 3D component have already been linked to their corresponding tasks, no further links are needed. But if the Methods used are unique to that CAD object, then new links need to be established with the corresponding tasks.

2.7.2.7 Changing the schedule

Changing the schedule includes either the modifications to be made to the existing tasks, or creating and inserting new tasks into the schedule. For the former scenario, the ease by which the user can change task attributes and preserve the already-established links is of importance. For the latter scenario, the process of creating new tasks and inserting them into the 4D model system by establishing new links, are the areas of interest to this research.

In the Repcon-Revit system, Repcon is where all the scheduling happens. In order to change existing tasks attributes such as duration, start/finish dates, etc., the user only needs to change the related parameters, and all the already-established links will be conserved between the process model and the product model. Compared to the Vico Software system, the process is quite similar in Control, as the links are already there when the changes are being implemented on the tasks. The only difference is that in Vico, we still need to bring the revised time data back to Constructor and attach it to the 3D components (using xml file format), as the dates and duration will not get updated automatically in Vico's 4D model system.

In order to create new tasks inside the schedule, the process is quite straight forward in the Repcon-Revit system, where the user needs to add and plan the new task in Repcon's process model and then link it to its corresponding product model components. The challenge for this system is that most of the input needs to be manual. In the Vico Software system, the process is a bit more complicated. To add a new task in a Vico 4D model, the process starts from Constructor where the task is defined and the corresponding Methods are attached to it. And then by transferring the data using xml file format to Control, the scheduler needs to update the schedule and perform planning on that task. Finally, the time data of that task needs to be brought back into Constructor (again using xml file format) to be attached to the corresponding 3D components.

2.7.2.8 Visualization/representation tools, methods, and options available

Generating the final 4D model in Vico happens inside Constructor, and the exported file can be visualized and reviewed in Vico 5D Presenter. This makes it almost impossible to modify the schedule, 3D model, or links, and watch the 4D model change in real-time in the Vico Software system. Generating a 4D model export in Constructor and bringing it into 5D Presenter is a time-consuming process and no further modifications are possible on the exported 4D model in 5D Presenter. However, the 5D Presenter module provides the users with tools by which navigating through the 4D model, generating video and snapshot outputs, and extracting complementary information by manipulating the 4D model is made possible (e.g. adjusting the transparency of the components which are not under progress to watch the internal work, getting information re the Methods and tasks assigned to a certain 3D component by selecting it, etc.). Another fundamental capability that Vico provides users with, is that several tasks which are mapped to the same set of 3D components, could be assigned and visualized with different color codes in the 4D model.

With respect to the Repcon-Revit system, to represent the status of construction at a given point in time, a Time Contour is created from Repcon that flags the physical components as either being completed (value of 1), or not yet started (value of 0) as of a specific progress date, given the breakdown of activity work on a location by location basis. Hence, work in progress is not shown in the 4D snapshots [26]. Also, since the integration between the product model and 3D CAD objects happens by means of the intermediate linking application, the changes made to either product/process model or 3D model will not be viewable in real-time on the 4D model. The Repcon-Revit system is only able to generate snapshots of the 4D model, and not much control is provided to manipulate the visualization of the resulting snapshots (e.g. by adjusting transparency or exploding the building levels to see internal work, it is still possible by means of the tools Revit provides us with. However extra time and effort should be spent to customize and visualize such 4D snapshots.).

Table 2.6 shows a comparison between the two systems with regard to the basic functions required from a 4D modeling environment.

Functionality	Repcon-Revit system	Vico Software system
Create links between CAD objects and schedule activities	Links are created between the product model in Repcon with family types and levels in Revit. Users have to manually map family types onto PCBS components.	Recipes are assigned to the CAD objects. By linking the Methods within each Recipe with their corresponding defined tasks, the links will be established.
Create/modify CAD objects	If the new family type to be used for the CAD objects, has already been used for other CAD objects, then no further links need to be established. Otherwise, new links need to be established.	As long as the same Methods are being assigned to the new/modified CAD objects, no further links need to be established.
Create/modify activities	Modified activities do not need to be re-linked as they preserve the links. However, the newly defined activities need to be associated with existing PCBS components.	Modified activities do not need to be re-linked as they preserve the links. But the newly-defined activities need to be associated with their corresponding Methods from CAD objects.
Change existing links between CAD objects and Schedule activities	Changes to the links can be done through the product model mapping. As long as the links between the two product models remain unchanged, changes to objects and activities will have no effect on the links.	Changes to links are easily made and managed by means of tools like Recipe Link Checker. As long as the links between the tasks and Methods remain unchanged, changes to 3D components and activities will have no effect on the links.

Table 2.6 Comparison of Repcon-Revit system and Vico Software system with regard to the basic functions required from a 4D environment.

2.8 Conclusions

In the previous sections of the thesis, two 4D systems were compared with respect to the major functions and features expected from a 4D modeling environment with linear scheduling capabilities which facilitates the formulation and evaluation of alternative construction scenarios. The features discussed attribute to formulation of a 4D model (base scenario), and then the application of changes to it (in form of an alternative scenario). As a general rule, the more automation is provided in a system, the less manipulating capabilities provided by the system. In the Vico Software system, the level of automation (especially in the linking process) is higher compared to the Repcon-Revit system, which means most of the links get established automatically and internally while the 3D model and schedule are being defined. However, it results in less user control over manipulation of the 4D model. On the other hand, the Repcon-Revit system needs more manual input, and at the same time gives more manipulating power to the user. As a result, the Vico Software would address the demands best, when the whole process of formulating the 3D model and schedule is taking place within the modules of this system from scratch. If the 3D model and/or the schedule are brought from another application, the Repcon-Revit system would respond more easily, but the process will be more time-consuming as the level of automation is limited.

The Vico Software system, provides the user with more capabilities and richer tools for zoning the project (e.g. different methods of zoning are available from which the user can choose one or a combination which matches his/her demands), as well as for visualizing the final 4D model (5D Presenter as a separate module for visualizing the 4D model and supporting the user by generating videos and snapshots, transparency adjustment capabilities, model navigation, etc.). When it comes to working with multiple levels of detail, the Repcon-Revit system is more responsive, because as long as the process and product models of the project have been formulated properly, the integration could be maintained easily. But in the Vico Software system, the user always needs to have a balanced level of detail throughout the project, while an unbalanced level of detail forces the user to bring in new elements (e.g. new Recipes), and to establish new links. Finally, both of the systems are rich in terms of the linear scheduling tools for formulation of the schedule. Also in both systems, as long as the changes are being made on the existing 3D model components and/or schedule tasks, the links are conserved, and no more linking is needed. More input is needed in both systems, when bringing in a new 3D component, task or link.

Each of the systems has its own strengths and weaknesses. Future work for the Repcon-Revit system could be focused on: automation capabilities in link establishment, zoning methods, and visualization options to represent the final 4D model. For the Vico Software system, the focus could be on: manipulation capabilities in establishing links and managing the level of detail needed, some adjustments on the linear scheduling module, and giving more support to the processes where the starting point is somewhere else than the system (e.g. the 3D model or/and the schedule are formulated in some other applications.). The areas where future work and research could be focused on include: dealing with design changes in pre-construction and/or execution phase of a project, the application of adding the "cost" data to 4D as the 5th dimension, and using the 5D tool for estimating the project, in addition to scheduling and quantity take off.

Chapter 3: Conclusions

In this thesis, two linear-scheduling-based 4D modeling systems were described. Repcon-Revit system as current state of a research approach being conducted at the University of British Columbia, and Vico Software system as a commercial platform. For each of the systems, we described the steps involved in the process of formulating the 4D model, and examined the challenges involved in formulating the “base scenario”. A delay in procurement of the building enclosure followed by the recession, resulted in a demand for an “alternative scenario”. The alternative scenario was introduced to the project by making changes to the base schedule. The ease by which each of the systems could cope with the modifications required to be made on the base scenario, was the second area we concentrated on in this research.

The benefits of Repcon-Revit system approach include a 2-way flow of data between scheduling and CAD and the ease with which the links between the product and process model can be generated and maintained, which enables the rapid exploration of alternative construction strategies in 4D. This functionality is possible because we have dual product models on the CAD and scheduling sides. Key contributions of the approach include the ability to support multiple product models, multiple mappings between product models, and multiple schedule visualizations [27].

With respect to the Vico Software system approach, the internal linking mechanism of Recipes, Methods and 3D components, and the way all these processes are integrated in the same module (Constructor), gives the user the power to easily manage all the links and examine the changes in real-time (using the WBS Manager). The ability to define alternative location/zone structures, intuitive methods of selection (e.g. Recipe Link Checker), and the 2-way flow of information between Constructor and Control, as well as Constructor and Estimator, are the capabilities by which the exploration of alternative construction scenarios have been made easy.

In the second chapter of this thesis, the two 4D systems were compared, with respect to the major functions and features expected from a 4D modeling environment with linear scheduling capabilities. The features discussed attribute to formulation of a 4D model (base scenario), and then application of changes to it (in form of an alternative scenario). As a general rule, the more automation is provided in a system, the less manipulating capabilities provided by the system. In the Vico Software system, the level of automation (specially. in the linking process) is higher compared to the Repcon-Revit system, which means most of the links get established automatically and internally while the 3D model and schedule are being defined. However, it results in less user control over manipulation of the 4D model. On the other hand, the Repcon-Revit system needs more manual input, and at the same time gives more manipulating power to its user. As a result, the Vico Software would address the demands best, when the whole process of formulating the 3D model and schedule take place within the modules of this system from scratch. If the 3D model and/or the schedule are brought from another application, the Repcon-Revit system would respond more easily, but the process will be more time-consuming as the level of automation is limited.

The Vico Software system, provides the user with more capabilities and richer tools for zoning the project (e.g. different methods of zoning are available from which the user can choose one or a combination which matches his/her demands), as well as for visualizing the final 4D model (5D Presenter as a separate module for visualizing the 4D model and supporting the user by generating videos and snapshots, transparency adjustment capabilities, model navigation, etc.). When it comes to working with multiple levels of detail, the Repcon-Revit system is more responsive, because as long as the process and product models of the project have been formulated properly, the integration can be maintained easily. But in the Vico Software system, the user always needs to have a balanced level of detail throughout the project, while an unbalanced level of detail will force the user to bring new elements (e.g. new Recipes), and to establish new links. Finally, both of the systems are rich in terms of the linear scheduling tools for formulation of the schedule. Also in both systems, as long as the changes are being made on the existing 3D model components and/or schedule tasks, the links will be conserved, and no more linking is needed. More input is needed in both systems, when bringing in a new 3D component, task or link.

Each of the systems has its own strengths and weaknesses. Future work for the Repcon-Revit system could be focused on: automation capabilities in link establishment, zoning methods, and visualization options to represent the final 4D model. For the Vico Software system, the focus could be on: manipulation capabilities in establishing links and managing the level of detail needed, some adjustments on the linear scheduling module, and giving more support to the processes where the starting point is somewhere else than the system (e.g. the 3D model or/and the schedule are formulated in some other applications.). The areas where future work and research could be focused on include: dealing with design changes in pre-construction and/or execution phase of a project, the application of adding "cost" data to 4D as the 5th dimension, and using the 5D tool for estimating the project, in addition to scheduling and quantity take off.

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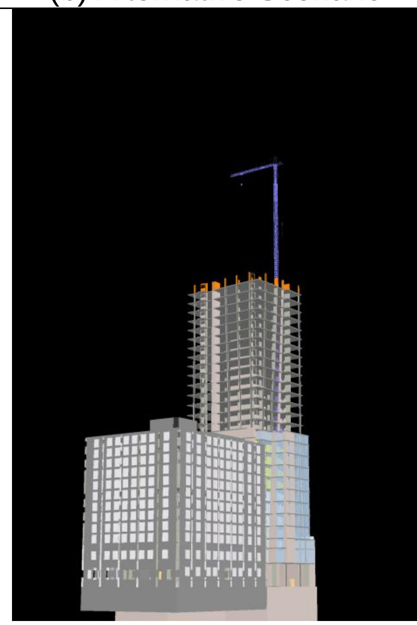
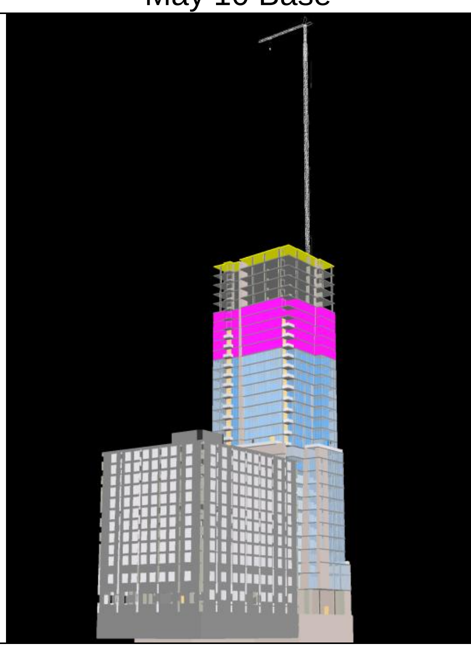
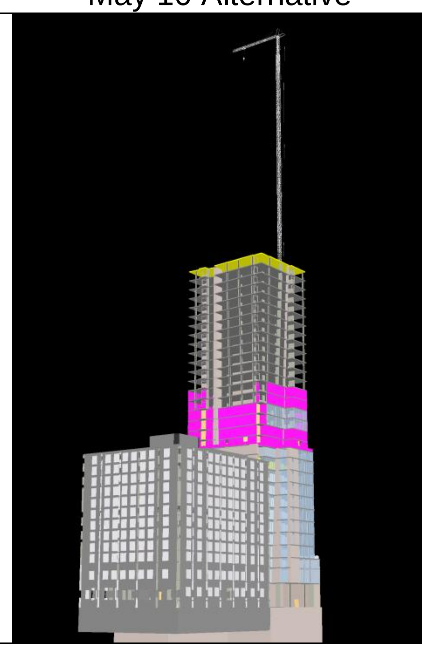
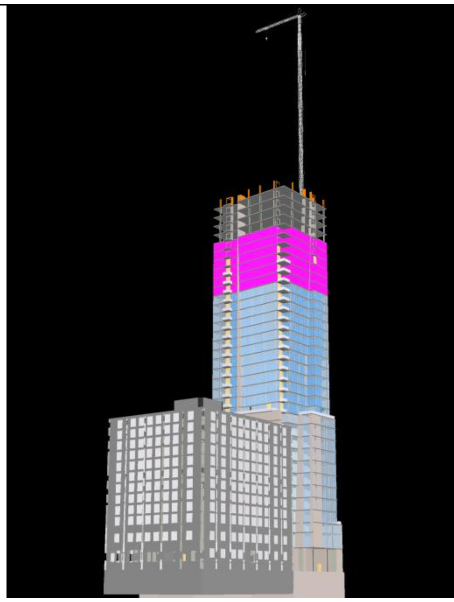
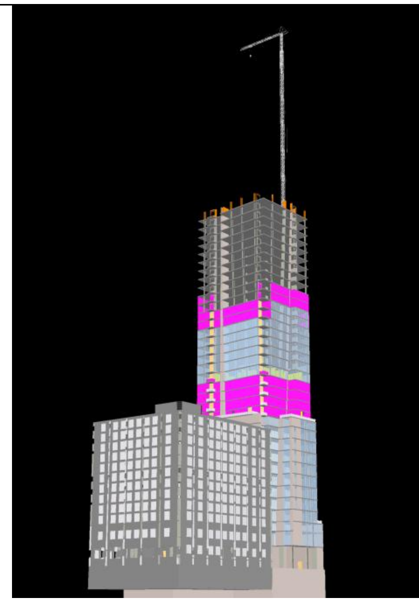
Appendices

Appendix A

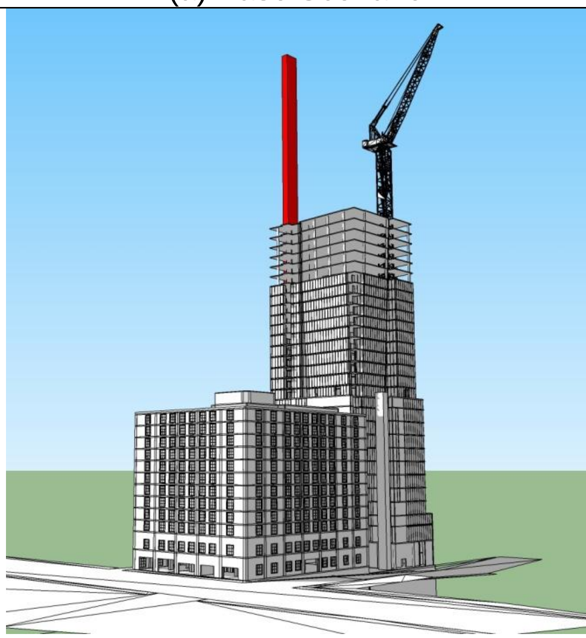
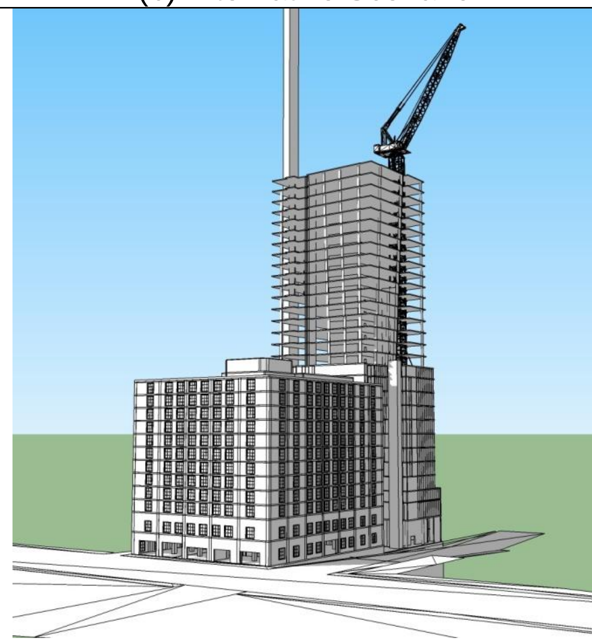
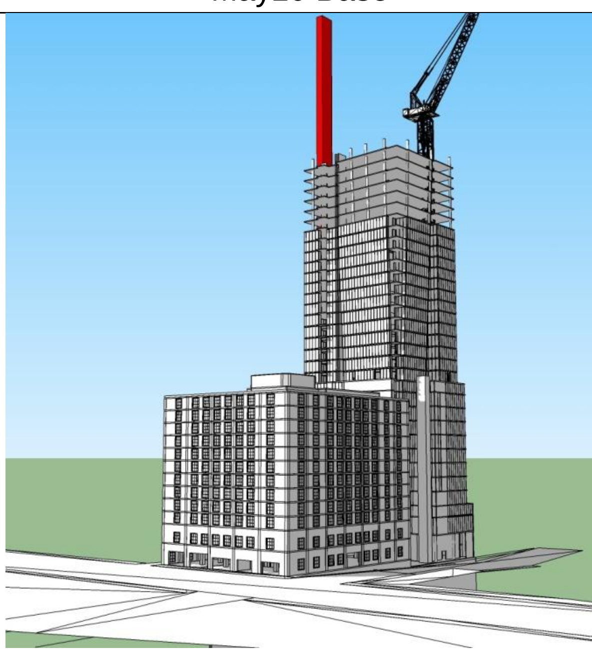
Snapshots of the 4D model formulated in Vico Software system. Different colors show the in progress components. Orange for verticals, yellow for slabs, and pink for enclosure.

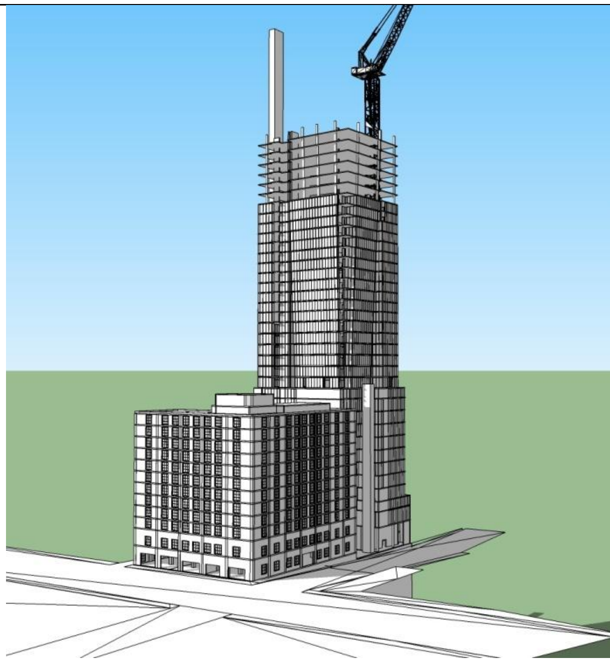
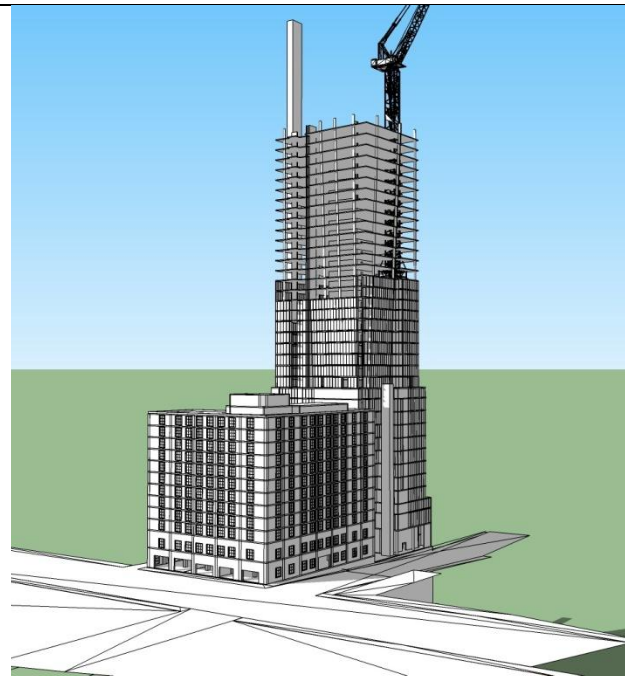
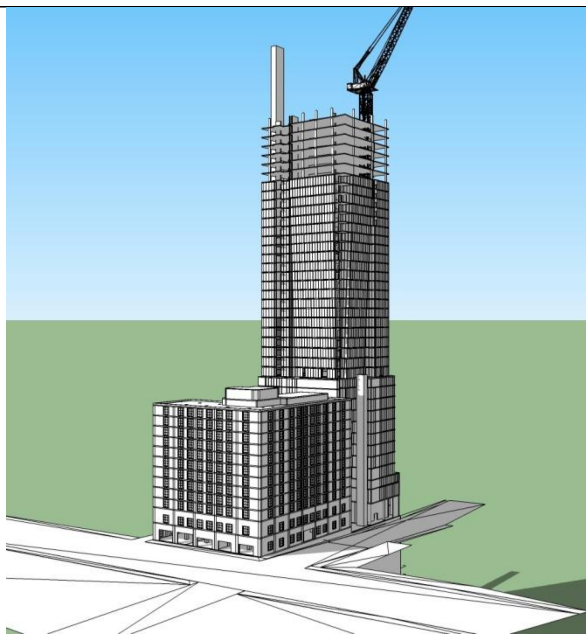
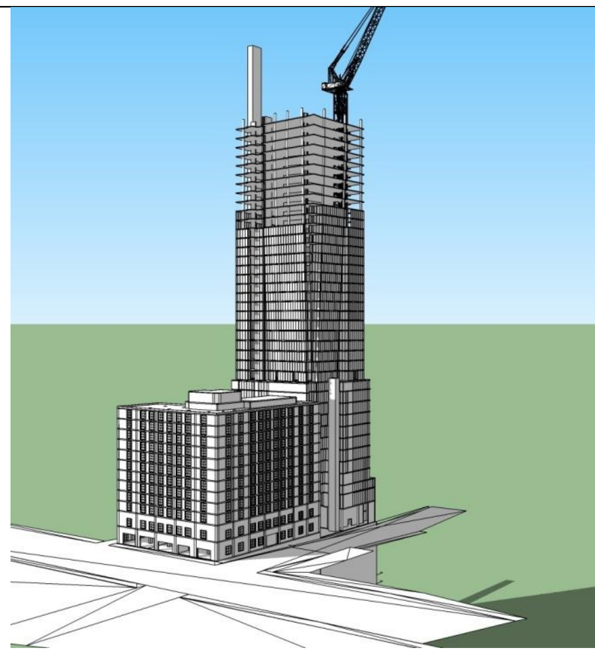
Vico Software system	
(a) Base Scenario	(b) Alternative Scenario
	
May 10 Base	May 10 Alternative
	

June 10 Base	June 10 Alternative
 July 10 Base	 July 10 Alternative
 August 10 Base	 August 10 Alternative

Appendix B

Snapshots of the 4D model formulated in Repcon-Revit system.

Repcon-Revit system	
(a) Base Scenario	(b) Alternative Scenario
 May10 Base	 May10 Alternative
 Jun10 Base	 Jun10 Alternative

 Jul10 Base	 Jul10 Alternative
 Aug10 Base	 Aug10 Alternative