LINEAR SCHEDULING AND 4D VISUALIZATION

by

NGOC TRAN

B.Sc. (Civil Eng.), Hanoi University of Civil Engineering, 2001

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ABSTRACT

Described in this thesis is a novel approach to 4D CAD. It involves a 2-way symbiotic relationship between 3D CAD software and a software implementation of linear planning that includes the ability to define a project product model and associate it with the process model. Strengths of the approach include the ability to readily modify construction sequences and examine their consequences using 4D CAD, and the ability to treat very large scale projects marked by significant repetition of their components. By building on a shared image of the project product model from both a design and construction perspective, the CAD model can be structured in a way that facilitates communication with the scheduling software and vice versa. Various challenges involved in making the 2-way process work are described, including consistency of product representation in the CAD and scheduling models, and the need to group CAD components at different levels of detail and locations to reflect the kinds of aggregation found in schedule representations of a project. The benefits of the approach include the ease with which different scheduling strategies can be explored and visualized, the links between 3D objects and activities can be maintained, and the completeness of the product model representations can be validated. An example is used to illustrate the approach adopted and challenges involved.

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CO-AUTHORSHIP STATEMENT

The author of this thesis, Ngoc Tran, was responsible for substantial contributions to the content and writing of the two co-authored manuscripts presented in Chapter 2 and 3.

The two co-authors: Dr. Alan Russell - Professor, Department of Civil Engineering, and Chair, Computer Integrated Design and Construction - UBC, and Dr. Sheryl Staub-French – Assistant Professor at the Department of Civil Engineering – UBC, participated in the development and drafting of ideas and were equal partners with the thesis author in the review and revision of the manuscripts.

Date (2007/04/20)

Signature of Research Supervisor _____

Signature of Thesis Author _____

CHAPTER 1 - THESIS OVERVIEW

1.1 INTRODUCTION

The context of this thesis is to demonstrate the feasibility and values of linking two different planning/scheduling paradigms: linear planning and 4D (3D CAD + time). Our focus is on the completion of proof of concept with classes of projects involving multiple repetitive locations. The key element in this approach is having a product model on the scheduling side as well as the CAD side. A mapping between the two product models allows for the two-way flow of information – quantity information from CAD to scheduling and component status at different points in time from scheduling to CAD. The challenges in making the 2-way process work include consistency of product representation in the CAD and scheduling models, and the need to group CAD components at different levels of detail and locations to reflect the kinds of aggregation found in schedule representations of a project. The benefits of the approach include the ease with which different scheduling strategies can be explored and visualized, the links between 3D objects and activities can be maintained, and the completeness of the product model representations can be validated.

1.2 MOTIVATION

Assessing the constructability of a design can be a significant challenge (Tabesh and Staub-French 2006), as can assessing the quality and workability of a schedule (Russell and Udaipurwala 2000). Getting both the design and schedule ‘right’ contributes significantly to timely delivery within budget and reduces the potential for changes and disputes. 3D-CAD allows designers, the client and construction personnel alike to assess the responsiveness of a design to client needs, the potential for design errors in terms of conflicts and overly constrained working spaces, and the ease with which components and systems can be constructed. From a

scheduling perspective, and especially for large scale projects, schedule visualizations using traditional means such as a bar chart or a time-scaled network diagram, while useful, offer limited assistance in assessing the quality / workability of a schedule, even when extensive filtering features are employed. 4D CAD offers the potential to animate a schedule thereby allowing an assessment of its correctness and workability to be made (e.g. Koo and Fischer 2000, Messner et al. 2002, Akinci et al. 2003). It also offers the potential to reassess elements of the design or construction strategy to enhance constructability (Staub and Fischer 1998).

To date, considerable work has been done on 4D CAD, and strengths and weaknesses of the current-state-of-the-art have been examined (e.g. McKinney and Fischer 1998, Staub-French and Fisher 2001, Heesom and Mahdjuobi 2004). One area of difficulty is the ease with which a connection can be made and modified between the CAD model and the scheduling model in order to assess the implications of different design features and alternative construction strategies in terms of methods, sequencing, and space utilization. We seek to address this area of difficulty in the context of projects characterized by significant repetition – e.g. high-rise building, housing, bridge, tunnel, high-way, and elevated guideway projects. In so-doing, we make use of a generalized implementation of linear planning (LP) (Russell and Wong, 1993, Russell et al. 2003) in the context of a multi-view representation (Russell and Udaipurwala 2004) of a project. For the class of projects examined, the 2D representation (time and location) of a schedule in LP chart form provides significant incremental insights into the quality and workability of a schedule, as well as assisting in the development of a mental image of project status at different points in time. Nevertheless, still missing is a detailed linkage between what is being built and how it is being built.

1.3 OBJECTIVES

In this research, we are focused on the following objectives:

- a) Investigating the implication for data structuring of 3D CAD models and a linear planning scheduling application to support the linkages the two models.
- b) Explore the feasibility of automation of two-way data flows between two systems: quantities information from CAD to scheduling and component status at different point in time from scheduling to CAD.
- c) Identify potential benefits and challenges for linking 3D CAD with linear planning schedules.

1.4 METHODOLOGY

Our methodology is developed to accommodate the 2-way linkage between 3D CAD models in ADT and process views (describing how project is built) and product views (what is being built) in REPCON, a research program developed in the Department of Civil Engineering at UBC. Another intermediary Visual Basic Application is built in Microsoft Access to facilitate linkages.

The starting point is the 3D CAD model in ADT. A model is built to present a classical case of a project with a multiple similar working locations. The case study is a six-storey condominium project which we have named UpperCrust Manor (Russell and Udaipurwala 2005). We chose this project for a number of reasons: 1. The building industry has long a history of being supported by CAD programs; 2. The building can be easily extended to demonstrate the scalability; 3. The project is complex enough to demonstrate proof of concept. However, we believe that our research results from the use case could be used for other types of

linear projects in future research, such as bridges, highways, where locations are distributed both horizontally and vertically. The building is located in Vancouver, British Columbia with construction scheduled for completion in August, 2004. The ground floor houses 4 suites, floors 2 through 5 house 3 suites per floor, and the sixth floor houses two penthouse suites. The mechanical penthouse houses elevator equipment and ventilation equipment. The lot dimensions are 132 feet (frontage) by 116 feet with a building floor plate of 4,900 ft² (70 feet by 70 feet).

This project captures the essence of real-world projects, both in terms of scale and complexity. The 3D design includes multiple classes of objects, multiple levels, and multiple drawings. The foundation consists of spread footings, with different sizes for perimeter walls, columns, and the core. For the substructure and superstructure, walls are typically 12 inches thick (except for the interior wall in the stairwell which is 8 inches thick). Columns measure 1'-0" by 2'-0", except for corner columns in the superstructure which measure 1'-0" by 1'-0". The slab on grade is 4 inches thick, the main floor slab is 8 inches thick, and the floor slab on typical floors is 7 inches thick.

The product and process view of that project are then built in REPCON. To model the product view, a Physical Component Breakdown Structure (PCBS) of project is built. Part of the Project Physical Components Breakdown Structure (PCBS) is shown in the Figure 1.2. Activities and their association with PCBS component are then entered into the process view (Figure 1.3).

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 ADT and the product view in REPCON. This main interface of the program is illustrated in the Figure 1.4. We chose to work with MS Access for the linking program because of its ease of use and availability. We

recognize that there are more robust programming applications available to interface with ADT, particularly if one is a member of the Autodesk Developer Network. MS Access is limited in its ability to interact directly with CAD data resulting in some inefficiency when exchanging data. However, this did not limit the functionality of the linking application that we created and we were able to successfully demonstrate proof of concept.

Novel and central to the approach is a product model on the scheduling side which is associated with schedule activities as well as mapped onto the CAD product model. Benefits of the approach include a 2-way flow of data between scheduling and CAD, the ease with which large scale projects with repetitive elements can be modeled, and the added value that a 4D representation in combination with a linear planning schedule representation can provide in order to generate insights into the quality and workability of a schedule. Although not described in this thesis, other virtues include the ease with which alternative construction strategies can be explored, and the ability to contrast as-planned progress with actual progress. Ongoing work is focused on: completing the two-way flow of data, especially with respect to component attribute values back to scheduling for purposes of duration estimation; how best to represent work started but not yet completed; addressing challenges with product model mapping; and investigating the expandability of models.

Figure 1.1. 3D CAD model of the case study in Autodesk Architectural Desktop

Figure 1.2. Physical component breakdown Structure including Location sets and their attributes in REPCON

Figure 1.3 Process view - Activities list expressing how project is built and are linked with product view

Figure 1.4 Main interface of the Linking program in Microsoft Access

1.5 FORM OF THESIS

This thesis consists of 4 chapters and 2 appendices. Chapters two and three present papers describing various aspects of our research. Two appendices are attached at the end of the

thesis. A version of chapter 2 will be published in the proceedings of the 2007 ASCE Construction Research Congress organized by ASCE and CIB at Grand Bahamas Island from 6-8 May 2007. The authorship of this chapter is Ngoc Tran – Graduate student at the Department of Civil Engineering – UBC, Alan Russell - Professor, Department of Civil Engineering, and Chair, Computer Integrated Design and Construction - UBC, and Sheryl Staub-French – Assistant Professor at the Department of Civil Engineering - UBC. Chapter 3 is an extended version of the conference paper in penultimate form for submission to the ASCE Journal of Computing in Civil Engineering. The authorship of this chapter will be Sheryl Staub-French, Alan Russell, and Ngoc Tran. Chapter 4 is a conclusion chapter, which summarizes the research conducted; the contributions made and describe future works.

Appendix I contains drawings of the 3D CAD model of the UpperCrust Manor project.

Appendix II contains the screen captures of process view and product view inside REPCON which are used for our project.

1.6 REFERENCES

- Akinci, B. Tantisevi, K., Ergen, E. (2003) "Assessment of the capabilities of a commercial 4D CAD system to visualize equipment space requirements on construction sites." *Construction Research Congress*, Honolulu, HI, 989-995.
- Heesom, D., Mahdjoubi, L. (2004) "Trends of 4D CAD applications for construction planning." *Construction Management and Economics*, 22(2), p 171-182.
- Koo, B. and M. Fischer (2000). "Feasibility Study of 4D CAD in Commercial Construction." *Journal of Construction Engineering and Management*, 126(4), 251-260.
- McKinney, K., and Fischer, M. (1998) "Generating, evaluating and visualizing construction schedules with 4D-CAD tools." *Automation in Construction*, 7(6), 433-447.
- Messner, J. Yerrapathruni, S.C., Baratta, A., Riley, D.R. (2002). "Cost and schedule reduction of nuclear power plant construction using 4D CAD and immersive display technologies." *Congress on Computing in Civil Engineering*, ASCE, Washington DC, 136-144.
- Russell, A. D. and W. C. M. Wong (1993). "New-Generation of Planning Structures." *Journal of Construction Engineering and Management*, ASCE, 119(2): 196-214.
- Russell, A. D., Udaipurwala, A. and Wong, W. (2003). "A Generalized Paradigm for Planning and Scheduling." *Construction Research Congress*, Honolulu, HI, 965-972.
- Russell, A. D. and Udaipurwala, A. (2004). "Using Multiple Views to Model Construction." *CIB World Building Congress*, May 2-7, Toronto, Canada, 12 pages.
- Russell, A. and Udaipurwala, A. (2005). "Case Study for Construction Planning and Control Course", Proceedings, CD Rom, 6th Construction Specialty Conference, Canadian Society of Civil Engineers, June 2-4, 2005, Toronto, Canada, 10 pages.

- Staub, S. and Fischer, M. (1998). "Constructability Reasoning based on a 4D Facility Model."
Structural Engineering World Wide, T191-1, Elsevier Science Ltd, 9 pages.
- Staub-French, S., and Fischer, M., (2001). "Industrial Case Study of Electronic Design, Cost, and Schedule Integration." *Technical Report No. 122*, CIFE, Stanford University, CA.
- Russell, A. D. and Udaipurwala, A. (2000). "Assessing the Quality of a Construction Schedule."
Construction Congress VI, Orlando, Florida, February, 928-937.
- Tabesh, A. and Staub-French, S. (2006) "Modeling and Coordinating Building Systems in 3D: A Case Study." *Canadian Journal of Civil Engineering*, 33 (12).

CHAPTER 2 - 4D CAD VIA LINEAR PLANNING AND 3D CAD¹

2.1 INTRODUCTION

Assessing the constructability of a design can be a significant challenge (Tabesh and Staub-French 2006), as can assessing the quality and workability of a schedule (Russell and Udaipurwala 2000). Getting both the design and schedule 'right' contributes significantly to timely delivery within budget and reduces the potential for changes and disputes. 3D-CAD allows designers, the client and construction personnel alike to assess the responsiveness of a design to client needs, the potential for design errors in terms of conflicts and overly constrained working spaces, and the ease with which components and systems can be constructed. From a scheduling perspective, and especially for large scale projects, schedule visualizations using traditional means such as a bar chart or a time-scaled network diagram, while useful, offer limited assistance in assessing the quality / workability of a schedule, even when extensive filtering features are employed. 4D CAD offers the potential to animate a schedule thereby allowing an assessment of its correctness and workability to be made (e.g. Koo and Fischer 2000, Messner et al. 2002, Akinci et al. 2003). It also offers the potential to reassess elements of the design or construction strategy to enhance constructability (Staub and Fischer 1998).

To date, considerable work has been done on 4D CAD, and strengths and weaknesses of the current-state-of-the-art have been examined (e.g. McKinney and Fischer 1998, Staub-French and Fisher 2001, Heesom and Mahdjuobi 2004). One area of difficulty is the ease with which a connection can be made and modified between the CAD model and the scheduling model in

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order to assess the implications of different design features and alternative construction strategies in terms of methods, sequencing, and space utilization. We seek to address this area of difficulty in the context of projects characterized by significant repetition – e.g. high-rise building, housing, bridge, tunnel, high-way, and elevated guideway projects. In so-doing, we make use of a generalized implementation of linear planning (LP) (Russell and Wong, 1993, Russell et al. 2003) in the context of a multi-view representation (Russell and Udaipurwala 2004) of a project. For the class of projects examined, the 2D representation (time and space) of a schedule in LP chart form provides significant incremental insights into the quality and workability of a schedule, as well as assisting in the development of a mental image of project status at different points in time. Nevertheless, still missing is a detailed linkage between what is being built and how it is being built.

Set out in this paper is an approach for forging a linkage between CAD and linear planning. The key element in this approach is having a product model on the scheduling side as well as the CAD side. A mapping between the two product models allows for the two-way flow of information – quantity information from CAD to scheduling and component status at different points in time from scheduling to CAD. A virtue of the approach is the ease with which different scheduling strategies can be explored.

The paper is structured as follows. A brief description of the tools used in demonstrating proof of concept is given. Emphasis is placed on the features of the linear planning model implementation central to interfacing with CAD. A step-by-step process is then described for creating 4D images, with important challenges highlighted. In presenting the process, use is made of a mid-rise building to further clarify the steps. Findings are then summarized and ongoing work outlined.

2.2 SYSTEMS USED

The two primary tools used in demonstrating proof of concept are Autodesk's Architectural Desktop (ADT), and REPCON (Russell and Udaipurwala 2004), a research system developed at the University of British Columbia. The linkage between the two tools is by way of a Microsoft Access database application (described later) which allows mappings to be made between the product model objects in ADT and the product view in REPCON. This is illustrated in Figure 1 with respect to the mapping of levels in ADT to locations in REPCON, along with product model mappings of physical elements between the two systems. Also shown in this figure is a rendering of the example project used to demonstrate proof of concept. ADT was chosen because of its ability to create *Building Information Models (BIM)*, semantically rich information models of construction projects that include both 3D geometric information (e.g., component dimensions) along with non-geometric properties (e.g., material properties). Figure 1 shows the 'Concrete Core' object (known as a Wall Style in ADT) and a specific wall's properties. Note that the properties listed include typical dimensional properties included with ADT (e.g., Length and Height) as well as user-defined properties (e.g., Formwork Area).

Featured in Figure 2.2 are aspects of the linear planning implementation central to the 4D-CAD work. Shown in Figure 2.2(a) is the product model view (called the physical component breakdown structure, PCBS) in REPCON. A partial breakdown of the physical components for the example project is given on the left hand side of Figure 2.2(a). In simple terms, the breakdown structure can be thought of as having two main branches: (i) location sets and their members (shown as a physical location set and individual locations identified, and a procurement sequence location set, members not shown); and (ii) physical components arranged in a hierarchical fashion (e.g. system, subsystem, element, etc.).

Figure 2.1: Mapping CAD and REPCON Product Models for 6-story project.

Each physical component can be described by user specified attributes (upper right hand corner), and values assigned by defining at which locations the attributes apply (see PCBS Planned Attribute Value screen), thus forging a link between the two branches of the PCBS tree. The intent of the product model on the scheduling side is to provide management personnel with information central to the management tasks of gauging productivity and production rates, tracking changes, and explaining reasons for performance – it is not meant to replace the kind of detail contained in the project's drawings. Shown in Figure 2.2(c) is the process view aspect of the system, with the activity structures listed on the left hand side, and two schedule representations shown on the right hand side in the form of a standard bar chart and a linear planning chart. We note in passing the additional value offered by the LP in terms of assessing how well production rates are matched, opportunities for work continuity, the potential for work congestion, and for 'visualizing' project progress at a given point in time. Central to the 4D

work is the ability to make associations between the product and physical views on the scheduling side, as shown in Figure 2(b) with respect to mapping the PCBS Subelement *Columns* which forms part of the PCBS Subsystem *Superstructure structural system*. Mapped onto the Columns subelement are two activity planning structures – *F/P/S columns* (form, pour, strip) and *Reinforce columns*. Considerable power exists in this association, as all shared location instances of the physical components and associated activities are treated in Figure 2.2(c). Differences in granularity between the product and process views can pose challenges. For example, schedule breakdowns may be more coarse than physical component breakdowns, resulting in many-to-one relationships – i.e. multiple physical components to one activity structure (the converse can also occur).

Figure 2.2: Planning system: (a) product (PCBS), (b) view association, and (c) process views.

2.3 APPROACH FOR INTEGRATING 3D/4D AND LINEAR PLANNING

Figure 2.3 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. In what follows, we examine briefly each of these steps, and treat in turn, where relevant, inputs and outputs, processes within, constraints to observe in order to facilitate communication between systems, and challenges, both from a system and user perspective.

Figure 2.3: The Process of Integrating CAD and Scheduling.

Step 1–Formulation of Product & Process Views in REPCON and Coordination with CAD

Step one involves the formulation of the project product (PCBS) and process views in the scheduling system in terms of hierarchically structured components, component attribute definitions, and attribute values.

Inputs and Outputs: Scheduler input for the product view includes characterization of the project in terms of locations, physical components, and component attribute definitions of interest for managing the construction process and capturing as-built information. In terms of

output from this view, it is this breakdown that must be coordinated with and communicated to the CAD system, in the form of a PCBS database as shown in Figure 3. Automated input to this step, which has yet to be fully implemented in the scheduling model, involves the derivation of attribute values from CAD model attributes and their assignment to the appropriate locations in the PCBS model – the quantities box in Figure 2.3. With respect to the process model in step 1, input from the scheduler consists of a representation of the project in terms of a set of activity structures. Properties of these structures include 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 (refer back to Figure 1). Output from the process consists of time contour information in the form of a comma delimited file which is imported into an Excel spreadsheet, 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 break down 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. We currently do not represent elements that are partially complete.

Processes: Internal processes for the PCBS view consist of downward inheritance as specified by the user of attribute definitions (thereby speeding the task of defining properties), and upward aggregation of attribute values to upper level components in the hierarchy which can be used for productivity analysis, etc. For the product view, internal processes deal with computation of durations as a function of associated component attribute values, productivity information and resource levels (as noted – not yet implemented), and schedule calculations.

Constraints: With respect to constraints, care must be taken to coordinate the definition of locations / levels (in general the CAD model will reflect only a subset of the locations defined in the scheduling system) and the vocabulary to be used to define attributes of interest. In general, far more attribute information is available in the CAD model, and attributes of interest for scheduling are derived from operations on a number of CAD object parameters – e.g. formwork area or concrete volume for all columns on a location by location basis.

Challenges: A number of challenges exist, including: treatment of PCBS components not normally represented in a CAD model (e.g. excavation, shoring systems, temporary facilities like scaffolding, etc.); the desire to work with collections of components on the PCBS side vs. single instances of a component on the CAD side; different naming conventions in CAD vs. scheduling; the need to structure the CAD representation level by level; the depiction of partially completed components; and, the duration calculation process when multiple components are associated with a single activity structure.

Step 2 – Formulation of 3D model in ADT

This step involves the creation of the 3D model in a way that is consistent with the PCBS.

Inputs and Outputs: Of particular importance in creating the 3D model is the way objects are defined (in the Style Manager in ADT) and locations are specified (Levels in ADT). Generally, the Style Manager is a central mechanism for defining and maintaining object styles. Users can rely on built-in styles or create their own styles from scratch for a particular project. When a new style is created for a particular component class (e.g., a new wall style), that style instance inherits the generic properties of that object. Users can also create new properties and set up custom calculations for determining that property value (e.g., Formwork Area). Users also define the Levels in ADT which correspond to a specific elevation, allowing CAD objects to inherit the level ID from the level of drawings. Multiple drawings can be associated with a

specific Level. CAD information can be exported using a built-in command in ADT. We exported the CAD data in the form of Microsoft Access mdb files (see Figure 3). The number of individual databases is equivalent to the number of drawings. Because each level in ADT may contain multiple drawings the focus here is on drawings rather than levels. The format of the output databases are primarily dictated by ADT and the user has very little control in determining their structure, which creates challenges in organizing this data (discussed in step 3). The databases contain multiple tables creating links between various ADT objects, styles, and property sets. The many databases created for a project in ADT need to be combined into a single database to support the linking with REPCON components (refer to step 3).

Processes: Internal processes relate to the object-based nature of ADT models that feature data "objects" to represent building components, such as doors, walls, and windows. These objects store symbolic data about a building (e.g., material properties) in a logical structure with the 3D building graphics (the geometry), and they interact with each other intelligently (e.g., if you move or delete a wall, the window in the wall reacts accordingly). Users can extract useful information from the model, such as component quantities and attributes. We selected ADT for this research because it provides this kind of functionality.

Constraints: As stated in the previous step, users should coordinate the definition of levels so that they are identical to locations specified in the PCBS. In our environment, the Level ID in CAD corresponds to the Location Code in REPCON. The Style Names are also critical for mapping CAD objects to PCBS components. We found that it was necessary to create new styles in ADT rather than using built-in styles because we needed the flexibility in style naming and the ability to create user-defined object attributes. In addition, users should specify the component attributes that will be 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 (see Figure 2.1).

Challenges: In addition to the challenges identified in step 1 for setting up the PCBS, objects modeled in ADT should also consider the physical representation of objects from the construction perspective. In other words, they should reflect how objects are built in reality and adjust the model accordingly. For example, concrete columns for each level should not run from level 1 to level 6, but should be modeled separately on each level because they will be linked to different locations in REPCON.

Step 3. Create Integrated CAD-PCBS Model

This step deals with the mapping of ADT objects to PCBS objects to create an integrated model.

Inputs and Outputs: This step involves both a forward pass to create a single database that contains all CAD and PCBS objects and a backward pass for generating 4D Snapshots. In the forward pass, inputs are the PCBS database and the CAD databases. Users have to select the specific ADT databases (drawings for the different levels) and styles (classes of components) that are of interest to link with REPCON. The result of this step is a single database that contains all objects for one project. We use an intermediate linking program to extract from REPCON the PCBS components and locations in the form of a comma delimited file. While yet to be implemented, the existence of the single database provides the basis for exporting attribute values to REPCON for calculating activity durations and conducting productivity analysis. In the backward pass, the input is the Time Contour showing the completion of PCBS components over time and the output consists of a set of filtered CAD Objects for creating 4D snapshots.

Processes: As shown in Figure 2.4, the main processes carried out in this step relate to the aggregation of ADT objects across styles (a) and locations (b), the creation of linkages between

PCBS components and CAD Styles (c), and the assignment of attribute values to PCBS components (d).

a) Select the Style and Attribute Aggregation Method: This task allows users to select the CAD style to be aggregated and define how CAD object attribute values are treated in the aggregation process. Figure 2.4(a) shows the Concrete Core wall style selected and some of the attributes defined for that style. There are different types of attributes, so the system must be able to accommodate different modes of aggregation. For example, to aggregate all the Concrete Core Walls on Level 2 to link with the corresponding PCBS component, the different attribute values must also be aggregated for that level. We currently represent three aggregation modes: (1) sum up attribute values (e.g., Formwork Area), (2) leave attribute values unchanged (e.g., Style Names), or (3) delete attribute (e.g., Object ID, which isn't useful at an aggregated level). Users first choose the style from ADT and equivalent attributes to transfer to PCBS components, and then choose the aggregation mode for the different attributes (Figure 4(a)).

b) Group Objects by Styles at Individual Locations: In this task, objects are grouped together by location and by style (Figure 2.4(b)). Users must select the Location ID (level ID in ADT) for the style selected in (a). The two main variables that drive this process are the Level ID (which are embedded into each object extracted from ADT), and the aggregation mode described in (a). The Level ID in ADT objects must match the Location ID in REPCON to facilitate linking. The result is a consolidated database of objects grouped by location ID.

c) Link PCBS components and CAD Styles at Specific Locations: This task involves the user choosing the style to be linked with PCBS at specific locations. Due to the differences between CAD Modelers and planner/schedulers in term of naming, there are several instances where one CAD style might be linked with different PCBS components. For example, the Concrete Core style in CAD is linked with the Concrete Core substructure, PR.02.01.01.04 at the parkade location, and with PR.02.02.01.03 from the ground floor (GFLR) to the roof (MPHRF).

d) Assign Aggregated Attribute Values to REPCON: The assignment module allows users to assign the attribute values of a group at the aggregated level to the PCBS components. This task could be automated or semi-automated by some user-defined “matching” template. However, in our system, it is currently a manual process. Users must select the style’s attributes to be assigned the calculated values in the PCBS components (Figure 2.4(d)).

The screenshot displays the 'Linkages/Value Assignment' window. It is divided into several functional areas:

- (a) Selected Style:** A dropdown menu shows 'Concrete Core'. Below it, a table lists 'Available Attributes from CAD object' with columns for 'AttributeName', 'Aggregated', and 'Unchanged'. Attributes like 'Area-RightGross', 'ConcreteVolume', and 'FormworkArea' are listed, with checkboxes for aggregation.
- (b) Select location:** A table with 'LocationCode' and 'Location Name'. Locations include 'GLOB' (Global project location), 'SITE' (Site at ground level), 'FDN' (Foundation level), 'PARKADE' (Parkade level), 'GFLR' (Ground floor), '2' (Second floor), '3' (Third floor), and '4' (Fourth floor).
- (c) Linking PCBS components:** This section includes dropdowns for 'Selected Style' (Concrete Core), 'Select PCBS Component to be linked/changed' (PR.02.02.01.03), and 'Select Location of the linkage' (2). It also shows a summary: 'You want to link the Style Concrete Core with PCBS component ID: PR.02.02.01.03 at location ID 2'. A button 'Link PCBS Component and CAD Styles' is present.
- (d) Assign Attribute from PCBS component:** A table titled 'Attributes' and 'Unit' lists 'Formwork area' (m2), 'Concrete volume' (m3), and 'Reinforcing steel weight' (mTn). Below this table are three buttons: 'Check Value of aggregated CAD object's attribute', 'Assign Attributes's Value to linked PCBS Component's attribute', and 'Add value to current value of PCBS component's attribute'.

At the bottom of the window, there are buttons for 'Refresh', 'Prepare Attributes Table to export', 'Assign Location to the exported table', 'Export to excel', and 'Exit'.

Figure 2.4. System User Interface for: (a) selecting the style and aggregation method, (b) grouping the objects by location, (c) linking PCBS components and CAD styles at individual locations, and (d) assigning the aggregated attribute values.

Challenges: The issues encountered in this step center around the inconsistencies between the product model representations, and the omissions or gaps in the different product views. The challenge lies in developing an approach that does not overly constrain the users, on both the CAD and scheduling sides. Tensions exist in terms of the degree of flexibility permitted, the

user input required, and the degree of automation provided. This work is still in the developmental stage and we are working through these issues.

Step 4 – Create 4D Snapshots

The linkages between PCBS and CAD objects are combined with the Time Contour generated from REPCON to create 4D visualizations in ADT.

Inputs and Outputs: The key input to this step is the filtered CAD Objects, which identifies the CAD objects that are associated with completed construction activities. The CAD objects are filtered based on the Time Contour generated by REPCON (described in step 1), which shows the status of construction of the physical components (either completed or not yet started) for each location based on the date specified by the user. The output of this step is a 4D Snapshot (or a series of 4D snapshots) at each progress date generated from REPCON that graphically highlights the completed construction activities (Figure 2.5).

Figure 2.5 - Shots of end-of-month progress: November 2003 – April 2004.

Processes: 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. In general, the system identifies the relevant CAD objects by tracing the following mappings: Progress date (PCBS REPCON) → Finished PCBS components at multiple Locations (REPCON) → CAD Styles at multiple Levels (ADT). We then created a table that includes only those CAD objects that are completed for the specified time period (shown as 'Filtered CAD Objects' in Figure 2.3). In ADT, a VBA routine reads these CAD objects from the table and makes equivalent objects visible or invisible in ADT.

Challenges: The primary challenge at the current time is the treatment of work in progress, especially when a PCBS component represents a collection of CAD objects, while at the same timing minimizing the need to proliferate schedule activities. Although this isn't a significant constraint given the shortness of activity durations for this type of repetitive work, it limits the completeness of the model. Another challenge, but a benefit at the same time, is ensuring consistency between the CAD and scheduling product models, and within the scheduling system, between the product and process models. Work is underway to develop checks for each in order to ensure the accuracy of both models.

2.4 CONCLUSIONS AND FUTURE RESEARCH

An approach that capitalizes on the strengths of a generalized implementation of linear planning coordinated with a 3D CAD model to produce 4D CAD images has been described. Novel and central to the approach is a product model on the scheduling side which is associated with schedule activities as well as mapped onto the CAD product model. Benefits of the approach include a 2-way flow of data between scheduling and CAD, the ease with which large scale projects with repetitive elements can be modeled, and the added value that a 4D representation in combination with a linear planning schedule representation can provide in order to generate insights into the quality and workability of a schedule. Although not described in the paper, other virtues include the ease with which alternative construction strategies can be

explored, and the ability to contrast as-planned progress with actual progress. Ongoing work is focused on: completing the two-way flow of data, especially with respect to component attribute values back to scheduling for purposes of duration estimation; how best to represent work started but not yet completed; and addressing challenges with product model mapping.

2.5 REFERENCES

- Akinci, B. Tantisevi, K., Ergen, E. (2003) "Assessment of the capabilities of a commercial 4D CAD system to visualize equipment space requirements on construction sites." *Construction Research Congress*, Honolulu, HI, 989-995.
- Heesom, D., Mahdjoubi, L. (2004) "Trends of 4D CAD applications for construction planning." *Construction Management and Economics*, 22(2), p 171-182.
- Koo, B. and M. Fischer (2000). "Feasibility Study of 4D CAD in Commercial Construction." *Journal of Construction Engineering and Management*, 126(4), 251-260.
- McKinney, K., and Fischer, M. (1998) "Generating, evaluating and visualizing construction schedules with 4D-CAD tools." *Automation in Construction*, 7(6), 433-447.
- Messner, J. Yerrapathruni, S.C., Baratta, A., Riley, D.R. (2002). "Cost and schedule reduction of nuclear power plant construction using 4D CAD and immersive display technologies." *Congress on Computing in Civil Engineering*, ASCE, Washington DC, 136-144.
- Russell, A. D. and W. C. M. Wong (1993). "New-Generation of Planning Structures." *Journal of Construction Engineering and Management*, ASCE, 119(2): 196-214.
- Russell, A. D., Udaipurwala, A. and Wong, W. (2003). "A Generalized Paradigm for Planning and Scheduling." *Construction Research Congress*, Honolulu, HI, 965-972.
- Russell, A. D. and Udaipurwala, A. (2004). "Using Multiple Views to Model Construction." *CIB World Building Congress*, May 2-7, Toronto, Canada, 12 pages.
- Staub, S. and Fischer, M. (1998). "Constructability Reasoning based on a 4D Facility Model." *Structural Engineering World Wide*, T191-1, Elsevier Science Ltd, 9 pages.
- Staub-French, S., and Fischer, M., (2001). "Industrial Case Study of Electronic Design, Cost, and Schedule Integration." *Technical Report No. 122*, CIFE, Stanford University, CA.

- Russell, A. D. and Udaipurwala, A. (2000). "Assessing the Quality of a Construction Schedule."
Construction Congress VI, Orlando, Florida, February, 928-937.
- Tabesh, A. and Staub-French, S. (2006) "Modeling and Coordinating Building Systems in 3D:
A Case Study." *Canadian Journal of Civil Engineering*, 33 (12).

CHAPTER 3 - LINEAR SCHEDULING AND 4D VISUALIZATION²

3.1 INTRODUCTION

Assessing the constructability of a design can be a significant challenge (Tabesh and Staub-French 2006), as can assessing the quality and workability of a schedule (Russell and Udaipurwala 2000). Getting both the design and schedule 'right' contributes significantly to timely delivery within budget and reduces the potential for changes and disputes. 3D-CAD allows designers, the client and construction personnel alike to assess the responsiveness of a design to client needs, the potential for design errors in terms of conflicts and overly constrained working spaces, and the ease with which components and systems can be constructed. From a scheduling perspective, and especially for large scale projects, schedule visualizations using traditional means such as a bar chart or a time-scaled network diagram, while useful, offer limited assistance in assessing the quality / workability of a schedule, even when extensive filtering features are employed. 4D CAD offers the potential to animate a schedule thereby allowing an assessment of its correctness and workability to be made (e.g. Koo and Fischer 2000, Messner et al. 2002, Akinci et al. 2003). It also offers the potential to reassess elements of the design or construction strategy to enhance constructability (Staub and Fischer 1998).

To date, considerable work has been done on 4D CAD, and strengths and weaknesses of the current-state-of-the-art have been examined (e.g. McKinney and Fischer 1998, Staub-French and Fisher 2001, Heesom and Mahdjuobi 2004). One area of difficulty is the ease with which a connection can be made and modified between the CAD model and the scheduling model in

² A version of this chapter will be submitted for publication to the Journal of Computing in Civil Engineering – American Association of Civil Engineers. Staub-French, S., Russell, A. and Tran, N. Linear Scheduling and 4D Visualization.

order to assess the implications of different design features and alternative construction strategies in terms of methods, sequencing, and space utilization. We seek to address this area of difficulty in the context of projects characterized by significant repetition – e.g. high-rise building, housing, bridge, tunnel, high-way, and elevated guideway projects. In so-doing, we make use of a generalized implementation of linear planning (LP) (Russell and Wong, 1993, Russell et al. 2003) in the context of a multi-view representation (Russell and Udaipurwala 2004) of a project. For the class of projects examined, the 2D representation (time and location) of a schedule in LP chart form provides significant incremental insights into the quality and workability of a schedule, as well as assisting in the development of a mental image of project status at different points in time. Nevertheless, still missing is a detailed linkage between what is being built and how it is being built.

Set out in this paper is an approach for forging a linkage between CAD and linear planning. The key element in this approach is having a product model on the scheduling side as well as the CAD side. A mapping between the two product models allows for the two-way flow of information – quantity information from CAD to scheduling and component status at different points in time from scheduling to CAD. The challenges in making the 2-way process work include consistency of product representation in the CAD and scheduling models, and the need to group CAD components at different levels of detail and locations to reflect the kinds of aggregation found in schedule representations of a project. The benefits of the approach include the ease with which different scheduling strategies can be explored and visualized, the links between 3D objects and activities can be maintained, and the completeness of the product model representations can be validated.

The paper is structured as follows. A brief introduction to the case study and challenges involved are presented. Then, a brief description of the tools used in demonstrating proof of concept is given. Emphasis is placed on the features of the linear planning model

implementation central to interfacing with CAD. A step-by-step process is then described for creating 4D images, with important challenges highlighted. Findings are then summarized and ongoing work outlined.

3.2 CASE STUDY

The case study focuses on a six-storey condominium project which we have named UpperCrust Manor (Russell and Udaipurwala 2005). The building is located in Vancouver, British Columbia with construction completed in August, 2004. The ground floor houses 4 suites, floors 2 through 5 house 3 suites per floor, and the sixth floor houses two penthouse suites. The mechanical penthouse houses elevator equipment and ventilation equipment. The lot dimensions are 132 feet (frontage) by 116 feet with a building floor plate of 4,900 ft² (70 feet by 70 feet). Figure 3.1 shows a 3D rendering of the UpperCrust Manor project.

This project captures the essence of real-world projects, both in terms of scale and complexity. The 3D design includes multiple classes of objects, multiple levels, and multiple drawings. The foundation consists of spread footings, with different sizes for perimeter walls, columns, and the core. For the substructure and superstructure, walls are typically 12 inches thick (except for the interior wall in the stairwell which is 8 inches thick). Columns measure 1'-0" by 2'-0", except for corner columns in the superstructure which measure 1'-0" by 1'-0". The slab on grade is 4 inches thick, the main floor slab is 8 inches thick, and the floor slab on typical floors is 7 inches thick.

The important thing to note here is the variability in component sizing and distribution of components across levels. There is variation in component sizing both across a single level (e.g., different sized columns on each floor) and across multiple levels (e.g., different wall sizes from floor to floor). This creates challenges in both modeling the necessary elements, and mapping those elements to related schedule activities (which will be described later).

3.3 SYSTEMS USED

The two primary tools used in demonstrating proof of concept are Autodesk's Architectural Desktop (ADT), and REPCON (Russell and Udaipurwala 2004), a research system developed at the University of British Columbia. The linkage between the two tools is by way of a Microsoft Access database application (described later) which allows mappings to be made between the product model objects in ADT and the product view in REPCON. This is illustrated in Figure 3.1 with respect to the mapping of levels in ADT to locations in REPCON (1), along with product model mappings of physical elements (2) and attributes (3) between the two systems. We chose to work with MS Access for the linking program because of its ease of use and availability. We recognize that there are more robust programming applications available to interface with ADT, particularly if one is a member of the Autodesk Developer Network. MS Access is limited in its ability to interact directly with CAD data resulting in some inefficiency when exchanging data. However, this did not limit the functionality of the linking application that we created and we were able to successfully demonstrate proof of concept.

We modeled the project in ADT because of its ability to create *Building Information Models (BIM)*, semantically rich information models of construction projects that include both 3D geometric information (e.g., component dimensions) along with non-geometric properties (e.g., material properties). Figure 1 shows the 'Concrete Core' object (known as a Wall Style in ADT) and a specific wall's properties. Note that the properties listed include typical dimensional properties included with ADT (e.g., Length and Height) as well as user-defined properties (e.g., Formwork Area). The object styles in ADT are critical for linking with

REPCON components and the object attributes will be shared with REPCON to derive component quantities.

Featured in Figure 3.2 are aspects of the linear planning implementation central to the 4D-CAD work. Shown in Figure 3.2(a) is the product model view (called the physical component breakdown structure, PCBS) in REPCON. A partial breakdown of the physical components for the example project is given on the left hand side of Figure 2(a). In simple terms, the breakdown structure can be thought of as having two main branches: (i) location sets and their members (shown as a physical location set and individual locations identified, and a procurement sequence location set, members not shown); and (ii) physical components arranged in a hierarchical fashion (e.g. system, subsystem, element, etc.). Each physical component can be described by user specified attributes (upper right hand corner), and values assigned by defining at which locations the attributes apply (see PCBS Planned Attribute Value screen), thus forging a link between the two branches of the PCBS tree. The intent of the product model on the scheduling side is to provide management personnel with information central to the management tasks of gauging productivity and production rates, tracking changes, and explaining reasons for performance – it is not meant to replace the kind of detail contained in the project's drawings. Shown in Figure 3.2(c) is the process view aspect of the system, with the activity structures listed on the left hand side, and two schedule representations shown on the right hand side in the form of a standard bar chart and a linear planning chart. We note in passing the additional value offered by the LP in terms of assessing how well production rates are matched, opportunities for work continuity, the potential for work congestion, and for 'visualizing' project progress at a given point in time. Central to the 4D work is the ability to make associations between the product and physical views on the scheduling side, as shown in Figure 3.2(b) with respect to mapping the PCBS Subelement *Columns* which forms part of the PCBS Subsystem *Superstructure structural system*. Mapped onto the Columns subelement are

two activity planning structures – *F/P/S columns* (form, pour, strip) and *Reinforce columns*. Considerable power exists in this association, as all shared location instances of the physical components and associated activities are treated in Figure 3.2(c). Differences in granularity between the product and process views can pose challenges. For example, schedule breakdowns may be more coarse than physical component breakdowns, resulting in many-to-one relationships – i.e. multiple physical components to one activity structure (the converse can also occur).

3.4 APPROACH FOR INTEGRATING 3D/4D AND LINEAR PLANNING

Figure 3.3 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. In what follows, we examine briefly each of these steps, and treat in turn, where relevant, inputs and outputs, processes within, constraints to observe in order to facilitate communication between systems, and challenges, both from a system and user perspective.

Step 1 –Formulation of Product & Process Views in REPCON and Coordination with CAD

Step one involves the formulation of the project product (PCBS) and process views in the scheduling system in terms of hierarchically structured components, component attribute definitions, and attribute values.

Inputs and Outputs: Scheduler input for the product view includes characterization of the project in terms of locations, physical components, and component attribute definitions of interest for managing the construction process and capturing as-built information. In terms of output from this view, it is this breakdown that must be coordinated with and communicated to the CAD system, in the form of a PCBS database as shown in Figure 3.3. Automated input to

this step, which has yet to be fully implemented in the scheduling model, involves the derivation of attribute values from CAD model attributes and their assignment to the appropriate locations in the PCBS model – the quantities box in Figure 3.3. With respect to the process model in step 1, input from the scheduler consists of a representation of the project in terms of a set of activity structures. Properties of these structures include 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 (refer back to Figure 1). Output from the process consists of time contour information in the form of a comma delimited file which is imported into an Excel spreadsheet, 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 break down 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. We currently do not represent elements that are partially complete.

Processes: Internal processes for the PCBS view consist of downward inheritance as specified by the user of attribute definitions (thereby speeding the task of defining properties), and upward aggregation of attribute values to upper level components in the hierarchy which can be used for productivity analysis, etc. For the product view, internal processes deal with computation of durations as a function of associated component attribute values, productivity information and resource levels (as noted – not yet implemented), and schedule calculations.

Constraints: With respect to constraints, care must be taken to coordinate the definition of locations / levels (in general the CAD model will reflect only a subset of the locations defined in the scheduling system) and the vocabulary to be used to define attributes of interest. In general,

far more attribute information is available in the CAD model, and attributes of interest for scheduling are derived from operations on a number of CAD object parameters – e.g. formwork area or concrete volume for all columns on a location by location basis.

Challenges: A number of challenges exist, including: treatment of PCBS components not normally represented in a CAD model (e.g. excavation, shoring systems, temporary facilities like scaffolding, etc.); the desire to work with collections of components on the PCBS side vs. single instances of a component on the CAD side; different naming conventions in CAD vs. scheduling; the need to structure the CAD representation level by level; the depiction of partially completed components; and, the duration calculation process when multiple components are associated with a single activity structure.

Step 2 – Formulation of 3D model in ADT

This step involves the creation of the 3D model in a way that is consistent with the PCBS.

Inputs and Outputs: Of particular importance in creating the 3D model is the way objects are defined (in the Style Manager in ADT) and locations are specified (Levels in ADT). Generally, the Style Manager is a central mechanism for defining and maintaining object styles. Users can rely on built-in styles or create their own styles from scratch for a particular project. When a new style is created for a particular component class (e.g., a new wall style), that style instance inherits the generic properties of that object. New styles are needed if a project component has a different composition or geometry. For example, all columns that are different sizes and shapes will need a different style. Users can also create new properties and set up custom calculations for determining that property value (e.g., Formwork Area). Users also define the Levels in ADT which correspond to a specific elevation, allowing CAD objects to inherit the level ID from the level of drawings. Multiple drawings can be associated with a specific Level. CAD information can be exported using a built-in command in ADT. We exported the CAD data in the form of

Microsoft Access mdb files (see Figure 3.3). The number of individual databases is equivalent to the number of drawings. Because each level in ADT may contain multiple drawings the focus here is on drawings rather than levels. The format of the output databases are primarily dictated by ADT and the user has very little control in determining their structure, which creates challenges in organizing this data (discussed in step 3). The databases contain multiple tables creating links between various ADT objects, styles, and property sets. The many databases created for a project in ADT need to be combined into a single database to support the linking with REPCON components (refer to step 3).

Processes: Internal processes relate to the object-based nature of ADT models that feature data "objects" to represent building components, such as doors, walls, and windows. These objects store symbolic data about a building (e.g., material properties) in a logical structure with the 3D building graphics (the geometry), and they interact with each other intelligently (e.g., if you move or delete a wall, the window in the wall reacts accordingly). Users can extract useful information from the model, such as component quantities and attributes. We selected ADT for this research because it provides this kind of functionality.

Constraints: As stated in the previous step, users should coordinate the definition of levels so that they are identical to locations specified in the PCBS. In our environment, the Level ID in CAD corresponds to the Location Code in REPCON. The Style Names are also critical for mapping CAD objects to PCBS components. We found that it was necessary to create new styles in ADT rather than using built-in styles because we needed the flexibility in style naming and the ability to create user-defined object attributes. In addition, users should specify the component attributes that will be 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 (see Figure 3.1).

Challenges: In addition to the challenges identified in step 1 for setting up the PCBS, objects modeled in ADT should also consider the physical representation of objects from the construction perspective. In other words, they should reflect how objects are built in reality and adjust the model accordingly. For example, concrete columns for each level should not run from level 1 to level 6, but should be modeled separately on each level because they will be linked to different locations in REPCON.

Step 3. Create Integrated CAD-PCBS Model

This step deals with the mapping of ADT objects to PCBS objects to create an integrated model.

Inputs and Outputs: This step involves both a forward pass to create a single database that contains all CAD and PCBS objects and a backward pass for generating 4D Snapshots (Figure 3.3). In the forward pass, inputs are the PCBS database and the CAD databases. Users have to select the specific ADT databases (drawings for the different levels) and styles (classes of components) that are of interest to link with REPCON. The result of this step is a single database that contains all objects for one project. We use an intermediate linking program to extract from REPCON the PCBS components and locations in the form of a comma delimited file. While yet to be implemented, the existence of the single database provides the basis for exporting attribute values to REPCON for calculating activity durations and conducting productivity analysis. In the backward pass, the input is the Time Contour showing the completion of PCBS components over time and the output consists of a set of filtered CAD Objects for creating 4D snapshots.

Processes: As shown in Figure 3.4, the main processes carried out in this step relate to the aggregation of ADT objects across styles (a) and locations (b), the creation of linkages between PCBS components and CAD Styles (c), and the assignment of attribute values to PCBS components (d).

a) Select the Style and Attribute Aggregation Method: This task allows users to select the CAD style to be aggregated and define how CAD object attribute values are treated in the aggregation process. Figure 3.4(a) shows the Concrete Core wall style selected and some of the attributes defined for that style. There are different types of attributes, so the system must be able to accommodate different modes of aggregation. For example, to aggregate all the Concrete Core Walls on Level 2 to link with the corresponding PCBS component, the different attribute values must also be aggregated for that level. We currently represent three aggregation modes: (1) sum up attribute values (e.g., Formwork Area), (2) leave attribute values unchanged (e.g., Style Names), or (3) delete attribute (e.g., Object ID, which isn't useful at an aggregated level). Users first choose the style from ADT and equivalent attributes to transfer to PCBS components, and then choose the aggregation mode for the different attributes. Figure 4(a) shows the aggregation modes selected for some of the attributes of the Concrete Core object.

b) Group Objects by Styles at Individual Locations: In this task, objects are grouped together by style at specified locations (Figure 3.4(b)). Users must select the Location ID (level ID in ADT) for the style selected in (a). The two main variables that drive this process are the Level ID (which are embedded into each object extracted from ADT), and the aggregation mode described in (a). The Level ID in ADT objects must match the Location ID in REPCON to facilitate linking. The result is a consolidated database of objects grouped by location ID.

The formulation of the consolidated database of CAD objects in MS Access requires the execution of multiple grouping routines due to the fragmented nature of exported CAD databases. Each drawing is exported as a single database and each database contains multiple tables. As shown in Figure 3.5, the structure of one database contains multiple tables with linkages between objects and styles. Objects are nested together by styles which have the same property data set (which describe the attributes to be attached to the objects in an extended data property). This structure creates challenges because our focus is on the CAD style rather than

the property set, and because different drawings have a different structure of objects. In our application, the user chooses the style names to be imported from each of the individual CAD databases. Then, the application executes several routines to extract the CAD style names and the related objects and properties from the different project databases, and then group all objects of the same type across the different locations.

c) Link PCBS components and CAD Styles at Specific Locations: This task involves the user choosing the style to be linked with PCBS components at specific locations. Due to the differences between CAD modelers and schedulers in term of component naming conventions, and the different levels of detail that schedulers may work, multiples types of mappings between CAD objects and PCBS components need to be supported. Table 3.1 shows the different mappings required to link the CAD and linear planning product models. There are several instances where many CAD styles might be linked to one PCBS Component. This situation may exist if multiple styles are needed to represent a component (e.g., multiple column styles for different column sizes) or if PCBS components are represented at a coarser level of granularity (e.g., for the PCBS component 'Build Verticals', all work associated with physical vertical components would need to be mapped onto this single component). Similarly, there are several instances where one CAD style might be linked with different PCBS components. For example, the Concrete Core style in CAD is linked with the Concrete Core substructure, PR.02.01.01.04 at the parkade location, and with PR.02.02.01.03 from the ground floor (GFLR) to the roof (MPHRF). Finally, there are instances where many CAD styles may need to be mapped onto many PCBS components. This typically occurs when there is a high degree of variability on the design side (e.g., multiple wall sizes on multiple floors) and there is a higher level of detail on the scheduling side (e.g., work is divided into Substructure and Superstructure). Due to the different types of mappings required and the need for flexibility in

terms of how CAD objects and PCBS components are defined, we have not fully automated this step.

d) Assign Aggregated Attribute Values to REPCON: The assignment module allows users to assign the attribute values of a group at the aggregated level to the PCBS components. This task could be automated or semi-automated by some user-defined “matching” template. However, in our system, it is currently a manual process. Users must select the style’s attributes to be assigned the calculated values in the PCBS components (Figure 3.4(d)). The result can then be transferred back to REPCON in the form of a comma delimited file. Table 3.2 shows an example of the quantities calculated for different PCBS components and locations in REPCON based on the CAD attribute values. Note that the quantities are aggregated at different levels of detail to suit the needs of the scheduler. Quantities are aggregated at the site level (e.g., gross area of the ground floor), at the component level (e.g., the formwork area of the concrete core), and at the detailed component level (e.g., the formwork area for round columns) for different locations.

Challenges: The issues encountered in this step center around the inconsistencies between the product model representations, and the omissions or gaps in the different product views. The challenge lies in developing an approach that does not overly constrain the users, on both the CAD and scheduling sides. Tensions exist 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 (Table 3.1). In CAD, the designation of a style name is based on the appearance of objects (composition of objects). For example, if the column or core at each level is made up of different sizes or shapes, then they would require a different style. However, in REPCON, we have much more flexibility in terms of defining the level of detail of the project product model. REPCON is structured as a

hierarchy of components including both locations and physical components. Each component can be described in terms of a number of user-specified attributes which can be quantitative, linguistic or Boolean. Those values could be aggregated at any level in the hierarchy. This allows us to work at a coarser granularity when doing things like checking productivity, estimating activity durations, etc. Schedulers can also work at a more detailed level (e.g., tracking Rectangular and Round Columns separately) if they choose. The variability in design details as represented by styles and the variability in levels of detail on the scheduling side make it challenging to automate this mapping process without overly constraining the user. We have chosen to use a semi-automated approach that requires some user input at this stage but we will continue to work through these issues.

Step 4 – Create 4D Snapshots

The linkages between PCBS and CAD objects are combined with the Time Contour generated from REPCON to create 4D visualizations in ADT.

Inputs and Outputs: The key input to this step is the filtered CAD Objects, which identifies the CAD objects that are associated with completed construction activities. The CAD objects are filtered based on the Time Contour generated by REPCON (described in step 1), which shows the status of construction of the physical components (either completed or not yet started) for each location based on the date specified by the user. The output of this step is a 4D Snapshot (or a series of 4D snapshots) at each progress date generated from REPCON that graphically highlights the completed construction activities (Figure 3.5).

Processes: 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. Figure 3.6 graphically illustrates the process for creating 4D snapshots.

(a) Import Time Contour: The Time Contour is imported into the MS Access linking program. The Time Contour shows the break down of activities on a location by location basis with the corresponding physical components flagged as either being completed (value of 1), or not yet started (value of 0) as of a specific progress date.

(b) Identify “Finished” Objects in ADT: Specific dates at the end of each month are then extracted out of the table and act as a milestone to filter all the PCBS components at the different locations. Based on the mapping of CAD styles and PCBS components, we interpolate the mapping of PCBS components with individual “finished” CAD objects at the given date.

(c). Create Table of Filtered CAD Objects: The “finished” CAD objects are then put into one table with all attributes that are necessary for referencing the CAD objects in the project drawings. Currently we use two attributes to reference each CAD object (AEC_ObjectID and Level ID). We created the attribute AEC_Object ID by combining the ADT referenced drawing number and the Handle ID. These ID’s, together with Level ID do not change with the opening and closing of drawings in ADT (in contrast with Object_ID).

(d) Import Table in VBA Application: All drawings in the project are then opened in ADT using the Project Navigator. To find all corresponding objects in ADT that are listed in the “finished” object table, we built a VBA application within ADT. This VBA application opens the MS Access database and based on the “finished” object table, finds all the instances of objects in the CAD drawings.

(e) Make “Finished” Objects Visible: If the attributes AEC_ObjectID and level ID of the “finished” CAD object in the table and the CAD object in the drawing are the same then we make that object visible in ADT. Drawings of the same project with “finished” objects are then grouped together to create a 4D snapshot at the specified date. The following pseudo code describes the routine depicted in Figure 3.6.

Open Access file:


```

OPEN File Open window.
SAVE the path in the Open dialog into path
ESTABLISHING connection with the database in the path
FROM Opened Database SELECT filtered CAD object table SAVE all objects into the
object table
FOR all drawings in the project
    OPEN drawing
    FROM the Opened Database SELECT the location list table and SAVE location ID into
    the Location list ID table
    DO UNTIL End of Location list ID table
        Check if current location ID = level ID of current drawing
        IF yes THEN
            FOR each object in the Model Space of this drawing
                Set object visible false
                Update object
            MOVE to next object

            WITH the object table
                DO WHILE NOT end of the object table
                    FOR each object in the model space of current dwg
                        IF object.Handle = object.[AEC__ObjectId] THEN
                            Set object visible = false
                            Update object
                        END IF
                    MOVE to next object.

        LOOP
            CLOSE object table
        END WITH
    END IF
    MOVE to next location ID.
    LOOP
        CLOSE location list ID table
    NEXT drawing

```

Challenges: The primary challenge at the current time is the treatment of work in progress, especially when a PCBS component represents a collection of CAD objects, while at the same timing minimizing the need to proliferate schedule activities. Although this is not a significant constraint given the shortness of activity durations for this type of repetitive work, it limits the completeness of the model. Another challenge, which can also be viewed as a benefit, is ensuring consistency between the CAD and scheduling product models, and within the scheduling system, between the product and process models. Work is underway to develop checks for each in order to ensure the accuracy of both models.

3.5 CONCLUSIONS AND FUTURE RESEARCH

An approach that capitalizes on the strengths of a generalized implementation of linear planning coordinated with a 3D CAD model to produce 4D CAD images has been described. Novel and central to the approach is a product model on the scheduling side which is associated with schedule activities as well as mapped onto the CAD product model. Benefits of the approach include a 2-way flow of data between scheduling and CAD, the ease with which large scale projects with repetitive elements can be modeled, and the added value that a 4D representation in combination with a linear planning schedule representation can provide in order to generate insights into the quality and workability of a schedule. Although not described in the paper, other virtues include the ease with which alternative construction strategies can be explored, and the ability to contrast as-planned progress with actual progress. Ongoing work is focused on: completing the two-way flow of data, especially with respect to component attribute values back to scheduling for purposes of duration estimation; how best to represent work started but not yet completed; and addressing challenges with product model mapping.

Table 3.1: Different types of mappings required to link CAD objects with PCBS components.

Condition	Mapping	Description	Example
Variability Horizontally	Many to One	Mapping of many CAD styles to one PCBS component.	Columns: There are two different sizes of columns (and two corresponding styles) that must be linked to one PCBS component for 'Columns.'
Variability Vertically	One to Many	Mapping of one CAD style to many PCBS components.	Concrete Core: The concrete core is mapped onto PCBS components for 'Substructure' and 'Superstructure.'
Variability Horizontally and Vertically	Many to Many	Mapping of many CAD styles to many PCBS components.	Concrete Core: If the concrete core has some variation in size (e.g., wall width) then multiple CAD styles would be mapped to multiple PCBS components.

Table 3.2: Example of exported table from MS Access to REPCON showing populated component attributes.

	Path to Component	Description	Attribute	Units	PR.LS1.GFLR	PR.LS1.2	PR.LS1.3
Locations	PR.LS1.GFLR	Ground floor	Gross Area	m ²	12340		
			Working Area	m ²	12300		
	PR.LS1.2	Second Floor	Gross Area	m ²		11550	
			Working Area	m ²		115	
	PR.LS1.3	Third Floor	Gross Area	m ²			11350
			Working Area	m ²			11250
Components	PR.02.02.01.03	Concrete core	Number	#	8	8	8
			Formwork Area	m ²	30	110	110
			Concrete Volume	m ³	6	18	18
	PR.02.02.01.02	Rectangular Column	Number	#	6	2	2
			Formwork Area	m ²	70	70	70
			Reinforcing Steel	mTn	12	12	12
	PR.02.02.01.02	Round Column	Number	#	0	4	4
			Formwork Area	m ²	0	75	75
			Reinforcing Steel	mTn	0	15	15

Figure 3.1: Mappings between CAD and REPCON product models for 6-story project, including (1) locations, (2) components, and (3) attributes.

Figure 3.2: Planning system: (a) product (PCBS), (b) view association, and (c) process views.

Figure 3.3: The Process of Integrating CAD and Scheduling.

Linkages/Value Assignment

Selected Style: Concrete Core (a)

Available Attributes from CAD object:

AttributeName	Aggregated	Unchanged
Area-RightGross	☒	☐
Area-RightGross <formatted>	☐	☐
ConcreteVolume	☒	☐
ConcreteVolume <formatted>	☐	☐
FormworkArea	☒	☐
FormworkArea <formatted>	☐	☐

Record: 6 of 27

Select location:

LocationCode	Location Name
GLOB	Global project location
SITE	Site at ground level
FDN	Foundation level
PARKADE	Parkade level
GFLR	Ground floor
2	Second floor (b)
3	Third floor
4	Fourth floor

Record: 6 of 20

The Style: Concrete Core

@ Location: 2 containing 8 component(s)

Has a attribute: ConcreteVolume

with aggregated value of 798.0649999999994

is linked with PCBS No. PR.02.02.01.03

Select Attribute from PCBS component: Core

Attributes	Unit
Formwork area	m2
Concrete volume	m3
Reinforcing steel weight	mTn
*	

(d)

Check Value of aggregated CAD object's attribute

Assign Attributes's Value to linked PCBS Component's attribute

Add value to current value of PCBS component's attribute

Selected Style: Concrete Core

Select PCBS Component to be linked/changed: PR.02.02.01.03 Core (c)

Select Location of the linkage: 2

You want to link the Style Concrete Core with PCBS component ID: PR.02.02.01.03 at location ID 2

Link PCBS Component and CAD Styles

Refresh

Prepare Attributes Table to export

Assign Location to the exported table

Export to excel

Exit

Figure 3.4. System User Interface for: (a) selecting the style and aggregation method, (b) grouping the objects by location, (c) linking PCBS components and CAD styles at individual locations, and (d) assigning the aggregated attribute values.

Figure 3.5. CAD Database including multiple tables exported from ADT for the 3rd Floor Structural drawing.

(a) Import Time Contour

STRATBSE.CSV

	A	B	C	K	L	M	N
1	Comp onent	Path to Component	Location				
2				31AUG06	30SEP06	31OCT06	30NOV06
54	Interior	PR.02.02.01.02		5	0	0	1
55	Interior	PR.02.02.01.02		6	0	0	1
56	Interior	PR.02.02.01.02	MPHRF		0	0	1
57	Core	PR.02.02.01.03	GFLR		1	1	1
58	Core	PR.02.02.01.03		2	1	1	1
59	Core	PR.02.02.01.03		3	1	1	1
60	Core	PR.02.02.01.03		4	0	1	1
61	Core	PR.02.02.01.03		5	0	1	1
62	Core	PR.02.02.01.03		6	0	1	1
63	Core	PR.02.02.01.03	MPHRF		0	0	1
64	Stairs	PR.02.02.01.04	GFLR		1	1	1

(c) Create Table of Filtered CAD Objects

30APR04-objects : Table

AEC	ObjectID	id	ObjectID	Level	PCBS
1CCE		11417	2087182448	PARKADE	PR.02.01.02.01
1EE6		11418	2127606384	GFLR	PR.02.01.02.02
1ECB		11419	2127606232	GFLR	PR.02.01.02.02
1EC8		11420	2127606208	GFLR	PR.02.01.02.02
1E71		11421	2085782600	GFLR	PR.02.01.02.02
1CD8		11422	2085781760	GFLR	PR.02.01.02.02
ED8		11423	2122972480	3	PR.02.02.01.01
ED6		11424	2122972464	3	PR.02.02.01.01
ED4		11425	2122972448	3	PR.02.02.01.01
E54		11426	2122972320	3	PR.02.02.01.01
ED8		11427	2120674624	4	PR.02.02.01.01
204D		11442	2127607144	GFLR	PR.02.02.01.01

(b) Identify "Finished" Objects in ADT

Time links from REPCON to CAD

Import Data Find Date on the table Empty Finished PCBS Refresh

Select Date: 31AUG04

Filtering PCBS Based on specified date Create Table of Finished Object

Record: 14 of 5

(d) Import Table in VBA Application

CAD Snapshot based on REPCON

D:\Study\Thesis\test new.mdb

Open Access file Filter objects

Turn everything On Turn everything Off

(e) Make "Finished" Objects Visible

Figure 3.6. The process of creating 4D Snapshots.

Figure 3.7. Shots of end-of-month progress: December 2003 – April 2004.

3.6 REFERENCES

- Akinci, B. Tantisevi, K., Ergen, E. (2003) "Assessment of the capabilities of a commercial 4D CAD system to visualize equipment space requirements on construction sites." *Construction Research Congress*, Honolulu, HI, 989-995.
- Heesom, D., Mahdjoubi, L. (2004) "Trends of 4D CAD applications for construction planning." *Construction Management and Economics*, 22(2), p 171-182.
- Koo, B. and M. Fischer (2000). "Feasibility Study of 4D CAD in Commercial Construction." *Journal of Construction Engineering and Management*, 126(4), 251-260.
- McKinney, K., and Fischer, M. (1998) "Generating, evaluating and visualizing construction schedules with 4D-CAD tools." *Automation in Construction*, 7(6), 433-447.
- Messner, J. Yerrapathruni, S.C., Baratta, A., Riley, D.R. (2002). "Cost and schedule reduction of nuclear power plant construction using 4D CAD and immersive display technologies." *Congress on Computing in Civil Engineering*, ASCE, Washington DC, 136-144.
- Russell, A. D. and W. C. M. Wong (1993). "New-Generation of Planning Structures." *Journal of Construction Engineering and Management*, ASCE, 119(2): 196-214.
- Russell, A. D., Udaipurwala, A. and Wong, W. (2003). "A Generalized Paradigm for Planning and Scheduling." *Construction Research Congress*, Honolulu, HI, 965-972.
- Russell, A. D. and Udaipurwala, A. (2004). "Using Multiple Views to Model Construction." *CIB World Building Congress*, May 2-7, Toronto, Canada, 12 pages.
- Russell, A. and Udaipurwala, A. (2005). "Case Study for Construction Planning and Control Course", Proceedings, CD Rom, 6th Construction Specialty Conference, Canadian Society of Civil Engineers, June 2-4, 2005, Toronto, Canada, 10 pages.
- Staub, S. and Fischer, M. (1998). "Constructability Reasoning based on a 4D Facility Model." *Structural Engineering World Wide*, T191-1, Elsevier Science Ltd, 9 pages.

- Staub-French, S., and Fischer, M., (2001). "Industrial Case Study of Electronic Design, Cost, and Schedule Integration." *Technical Report No. 122*, CIFE, Stanford University, CA.
- Russell, A. D. and Udaipurwala, A. (2000). "Assessing the Quality of a Construction Schedule." *Construction Congress VI*, Orlando, Florida, February, 928-937.
- Tabesh, A. and Staub-French, S. (2006) "Modeling and Coordinating Building Systems in 3D: A Case Study." *Canadian Journal of Civil Engineering*, 33 (12).

CHAPTER 4 – CONCLUSIONS AND FUTURE WORK

4.1 SUMMARY

We have successfully implemented a generalized method to link 3D CAD model with linear planning program to produce 4D images. Though we managed this linkage at the level of proof of concept, the benefits and advantages of this method has been exposed including the interactive data flows between the two systems, the ease of modeling large scale project with repetitive elements, and the 4D representation synchronized with linear planning charts.

Central to our approach is the linkage of two product models inside REPCON and ADT. As each product model represent different viewpoints of users from different parties in project, they could be used to calculate other variables specifically for those users, and used to check the consistency of the model. Potential benefits and further developments will be investigated in the future.

4.2 CONTRIBUTIONS

The major contribution of this research is the 2-way linkage between a 3D CAD program and a linear planning program. Data from 3D CAD objects could be transferred to linear planning program to calculate durations and conduct productivity analysis. Scheduling information could then be transferred to CAD to create 4D representation to be used in the constructability analysis process in conjunction with linear planning charts.

Another contribution is the investigation of the structure of 3D CAD to be linked with the scheduling program. We focus on the flexibility of the method to capture 3D CAD objects' attributes as well as the structuring of CAD objects in a manner to support scheduling.

4.3 RECOMMENDATIONS FOR FUTURE WORK

This research could be further developed in the following ways:

- Test the expandability of the methodology - by expanding the model in CAD and REPCON both horizontally and vertically.
- Further automate the linkages in the current 2-way flow of data between 3D CAD and linear planning program.
- Develop a more efficient and robust process using a hierarchical data structure (XML) instead of current “flat” files.
- Further investigate the treatment of linkages (one to many, many to one, many to many) between 3D CAD and the scheduling product model.

4.4 REFERENCES

- Akinci, B. Tantisevi, K., Ergen, E. (2003) "Assessment of the capabilities of a commercial 4D CAD system to visualize equipment space requirements on construction sites." *Construction Research Congress*, Honolulu, HI, 989-995.
- Heesom, D., Mahdjoubi, L. (2004) "Trends of 4D CAD applications for construction planning." *Construction Management and Economics*, 22(2), p 171-182.
- Koo, B. and M. Fischer (2000). "Feasibility Study of 4D CAD in Commercial Construction." *Journal of Construction Engineering and Management*, 126(4), 251-260.
- McKinney, K., and Fischer, M. (1998) "Generating, evaluating and visualizing construction schedules with 4D-CAD tools." *Automation in Construction*, 7(6), 433-447.
- Messner, J. Yerrapathruni, S.C., Baratta, A., Riley, D.R. (2002). "Cost and schedule reduction of nuclear power plant construction using 4D CAD and immersive display technologies." *Congress on Computing in Civil Engineering*, ASCE, Washington DC, 136-144.
- Russell, A. D. and W. C. M. Wong (1993). "New-Generation of Planning Structures." *Journal of Construction Engineering and Management*, ASCE, 119(2): 196-214.
- Russell, A. D., Udaipurwala, A. and Wong, W. (2003). "A Generalized Paradigm for Planning and Scheduling." *Construction Research Congress*, Honolulu, HI, 965-972.
- Russell, A. D. and Udaipurwala, A. (2004). "Using Multiple Views to Model Construction." *CIB World Building Congress*, May 2-7, Toronto, Canada, 12 pages.
- Russell, A. and Udaipurwala, A. (2005). "Case Study for Construction Planning and Control Course", Proceedings, CD Rom, 6th Construction Specialty Conference, Canadian Society of Civil Engineers, June 2-4, 2005, Toronto, Canada, 10 pages.
- Staub, S. and Fischer, M. (1998). "Constructability Reasoning based on a 4D Facility Model." *Structural Engineering World Wide*, T191-1, Elsevier Science Ltd, 9 pages.

- Staub-French, S., and Fischer, M., (2001). "Industrial Case Study of Electronic Design, Cost, and Schedule Integration." *Technical Report No. 122*, CIFE, Stanford University, CA.
- Russell, A. D. and Udaipurwala, A. (2000). "Assessing the Quality of a Construction Schedule." *Construction Congress VI*, Orlando, Florida, February, 928-937.
- Tabesh, A. and Staub-French, S. (2006) "Modeling and Coordinating Building Systems in 3D: A Case Study." *Canadian Journal of Civil Engineering*, 33 (12).

APPENDIX I

3D CAD MODEL IN AUTODESK ARCHITECTURAL DESKTOP 2006

Figure I.1 3D rendering of the 3D CAD Model

Figure I.2. Exploded version of the model to show the drawing composition of the project

Figure I.3. 3D rendering of the vertical CAD component at Parkade level

Figure I.4. Style Manager – ADT’s mechanism for controlling predefined and user-defined 3D CAD objects styles

Figure I.5. Project Navigator – ADT’s hierarchical mechanism to group drawings vertically in ADT

Figure I.6. Conceptual mechanism for attaching attributes to objects in ADT

Figure I.7 Mapping of Documentation object onto Architectural objects to attach attributes

Figure I.8. Equivalent of location set in REPCON and in ADT

Figure I.9. Style Manager – User-defined styles Definition

Figure I.10. Example of automatic attributes in ADT

Figure I.11. Objects are assigned styles with user-defined attributes

Figure I.12. Structural members - Columns styles

Formula Property Definition

Name:

☒ Use formula for description

Formula:

Sample Result:

Enter Sample Values:

Property	Value	Format	Data type
[Area-LeftNet]	Sample	Standard	Automatic
[Area-RightNet]	Sample	Standard	Automatic
[Height]	Sample	Standard	Automatic
[Width]	Sample	Standard	Automatic

Insert Property Definitions:

- 1
 - Brick Wall Style
 - Concrete Wall
 - wall foundation**
 - Area-LeftNet
 - Area-RightNet
 - ConcreteVolume
 - FormworkArea [Self]
 - Handle
 - Height
 - Length
 - Level
 - ObjectID

Insert VBScript code:

- Miscellaneous
 - Constants
 - Functions
 - Keywords
 - Methods
 - Objects and Collections
 - Operators
 - Statements

OK Cancel Help

Formula of the formwork area of the wall foundation

List of automatic attributes needed to form the formula

Figure I.13. Required attributes for foundation defined by users in ADT

Project PCBS

Project UPPERCRUST MANOR - BASE PROJECT SCHEDULE

- PR Location Set: Physical Location Set
 - LS1 Location: Global project location
 - GLOB Location: Site at ground level
 - SITE Location: Foundation level
 - PARKADE Location: Parkade level
 - GFLR Location: Ground floor
 - 2 Location: Second floor**
 - 3 Location: Third floor
 - 4 Location: Fourth floor
 - 5 Location: Fifth floor
 - 6 Location: Sixth floor
 - MPHRF Location: Mechanical penthouse & roof
 - RFMPH Location: Penthouse roof
 - LS2 Location Set: Procurement sequence
 - 01 System: Foundation system
 - 02 System: Structural system
 - 03 System: Enclosure system
 - 04 System: Mechanical system
 - 05 System: Electrical system
 - 06 System: Vertical transportation system
 - 07 System: Interior partitioning/ceiling system
 - 08 System: Interior finishing system

Project PCBS

Attributes Values Standard PCBS Records Activities Pay items Quality Mgt Changes EBS Risk Issues / E

Path: PR.LS1.

Code: Description:

Type:

Description	I.	Class	B/Q/L	Unit
Gross area	Y..		Q	m2
Working area	Y..		Q	m2
Interstory height	Y..		Q	ft
Shape	Y..		L	

☒ Inherit attribute definition from above level

Add Delete Edit

OK Cancel

Figure I.14 Definition of locations and their attributes in REPCON

Figure I.15. Using Area styles to capture location's information data

Figure I.16. Style Manager – ADT’s mechanism for controlling predefined and user-defined 3D CAD objects styles

Figure I.17. Snapshot at the end of November 2003

Figure I.18. Snapshot at the end of December 2003

Figure I.19. Snapshot at the end of January 2004

Figure I.20. Snapshot at the end of February 2004

Figure I.21. Snapshot at the end of March 2004

Figure I.22. Snapshot at the end of April 2004

Figure I.23. Snapshot at the end of May 2004

Figure I.24. Snapshot at the end of June 2004

Figure I.25. Snapshot at the end of July 2004

APPENDIX II

PRODUCT AND PROCESS VIEW IN REPCON

Figure II.1. Product View - Physical component breakdown Structure including Location sets and their attributes in REPCON (6 Storey Version)

Process View - Activity List Interface

Code	Description	Type	Calendar	Responsibility Code	Subproject	Phase	Subphase
01	Receipt of Notice to Proceed	Start Milestone	1 Default Calendar	G001 General Contractor			
02	Mobilize & clear site	Ordered	1 Default Calendar	G001 General Contractor			
03	Bulk excavate substructure	Ordered	1 Default Calendar	T001 Excavation & Shoring			
04	Shotcrete shoring	Ordered	1 Default Calendar	T001 Excavation & Shoring			
05	Excavate wall, core, column footings	Ordered	1 Default Calendar	T001 Excavation & Shoring			
051	Excavate crane footing	Ordered	1 Default Calendar	T001 Excavation & Shoring			
06	Build wall, core, column, crane footing	Ordered	1 Default Calendar	G001 General Contractor			
01	F/P/S perimeter wall footings	Ordered	1 Default Calendar	G001 General Contractor			
02	Reinforce perimeter wall footings	Ordered	1 Default Calendar	T006 Rebar			
03	F/P/S column footings	Ordered	1 Default Calendar	G001 General Contractor			
04	Reinforce column footings	Ordered	1 Default Calendar	T006 Rebar			
05	F/P/S core footing	Ordered	1 Default Calendar	G001 General Contractor			
06	Reinforce core footing	Ordered	1 Default Calendar	T006 Rebar			
07	F/P/S crane footing	Ordered	1 Default Calendar	G001 General Contractor			
08	Reinforce & set crane footing anchor	Ordered	1 Default Calendar	T006 Rebar			
07	Build substructure verticals	Ordered	1 Default Calendar	G001 General Contractor			
01	F/P/S perimeter walls	Ordered	1 Default Calendar	G001 General Contractor			
02	Reinforce perimeter walls	Ordered	1 Default Calendar	T006 Rebar			
03	F/P/S columns	Ordered	1 Default Calendar	G001 General Contractor			
04	Reinforce columns	Ordered	1 Default Calendar	T006 Rebar			
05	F/P/S core	Ordered	1 Default Calendar	G001 General Contractor			
06	Reinforce core	Ordered	1 Default Calendar	T006 Rebar			
07	F/P/S stairs	Ordered	1 Default Calendar	G001 General Contractor			
08	Reinforce stairs	Ordered	1 Default Calendar	T006 Rebar			
08	Backfill footings, prepare SOG	Ordered	1 Default Calendar	T001 Excavation & Shoring			
09	Dampproof perimeter substructure walls	Ordered	1 Default Calendar	T001 Excavation & Shoring			
10	Construct slab on grade	Ordered	1 Default Calendar	G001 General Contractor			
01	Reinforce SOG	Ordered	1 Default Calendar	T006 Rebar			
02	Place & finish SOG	Ordered	1 Default Calendar	T003 Concrete Placing & Finishing			
11	Construct ground floor slab	Ordered	1 Default Calendar	G001 General Contractor			
01	Form ground floor slab	Ordered	1 Default Calendar	T001 Excavation & Shoring			
02	Reinforce ground floor slab	Ordered	1 Default Calendar	T006 Rebar			
03	Place electrical conduit in slab	Ordered	1 Default Calendar	T015 Mechanical			
04	Place mechanical sleeving in slab	Ordered	1 Default Calendar	T015 Mechanical			
05	Place & finish GFLR slab	Ordered	1 Default Calendar	T003 Concrete Placing & Finishing			
12	Backfill external perimeter of substructure	Ordered	1 Default Calendar	T001 Excavation & Shoring			
13	Build superstructure	Derived	1 Default Calendar	G001 General Contractor			
01	Build superstructure verticals	Ordered	1 Default Calendar	G001 General Contractor			
01	F/P/S columns	Ordered	1 Default Calendar	G001 General Contractor			
02	Reinforce columns	Ordered	1 Default Calendar	T006 Rebar			
03	F/P/S core	Ordered	1 Default Calendar	G001 General Contractor			

Activity Data/Production Data

Path: 13.01.
 Code: 01 Description: F/P/S columns
 Type: Ordered Responsibility Code: G001 Cat: 1 FS: 0
 Subproject:
 Phase:
 Subphase:
 Quantity Unit:
 Descriptor:
 Governing Resource:
 Production Rate

Start Location	Finish Location	Wt	Sk	Duration/Loc	Quantity/L	Average F	Average Pro	Calculate
GFLR		1	0	7	0.00	0.00	0.00	
2		1	0	5	0.00	0.00	0.00	
3		1	0	4	0.00	0.00	0.00	
4	6	1	0	3	0.00	0.00	0.00	

Use Location Profile Use Calculated Duration Add Row Delete Row
 OK Cancel

Figure II.2 Process View - Activity List with Activity Data windows showing linkages between activities and Locations in PCBS - Part 1

Process View - Activity List Interface

Code	Description	Type	Calendar	Responsibility Code	Subproject	Phase	Subphase
02	Reinforce slab	Ordered	1 Default Calendar	T006 Rebar			
03	Place electrical conduit in slab	Ordered	1 Default Calendar	T016 Electrical			
04	Place mechanical sleeving in slab	Ordered	1 Default Calendar	T015 Mechanical			
05	Place & finish slab	Ordered	1 Default Calendar	T003 Concrete Placing & Finishing			
14	Erect, use, dismantle crane	Derived	1 Default Calendar	G001 General Contractor			
01	Erect crane	Ordered	1 Default Calendar	G001 General Contractor			
02	Dismantle crane	Ordered	1 Default Calendar	G001 General Contractor			
15	Build masonry walls	Ordered	1 Default Calendar	T004 Masonry			
16	Build exterior brick facade	Ordered	1 Default Calendar	T004 Masonry			
161	Erect scaffolding for brickwork	Ordered	1 Default Calendar	T004 Masonry			
162	Dismantle scaffolding	Ordered	1 Default Calendar	T004 Masonry			
17	Install interior/exterior wall studding	Ordered	1 Default Calendar	T009 Drywall			
18	Install exterior sheathing	Ordered					
19	Install exterior windows & doors	Ordered					
20	Install drywall	Derived					
01	Board drywall	Continuous					
02	Tape & fill drywall	Shadow					
21	Install elevator rails	Continuous					
22	Install elevator cabs & equipment room	Ordered					
23	Rough-in horizontal plumbing/fire system	Ordered					
24	Rough-in vertical plumbing/fire system	Ordered					
25	Rough-in electrical system	Ordered					
26	Install interior finishes	Derived					
01	Paint out each location	Continuous					
02	Install kitchen/bathroom/laundry cab	Ordered					
03	Install floor coverings of all types	Ordered					
04	Install appliances	Ordered					
05	Install window coverings	Ordered					
06	Finish electrical work	Ordered					
28	Install roofing	Ordered					
29	Hard & soft landscaping	Derived					
01	Hard landscaping - concrete planters	Ordered					
02	Waterproofing of exterior ground floor	Ordered	1 Default Calendar	T005 Roofing			
03	Soft landscaping - planting	Ordered	1 Default Calendar	G001 General Contractor			
30	Cleanup & rectify deficiencies	Ordered	1 Default Calendar	G001 General Contractor			
31	Obtain occupancy permit	Ordered	1 Default Calendar	G001 General Contractor			
40	Procure windows & doors	Ordered	1 Default Calendar	T010 Doors & Windows			
41	Procure elevator rails	Ordered	1 Default Calendar	T014 Elevators			
42	Procure elevator cab	Ordered	1 Default Calendar	T014 Elevators			
43	Procure electrical fixtures	Ordered	1 Default Calendar	T016 Electrical			
44	Procure reinforcing trade	Ordered	1 Default Calendar	G001 General Contractor			

Activity Data/PCBS

Path: 13.01.

Code: 01 Description: F/P/S columns

Type: Ordered Responsibility Code: G001 Cal: 1 FS: 0

Subproject: Phase: Subphase:

PCBS

Path

PR.02.02.01.01

OK Cancel

Figure II.3 Process View - Activity List with activity data windows showing the linkages between activities and Physical components in PCBS – Part 2

Figure II.4. Linear Planning Schedule with physical locations for the project

Figure II.5. Bar Chart Schedule of the project – Part 1

Figure II.6. Bar Chart Schedule of the project – Part 2