Visualizing high-rise building construction strategies using linear scheduling and 4D CAD

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ABSTRACT

Project teams face ever increasing pressure to deliver projects as quickly as possible. To meet these demands, contractors are faced with the need to explore various construction strategies in order to meet delivery dates, and to assure themselves as to the achievability and quality of a schedule. Various visual representations of a project’s schedule and associated information combined with visual representations of the project in progress, i.e. 4D CAD, can assist with these tasks of identifying effective construction strategies for shortening project duration, assessing their workability, and judging schedule quality. Such visual representations aid communication amongst project staff and facilitate brainstorming, and, implemented well they can provide clear, fast, and multi-dimensional feedback to the project team. In this paper, we describe aspects of our work which is directed at formulating a dynamic visualization environment that links 3D CAD, a generalization of traditional CPM which embraces linear scheduling, dual product representations (scheduling and CAD system) and their mapping onto each other, and schedule and CAD graphics in a manner which facilitates the relatively rapid exploration of alternative construction method and scheduling strategies for large scale linear projects (e.g. high-rise buildings, bridges, etc.). Requirements of such an environment include quickness, treating scale, working at multiple levels of detail, dealing with design variability, and realistic representation of the work. Use is made of a realistic example to highlight aspects of our approach and identify important issues that must be addressed if a visualization environment useful for construction professionals is to be developed.

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1. Introduction

Project designers and contractors face ever increasing pressure to deliver projects as quickly as possible, with clients being driven by a range of market forces. Hence, the situation where time is of the essence has become the norm. Leaving aside the challenge of fast-track delivery where design and construction overlap, the contractor is faced with the need to explore various construction strategies in order to be competitive and to meet contractually specified delivery dates, and both client and contractor alike need to assure themselves as to the achievable and quality of a schedule [1,2]. In so doing, the workability and cost effectiveness of alternative construction strategies must be assessed — i.e. does the sequencing of the work make sense?; are the production rates achievable?; are work areas becoming congested?; can safety requirements be met?; and so forth.

Various visual representations of a project’s schedule and associated information (e.g. congestion plots) combined with visual representations of the project in progress (i.e. 4D CAD) can assist greatly with the tasks of identifying effective construction strategies for shortening project duration, assessing their workability, and judging overall schedule quality. Such visual representations are hard to beat in terms of effectiveness — they aid communication amongst project staff and facilitate brainstorming, and, implemented well they can provide clear, fast, and multi-dimensional feedback to the project team. With respect to 4D images in particular, this feedback can simply be confirming in nature — i.e. the in progress images match the mental models of seasoned construction personnel based on their review of the schedule and project drawings. Alternatively, especially for complex projects and or highly accelerated ones, the feedback can highlight the impracticality of a schedule, a message which is simply not deductible from the schedule itself.

But there are challenges with the current state-of-the-art. Using today’s tools, the lack of ease with which alternative strategies can be formulated and evaluated precludes meaningful exploration. Creating a new schedule, adding the necessary detail in the CAD model, and then re-linking the schedule activities and 3D objects in the 4D model for each strategy involves tedious and lengthy tasks [3]. Other challenges relate to scale, granularity of schedule representation and the ability to see progress ‘inside’ a structure.

Described in this paper are selected aspects of work and related findings of the authors directed at formulating a dynamic visualization
environment that links 3D CAD, a generalized version of CPM which embraces linear scheduling (we use the terms linear scheduling (LS) and linear planning (LP) interchangeably in the paper) to assist with the requirement to formulate and evaluate construction and associated schedule strategies to meet project duration requirements, while addressing some of the challenges identified earlier. In particular, we are interested in exploring product and process modeling (representation) issues in terms of scale, levels of detail, and design variability to create the models needed to explore multiple construction strategies. As noted later, to date minimal work by the research community has been focused on exploring the combined benefits of LS/LP and 4D. Our work is being performed in the context of linear projects, but it could also be applied to other projects.

Nevertheless, we are interested in projects which have significant repetition of components within a given project, and which are constructed on a repeated basis. In the vertical domain, this means high-rise construction, while the horizontal domain includes highway, pipeline, transmission line, elevated guideway, tunnel, and housing projects. Our particular focus in this paper is high-rise construction, with emphasis on schedule time reduction. Thus, we take the design as a given (except for the ability to change material properties – e.g. use of admixtures in concrete, and the design of temporary facilities – e.g. shoring system) and examine those variables that are the purview of the construction team.

Use is made of a relatively simple high-rise building project that is of sufficient scale (15 stories and 2 substructure levels) to highlight aspects of our approach and identify important issues that must be addressed if a visualization environment useful for construction professionals is to be developed. Exploring various construction strategies necessary to shorten the project duration in order to meet owner requirements. In practice, such a project would not require full 4D modeling; still there are benefits which would be magnified very substantially for more unique and complex projects – i.e. large scale, mixed use, high-rise projects – ones with unique configurations, highly constrained sites, and multi-building complexes.

The remainder of the paper is organized as follows. In the next section, we provide a brief overview of the state-of-the-art as it relates to 4D CAD, linear scheduling and the combination of the two. A description of the main elements of our approach for combining CAD and linear scheduling is then given. This is followed by treatment of our 15 story condominium building project to illustrate aspects of our approach and the ease with which various construction strategies can be formulated and evaluated based on the visual representation of the schedule in linear scheduling format combined with a 4D representation of the project at different states of progress. Extensive discussion is then presented about a number of product and process modeling issues, including scaling and representing the construction perspective. The paper concludes with a discussion of what has been achieved to date, and future work required to meet the overall research goal of developing a visualization environment for construction professionals to formulate and evaluate alternative construction strategies rapidly.

2. Brief overview of the state-of-the-art

In this section, we provide a brief review of the state-of-the-art with respect to 4D CAD, LS as a practical tool, and LS in combination with 4D CAD.

2.1. 4D CAD

4D CAD has been a topic of research for many years. There are now several commercially available 4D modeling tools and there is a growing interest from industry to adopt these tools [4]. Prior research efforts have assessed the benefits and limitations of these tools and their impact on project performance e.g. [5,6,7]. Researchers have also critiqued the functionality of 3D and 4D technologies to meet the needs of industry (e.g. [8],[25]). These studies and others have identified various challenges in creating and maintaining a 4D model in practice.

As noted in the literature, common issues related to these challenges deal with appropriate and consistent levels of detail in the product and process models, the flexibility needed to vary the groupings of components or sectioning of work as a function of work type, the challenge of linking CAD objects and schedule activities, and the ability to represent scale, which we have found in our own work. Added to the foregoing is the need for mechanisms to view the progress of internal work – i.e. the ability to see through the structure – a topic that has not received significant attention but is necessary for visualizing progress in building construction.

Several research efforts have tried to address some of these issues. Akbas [9] addressed the significant challenge of managing the level of detail required to graphically show construction zones in 4D. He developed mechanisms to aggregate components (e.g. group columns on a single level) and decompose components (e.g. break a slab element into zones) in both the product and process models. These mechanisms ensure consistency between the product and process models considering the work type, work flow, and trade productivity. This approach also minimizes the links that need to be made between the product and process models when the models change based on different construction zones. However, it focuses specifically on construction zoning and does not address these issues when creating and maintaining the 4D model in general.

Other research efforts have confronted the challenges of linking product and process models using Industry Foundation Classes (IFC) [3] and the Unified Classification for the Construction Industry (UNICLASS) [10]. However, these approaches still require users to manually link building components and activities and do not represent relationships between lower-level building elements, such as drywall and studs.

Several researchers have applied 4D on projects with an emphasis on interior work e.g. [11,6]. Some efforts have looked at enhancing 4D models thru annotation and highlighting techniques, which help to communicate the 4D context including interior activities e.g. [12]. However, few efforts have looked at creating customized views that allow different parts of the interior portions of a 4D model to be visualized from different perspectives without obstruction.

In summary, substantial progress has been made in the area of 4D CAD. However, significant issues still persist that limit the usability of this tool to support the exploration of multiple construction strategies. Specifically, the tedious process of linking product and process models, particularly at lower levels of detail, makes such exploration prohibitive. Moreover, the restricted visual access to interior work limits the usability of 4D models for a large portion of high-rise construction activities. Our approach takes a significant step in addressing these challenges by leveraging a generalized implementation of CPM which includes linear scheduling, coordinated with a 3D CAD model to produce 4D CAD images.

2.2. Linear scheduling

The topic of linear scheduling (LS) and its synonyms has been an area of focus by a number of researchers for over 40 years. Stradal and Cacha [13] wrote a seminal paper that described the representation of various construction strategies using a linear schedule representation which they called time–space planning. In that paper, they acknowledged the advantages offered by such a visual representation but stated that to date formulation and implementation of a computational schema had yet to be achieved, limiting the usefulness of the approach. Since that time, many researchers have explored the topic. A recent paper by Ipsilandis [14] provides a reasonably comprehensive list of references of work performed over the last 25–35 years, with its primary focus being on algorithmic issues and optimization. In our
view, a limitation of much of this past work stems from the working premise of others that treatment of linear scheduling requires a distinctly different approach to modeling a project, computing a schedule, and representing a schedule in visual form.

For linear scheduling to become a practical tool, an important issue is how to implement it so that it can do everything that traditional CPM can do, including providing the relevant results/data, as well as realize the full potential of LP. By the latter we mean not only a representation strategy in the form of a visual image, but a way of thinking about scheduling with accompanying modeling structures and a human computer interaction interface (HCI) effectively creating a design environment within which alternative construction strategies can be readily explored. However this is accomplished, we believe that 4 building blocks are involved: (i) a generalization of the concepts of activity and precedence relationship to embrace multiple location instances (we call them planning structures and generalized precedence relationships respectively), (ii) the inclusion of a product model in the scheduling system which treats both the spatial dimension and the products to be produced; (iii) the ability to forge associations between product and process entities within the scheduling system; and (iv) support for a number of visual representations of schedule and related data, including a time–space or linear planning representation of a project. How this has been accomplished by the authors has been described in Russell and Wong [15], Russell and Udaipurwala [16] and Russell et al. [17]. Use is simply made of these concepts as implemented in a research construction management system called REPCON, with minimal elaboration herein as the focus of this paper is on the benefits and issues associated with combining linear scheduling and a scheduling system product model with 3D CAD to create a 4D environment for exploring alternative construction strategies.

2.3. 4D CAD and linear scheduling

There has been very little research to date on the integration of 4D and LS. A few efforts have looked at combining 4D with line-of-balance (LOB) representations. For example, Jongeling and Olofsson [18] explore the benefits of combining 4D with line-of-balance (LOB) techniques on a project in Sweden. They found that 4D helped to identify work flow issues that were not evident in the LOB charts. Based on these results, they propose a process model for the planning of work flow in construction that includes model-based methods for cost estimation, production planning and simulation. Akbas [9] developed a LOB diagram style interface as part of a 4D application. The LOB interface aids the definition of crew sequences, their mobilization date and the production capacity. This approach also supports the generation of LOB charts for a given 4D status. However, these approaches focus more on the presentation of LOB charts rather than the integration of linear scheduling and 4D. The main point here is that very little work has been done to date by others on exploiting the combined benefits of LS and 4D CAD.

3. Approach for integrating 3D/4D and linear scheduling

Our approach is unique in that it leverages a generalized implementation of CPM that includes linear scheduling coordinated with a 3D CAD model to produce 4D CAD images [19]. This approach enables a more generic mapping mechanism between product and process models that works at multiple levels of detail. This type of linking mechanism minimizes the number of links that need to be made, and eliminates the need to manually re-link CAD objects and activities as the design and schedule changes. Therefore, with LS and the ease with which 4D snapshots can be generated, it is now possible to explore a variety of construction strategies relatively quickly.

The two primary tools used in our approach are Autodesk's Architectural Desktop (ADT), and the REPCON research system identified previously. This prototype construction management system treats generalized CPM including linear or time–space scheduling, true hierarchical scheduling, and a multi-view representation of a project, including a product view (referred to as the physical component breakdown structure (PCBS)). An association between PCBS components (product view) and schedule activities (process view) can be mapped onto the CAD product model. The linkage between the two tools is by way of a Microsoft Access database application which allows mappings to be made between the product model objects in ADT and the product view in REPCON.

Fig. 1 illustrates four of the five 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. The details and challenges associated with each step are described in Staub-French et al. [19]. Here we summarize the key elements of our approach. Discussion of modeling issues is given in a later section, including those not yet tackled in a detailed way.

3.1. Step 1 — formulation of scheduling system product and process views and coordination with CAD

This step involves the formulation of the project product (PCBS) and process views (see Figs. 3 and 4, respectively) in the scheduling system in terms of hierarchically structured components, component attribute definitions and attribute values. Schedulers define the...
product view in terms of locations, physical components, component attribute definitions, and as-planned and as-built attribute values as a function of location. It is this breakdown that must be coordinated with and communicated to the CAD system, in the form of a PCBS database. With respect to the process model, input from the scheduler includes the locations at which work is to be performed and the sequence in which locations are to be worked, production rates at each location (this is where quantity information for PCBS component attributes fed back from the CAD model comes into play), and logic linking the activities as well as other date constraints. Other scheduler input deals with linking the product and process views. Output from the process consists of Time Contour information given the mapping between the product and process views, and a progress date or series of progress dates specified by the user. Specifically, given the 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.

3.2. Step 2 — formulation of 3D model in ADT

This step involves the creation of the 3D model, preferably in a way that is consistent with the PCBS. Of particular importance in creating the 3D model is the way objects are defined (Styles in ADT) and locations are specified (Levels in ADT). In our environment, the Level ID in CAD corresponds to the scheduling system Location Code. The Style Names are also critical for mapping CAD objects to PCBS components. We created new styles in ADT rather than use built-in styles because we wanted to leverage the flexibility in style naming and the ability to create a variety of user-defined object attributes to more easily map onto PCBS components. In addition, users 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. This quantity information will be transferred to the scheduling system in the next step.

3.3. Step 3 — create integrated CAD-PCBS model

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

3.4. Step 4 — create 4D snapshots

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

3.5. Step 5 — customize 4D snapshots

In this step, the 4D snapshot is transformed into a custom 4D image that is more realistic and useful for construction. Fig. 10 shows the different custom 4D snapshots created for the base and revised strategies. Different rendering and modeling techniques were used to visualize the different construction activities. Specifically, we exported the model to Viz Render for ADT to enhance the image in the following ways: (1) grouping similar elements to show work in progress (e.g. group all the drywall work in progress), (2) exploding the different levels to see interior work (e.g. explode the levels above the locations where drywall work is in progress), (3) adjusting the transparency of elements to see inside the building (e.g. adjust the transparency of slabs that obscure drywall work in progress), (4) applying materials to enhance the realism of the elements’ appearance (e.g. applying a concrete material to the columns), (5) changing colors to distinguish objects and to differentiate activities (e.g. drywall work is shown in yellow), and (6) adjusting the view angle and sunlight to maximize the view of objects (e.g. we adjusted the sun intensity by setting the time and location to 3 pm in Vancouver).

The benefits of this approach include a 2-way flow of data between scheduling and CAD, 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. Of particular importance is the ease with which the links between the product and process model can be generated and maintained, which enables the rapid exploration of alternative construction strategies in 4D. This functionality is possible because we have dual product models on the CAD and scheduling sides. Key contributions of the approach include the ability to support multiple product models, multiple mappings between product models, and multiple schedule visualizations. This approach was described in detail in Staub-French et al. [19]. The work described here leverages this approach to explore modeling issues associated with providing a visualization environment that allows construction professionals to search for and evaluate alternative construction strategies to meet project duration requirements.

4. Modeling alternative construction strategies

We use an example high-rise building project to illustrate: (a) aspects of our approach, (b) how insights can be generated by combining linear scheduling with 4D CAD, (c) issues of scale and scalability, (d) differences between the needs of designers vs. construction practitioners in terms of formulating the CAD model (e.g. exterior enclosure), and (e) visualizing internal work. We work with existing technologies and technology frameworks and provide the glue to join them together.

4.1. Background on project

The example project is a 15-storey higher end condominium project, which we have named UpperCrust Manor (Fig. 2). This project has been scaled up from a 6-story version analyzed previously [19]. We have attempted to capture the essence of a project of this type, both in terms of the product and process models, but there is a certain level of abstraction to ensure ease of understanding. It is important to note, however, that we are not only concerned with structure and enclosure, but interior work as well, and how its status at any point in time may be represented.

The building is situated in Vancouver, British Columbia with construction to be completed by no later than 31 January 2009 and preferably by 31 December 2008. The ground floor houses three suites,
floors 2 through 14 house four suites per floor, and the 15th floor houses two penthouse suites. Shown in Fig. 2(b) is a typical floor plan. The mechanical penthouse houses elevator and ventilation equipment. The gross area of each parkade level is 11,721 ft² (1088.9 m²) and the typical floor is 5235 ft² (486.3 m²) inclusive of balconies. The working area on a typical floor is 4539 ft² (421.7 m²). The lot dimensions are 132 ft (40.2 m) (frontage) by 116 ft (35.6 m). Floor to ceiling height in the parkade is 8 ft (2.4 m); for all other floors, it is 9 ft (2.7 m).

The scope of the 3D CAD model of the Uppercrust Manor project embraces: (1) architectural components including partition walls, floors, ceilings, doors and windows; (2) structural components including columns, beams, concrete walls and slabs; (3) envelope components including studs, sheathing, and masonry; and (4) amenities including fixtures, appliances, and cabinets. We represent these components at different levels of detail to explore issues related to modeling and scale, which are elaborated on in Section 5. Specifically we modeled interior partition walls and exterior walls at a more refined level of detail that included studs, drywall, sheathing, insulation and painting. It is also worth noting that there is very little variability in the layout of the different floors with the exception of the parkade and the upper levels.

The product model for the scheduling system (called the physical component breakdown structure, PCBS) is shown in Fig. 3. The structure should be thought of as two branches of a tree: (i) one or more location sets consisting of physical locations and procedural ones (e.g. a procurement sequence); and, (ii) physical systems and related components. The two branches are mapped onto one another by way of values assigned to user-defined component attributes for locations at which the component is present. One difference between the schedule and CAD product models is that a component in the former is typically a collection or grouping of individual instances of CAD entities on a location by location basis (e.g. all columns at location as opposed to individual columns within the CAD model at the same location). Thus the granularity of the two models differs.

In what follows, we first describe the base schedule scenario and then describe the strategies explored to reduce the project delivery date and how the 4D model helped confirm the workability of the modified construction strategy.

4.2. Base schedule scenario

The scoping of the project in terms of a hierarchical breakdown of activities is shown in Fig. 4. It involves the use of 112 activity planning structures which corresponds to 803 activities in a traditional CPM schedule. If the number of floors was doubled, the number of activity planning structures would remain unchanged while the number of traditional CPM activities would be almost doubled. Thus the LS implementation used provides significant advantages when dealing with project scale, as measured in terms of number of physical locations (discussed in more detail later). We have attempted to capture the main activities associated with such a project but have made some simplifications in terms of detail to enhance readability. Interestingly, actual contractor schedules for projects of this type often include less detail than that shown.

A traditional bar chart representation of the project schedule is shown in Fig. 5(a), in which activity planning structures have been broken apart so that they may be sorted by location (e.g. 2nd floor as shown), and within a location by early start date. Alternatively, Fig. 5(b) depicts the planning structures in compact form for all substructure structural work and all locations, and has the advantage of compactness. Both schedule representations, while useful for providing guidance to site staff on the timing of work offer little help in assessing the quality and workability of the construction strategy being pursued, or insights on how best to improve or shorten the schedule. This is where a LP representation of the schedule can be very helpful, especially for the type of work represented by our example project.

Shown in Fig. 6(a) and (b), respectively, are the base schedule and a shortened version in LP format, with details of the latter discussed in Section 4.2. Our focus here is on the base construction strategy and its representation in visual form for purposes of analysis and the insights.

![Fig. 2. 3D model of the 15 story building (a) and typical floor plan (b).](image-url)
it offers, as opposed to computational issues. Differences in color reflect different trades, and locations of activity structures shown in heavier lines are critical in the conventional sense of CPM. One immediate observation that can be made is that of compactness of the schedule image — at a glance, it is possible to have an overview of the entire schedule, and for the seasoned construction observer, the sequence of work portrayed can be readily envisaged. Fig. 7 shows complementary images that can assist in assessing schedule quality. Fig. 7(a) shows a congestion plot (congestion is measured in terms of area/worker) that helps to identify locations with potential congestion problems. Fig. 7(b) shows a resource histogram which is similar to existing scheduling tools, that shows the resource usage over time as a bi-modal distribution. These complementary images (automatically created by REPCON) helped to confirm the workability of the base schedule.

While somewhat conservative in approach, and as seen from Fig. 6(a), the schedule is of reasonably good quality in terms of the matching of activity production rates and separation of work to avoid congestion. For
superstructure construction, there is a 4 floor separation between structural work and follow-up rough-in work, to reflect the requirement for curing and the presence of re-shoring members. After an initial period where learning takes place, the structural work falls into a rhythm of 1 floor per 5 day work week, and follow-up work matches that pace or in some instances is faster. Space buffers have been used as appropriate to separate trades and in some cases to allow sufficient time for inspection of work before follow-up work is performed. The building is fully enclosed before weather sensitive work (e.g. dry-walling and painting) is allowed to start, resulting in the time gap in repetitive work in the middle of Fig. 6(a) — i.e. the start of drywall boarding on the ground floor has to wait until installation of windows is complete on floor 15. Further, a requirement for work continuity for the dry-walling and painting trades has been imposed to make the project attractive to these trades in terms of their ability to maximize productivity. This constraint has not resulted in a lengthening of the schedule. Use is made of the elevator as soon as possible to transport cabinets and personnel as opposed to using the man-hoist, allowing the latter’s timely removal (this is not obvious from viewing Fig. 6(a)). While it might appear that conflicts will arise by the two planning structures that cross over other structures, such is not the case: one of the steeply ascending structures corresponds to the installation of rails in the elevator shaft—a dedicated work space, while the other steeply ascending structure corresponds to work on the exterior balconies. However, there is one problem — the completion date of 23 March 2009 does not meet the client’s minimum requirement of 31 January 2009, so shortening the schedule is required. Fig. 8 depicts from an exterior vantage point physical progress of the project as of the end of every other month, starting with December 2007 using 4D CAD based on the schedule shown in Fig. 6(a) and the process shown in Fig. 1. We observe that the progress shown is not

Fig. 4. Scoping of the project in REPCON in terms of activity planning structures.
perfectly exact, as we only show a component at a location if work is totally completed at that location. For example, for the December 2007 snapshot of progress, in reality, interior and exterior perimeter walls are well underway, but, as they are not yet finished for the P2 level, they are not shown. Showing partially completed work is a topic for future work. By making completed floor slabs transparent for the April and June 2008 snapshots, the progress of interior work can be viewed. Given the relative simplicity of the project, the value of the 4D CAD representations shown was limited to confirming the workability of the base schedule from a construction as opposed to contractual perspective.

4.3. Strategies for shortening the construction schedule

As indicated previously, the client requires the project to be delivered by no later than 31 January 2009, and preferably by 31 December 2008. The question thus becomes: what strategy or combination of strategies should be pursued to achieve the required completion date? In what follows, we examine how the 31 January date was met and hint at how the preferred date of 31 December 2008 might be achieved.

Normally, when faced with shortening a schedule, one would apply conventional time–cost trade-off procedures. However, that paradigm breaks down for projects that have many repetitive components and activities and the underlying assumptions do not apply or are too restrictive [20]. Rather, we examine the base strategy to see if the schedule can be tightened through changes to logic, enhancement of material properties, interventions at intermediate floors, etc. — i.e. we reason about the construction process, as opposed to applying an algorithmic approach like time–cost trade-off where one ‘simply’ starts shortening critical activities and assumes that logic and methods are basically fixed, and only resource levels, calendar definition, and methods at the local level can be altered.

Study of the schedule representation in Fig. 6(a) suggests a number of rather obvious low or no cost strategies to shorten project duration which are summarized in Table 1. These include that use of admixtures to the concrete to speed strength gain allowing the separation...
Fig. 6. LP schedule representation for base construction strategy — completion date 23 March 2009 (a), and LP schedule for revised strategy — completion date 28 January 2009 (b).
between structural work and follow-up rough-in work to be lessened (Schedule A.1.1), reduce the vertical separation of trades by controlling the cycling of work in the horizontal domain (Schedule A.1.2), seal intermediate floors to allow drywall to start earlier (Schedule A.1.4), and possibly go to a 4 day cycle for all finishing trades (not implemented). In addition, some fine tuning of the use of spatial and time offsets was done.
to ensure consistency of application. As summarized in Table 1, selective use of these strategies has been made on an incremental basis, resulting in project completion moving from 23 March 2009 to 28 January 2009, thereby satisfying the client's minimum requirement. The biggest time saving resulted from sealing of the 8th floor (Schedule A.1.4), an inexpensive process. The resulting schedule is shown in Fig. 6(b) — note the reduction in 'white' space. No attempt has been made to achieve the preferred delivery date of 31 December 2008, although how this might be achieved is described in the last row of Table 1 (Schedule A.1.5).

If the logic changes described in Table 1 were to be performed using traditional CPM modeling, the number of changes would be very significant and errors could easily be made. The problem would be compounded if the building was 30, 45 or 60 stories, heights typically encountered in today's urban environments. Using the planning structures and generalized precedence relationships that accompany our implementation of linear scheduling, the changes can be readily made, as shown in Fig. 9 and of the changes made in terms of time and space logic, most are independent of project scale and involve a single

Fig. 8. 4D CAD snapshots for the base construction strategy (December 07, February 08, April 08, June 08, August 08, October 08).
Finally, the primary role of the 4D CAD model in assessing workability of the strategies used was one of confirming technical feasibility (i.e. did it look right), as opposed to suggesting potential strategies. For more complex facilities, the 4D model would be useful for both.

5. Discussion

In this section, we highlight some of the insights we have derived so far and discuss in some considerable depth a number of issues related to product modeling on the CAD and scheduling sides, and process modeling on the scheduling side. An important focus of the discussion relates to the desire to create an environment that facilitates in a relatively easy fashion the exploration of multiple construction strategies. Therefore, part of the discussion is focused on barriers to exploring multiple strategies with traditional tools, including the challenges of creating and maintaining the links between activities in a scheduling environment (e.g. P3) and between CAD objects and activities in 4D.

5.1. Representing multiple levels of detail

A significant issue with respect to 3D modeling is the difference between the designer view and the contractor view. Often cited in the literature are issues of modeling techniques [21] and the level of detail [8]. Our goal is to help make 4D more accessible as a tool for contractors to examine construction strategies, and perhaps at a more refined level, examine constructability issues, which deals with the level of granularity in the model.

Consider interior and exterior walls as an example. From a designer perspective, interest is in showing the finished wall in place. So if a wall is made up of multiple layers, all that is shown is the finished wall. This is the approach we took in our initial implementation [19]. But from a contractor's perspective, some elements are constructed in multiple passes. For interior partitions, contractors put in the studs, the board, then tape and fill, then paint, then perhaps put moulding on, etc. For the exterior walls, contractors put in studding, sheath, insert windows, doors, insulate in side, perhaps put Tyvek on, do masonry work, tape and fill inside, and then paint. The question becomes, for realism, how far do you go?

Kamat and Martínez [22] discussed the need for construction process visualizations at two levels of detail to facilitate construction planning and control based on Halpin and Riggs [23] hierarchy of construction: project- and operations-levels. Project-level visualizations link construction activities (e.g. 'Pour concrete columns on the second floor') at the building component-level (e.g. concrete columns) to visualize the progression of the construction product over the period of its construction. Operations-level visualizations focus on the work at the field level and the methods, resources and strategies required to accomplish an activity or group of activities.

Naturally these different types of visualizations require different levels of detail in the product model. Project-level visualizations are typically modeled at the building component-level (e.g. walls) while operations-level visualizations are typically modeled at the elemental-level, which are the elements that are required to build a building component (e.g. studs, drywall, etc.). We use this terminology throughout the remainder of this section when discussing the different levels of detail in the context of product modeling and 4D-visualization.

In our approach, we considered the nature of the construction activity and the potential benefits of modeling for field personnel to determine whether more fine-grained representations were required. For example, activities for walls required more levels of detail (e.g. showing elements, such as drywall and studding) whereas concrete columns do not. The key distinction is that walls require follow-on activities for multiple trades and across multiple locations while the

Table 1

<table>
<thead>
<tr>
<th>Schedule</th>
<th>Strategy</th>
<th>Completion date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>5 day cycle time for superstructure construction; 4 floor separation between structural work and follow-up rough-in work; spatial offsets used to separate trades and allow time for inspection; enclosure completed to 15th floor (sheathing, windows, doors) prior to start of dry wall boarding on ground floor, work continuity for dry wall and painting trades</td>
<td>23 March 2009</td>
</tr>
<tr>
<td>A.1.1</td>
<td>Change space offset of 15 build interior masonry walls, 28 rough-in vertical plumbing/fire system piping, and 29 rough-in gas lines from 4 to 3 through use of admixtures to concrete, allowing earlier removal of slab shoring</td>
<td>18 March 2009</td>
</tr>
<tr>
<td>A.1.2</td>
<td>As soon as exterior sheathing is installed on a floor, insert windows and exterior doors. Used to have 1 floor offset.</td>
<td>13 March 2009</td>
</tr>
<tr>
<td>A.1.3</td>
<td>Made time and space offset consistent for rough-in vertical plumbing, interior masonry, and rough-in gas lines — the time offset varied between 10 and 20 days, now a consistent 15 days</td>
<td>11 March 2009</td>
</tr>
<tr>
<td>A.1.4</td>
<td>Seal off floor eight; start drywall as soon as floor eight sealed and windows installed at this level; delay removal of man-hoist and use to transport all cabinetry up to floor 10; other minor adjustments made to logic to avoid artificial critical paths</td>
<td>28 January 2009</td>
</tr>
</tbody>
</table>
| A.1.5    | Strategy to get from 28 January 2009 to 31 December 2008: separation not 3; seal fenestration at this level simply involves inserting a new activity (in this case 'Seal off intermediate floors to start drywall' at location 8), assigning it a predecessor, and then making the seal off activity a predecessor of the 'Board Drywall' activity structure, linking the location of the seal office activity to the ground floor (GFLR) location of 'Board Drywall', as shown in Fig. 9(b). Similar efficiencies are available when altering production rates of an activity or exploring crewing strategies where multiple locations can be executed simultaneously. The power afforded by these constructs removes many of the impediments associated with exploring alternative strategies using a traditional CPM model and bar chart representation for this type of project. | }
successors of concrete columns require that the columns be complete before they can be started. Our feeling is that certain decisions on detailed construction of components should not be treated in modeling – they are best left to field personnel – decisions made based on opportunism at the time. Thus, we suggest the following guiding principle – include intermediate detail or states for a component when successor activities for non-related work are dependent on partial completion of the component – e.g. a specific layer of an enclosure wall. Based on this principle, it becomes necessary for 4D visualizations to represent multiple levels of detail simultaneously to support the needs of field personnel and to ensure that the 4D model captures reality which is essential for credibility with model users.

For the example project, we modeled building components at different levels of detail to get a sense for the implications these different types of models have on exploring multiple construction strategies. We modeled walls at the elemental-level (e.g. drywall, studding, etc.), and modeled the other building components at the component-level (e.g. columns, slabs, etc). For our treatment of walls, we use multiple style sheets for wall elements, then superimpose one on top of the other, with some geometric separation that represents their placement in the wall. Our intent was to illustrate the issues involved with modeling at multiple levels of detail. We recognize the limitations of this approach to modeling both in terms of accuracy (e.g. studs not modeled precisely) and in terms of efficiency (it is time consuming to create these different elements separately). However, it was necessary to represent this level of detail to demonstrate proof of concept. Ideally, most of this detailed modeling would be done automatically. For example, there are commercially available tools, such as Cadwork, that automatically create the layout of studs given a 2D wall layout. Our 3D model ultimately contained 150 CAD objects at the component-level, and 488 CAD objects at the elemental-level for each story.

Fig. 9. Planning structures and generalized precedence relationships represented in REPCON.

5.2. Scaling the product and process models

This section discusses the ease with which large scale projects characterized by significant repetition can be treated, both on the CAD and scheduling side (process and product models). It demonstrates the value of having dual product models on the CAD and scheduling sides to resolve many of the difficulties associated with linking/re-linking product and process models. As stated previously, we explored this issue by scaling up a 6-story project we developed previously [19] and extended it to 15 stories to more fully study the issue of scale. There are two directions in which scale is important to consider: vertically across multiple levels and horizontally across a single level. Here we restrict our discussion to the vertical direction based on the discussion of the horizontal dimension in the previous section. While our approach involves no limitations on scale in the vertical direction, topics worthy of discussion include challenges associated with: (1) scaling the 3D model, (2) scaling the construction schedule, and (3) scaling the 4D model.
5.3. Treating horizontal zoning

There are two other important levels of detail in the context of high-rise buildings from the lowest to highest levels which we have yet to address and which relate to the issue of scale in the horizontal dimension. (The foregoing was not an issue for our example building because of its rather modest yet realistic horizontal scale.) It is essential that they are treated in future work if 4D CAD and associated schedule modeling are to reflect the range of strategies employed in actual high-rise construction. Simply stated, the challenge is to describe the spatial context and building components in terms of flexible zoning. Consider for example, a large floor slab which is...
considerably greater in scale than what constitutes the optimum slab pour. Thus it will be built in stages (2 or 3 depending on slab size). In exploring different construction strategies, the extent of zoning may become a decision variable and the decision will depend on what the structural engineer will allow and where construction joints can be placed, and what is feasible from a construction strategy perspective. Given a strategy, it must be expressed in terms of activity descriptions which reflect the scope of work to be done in terms of a process and spatial context (e.g. Build slab Grid A1-E6), and a CAD product model which reflects this work scope, or for our approach, two product models. But, that same zoning may not be relevant to other follow-up work, e.g. Mechanical rough-in, where horizontal zoning may not be required. Hence there is a need for flexibility in terms of spatial zoning and related grouping of physical components. The topic of zoning has attracted the attention of other researchers, notably Akbas [9], Riley and Sanvido [24], and Staub-French and Fischer [21]. A general paradigm for treating it has yet to be developed. As part of our approach to treating zoning, we are examining ways of describing internal space for each location or group of locations in our physical component breakdown structure. For high-rise construction, the use of grid lines and types of space would be appropriate. However, we seek an approach that is applicable to all types of construction, not just high-rise buildings, and which is practical from the viewpoint of the level of detail at which practitioners are willing to model. By communicating spatial descriptions that are already encoded in the CAD model (e.g. grid lines), it may be possible to automatically break CAD objects into sub-objects, and it is these sub-objects that would be represented in 4D.

5.3.1. Scaling the 3D model
Scaling the CAD model vertically is a relatively straightforward process that depends largely on the CAD application being used. The primary challenges in scaling up the number of stories relate to the degree of design variability in the new stories. If most of the new stories contain the same components and component types then adding more stories will be relatively easy. For example, if you wanted to add ten new stories that were exactly the same as the previous one, then you would just need to copy all the objects on that story and paste them on to the new levels. However, if CAD objects have to be changed or if new objects are needed, then it can be a more cumbersome process, depending on whether or not the composition of objects used has to be changed (i.e. some variability in design moving from floor to floor can simply be handled by changing the properties of existing objects, without adding a new style). In ADT, to change the composition of objects, you have to go into the style database to modify the object and its attributes before it can be populated to the new levels. To add new objects, you need to create that object in the style manager and add any new properties, and then insert it into all the new levels. This is particularly cumbersome if components are being modeled at the elemental-level (e.g. studs, drywall) to represent the construction perspective. Modeling new components at this level would require new objects for each element including element properties, and then these new objects would need to be inserted into the model.

5.3.2. Scaling the schedule
In this section, we outline briefly the steps involved in accommodating an increase in vertical scale of the building for the schedule and accompanying physical (product) model. We focus on the leverage offered by the activity planning structures and the manner in which the physical product model has been designed and implemented. By way of context, it is useful to consider common practice in the industry, in which one starts with a plan of a previous similar project, and then adapts it to the project at hand. For our case, we went from a previously planned 6 story residential building with 1 parkade level to our current example of 15 stories and two parkade levels. For simplicity here we assume that the activities already existing in the schedule cover the full spectrum of tasks that must be performed and that methods remain constant. We conclude our discussion with a few observations on other model fine-tuning that might be required if construction methods are altered, greater design variability accompanies the increase size of building, or additional detail is desired in the product and process models.

Steps in the vertical scaling can be itemized as follows: (a) within the physical view, add the additional levels to the project location and enter location attribute values as appropriate; (b) for the mapping of physical components on to locations, readjust the location ranges for component attribute values; (c) no change in association between physical components and activities needs to be made; (d) on the planning side, change the production rate ranges for activity planning structures to reflect the additional levels added to the building — no additional planning structures are required; (e) adjust non-typical logic as required, but typical precedence relationships need not be changed — they are automatically extended to cover the set of locations assigned to each activity (refer to Fig. 9); and, (f) compute the schedule. The foregoing should be contrasted with the level of effort involved in extending a traditional CPM model.

When scaling up from a previous building, the size in the horizontal dimension could change as well, although in this discussion we assume no need for zoning accompanies this increase in size. Adjustments will then have to be made for the change in scope as reflected in the change of attribute values for the locations themselves as well as the physical element attributes values at each location. These adjustments could be made using component attribute values passed back from the CAD model. Depending on the magnitude of these adjustments, production rates may have to be altered, or additional resources assigned to the activity.

5.3.3. Scaling the 4D model
We considered the issue of scale in the context of creating project-level and/or operations-level 4D visualizations. As discussed previously, our example project contains a combination of component-level and elemental-level representations. We used these different levels to get a sense for the effort required to create the different types of 4D visualizations using traditional tools and to contrast that with our approach.

Dealing with scale is a significant challenge using traditional 4D modeling tools, particularly considering the level of detail in an operations-level 4D model. Typically, any new CAD and schedule objects have to be manually linked when creating a 4D model. So, for every story that is added, all the CAD objects on that story would have to be linked. A single story of our example project contains over 150 CAD objects at the project-level, and 488 CAD objects at the operations-level. To scale up the 4D model for the nine additional stories, this would require as many as 1350 links to create a project-level 4D model, and close to 4400 links to create an operations-level 4D model. Depending on the control afforded the user by the CAD system, some of this effort could be reduced by working with groupings of objects. It is possible to automate some of this linking process but it requires extensive set up and coordination of the CAD and schedule models, such as consistently naming CAD layers and activity names [21]. Consequently, most 4D models in practice today are created by manually linking CAD objects and schedule activities.

This manual linking process in conventional 4D tools limits the flexibility of project-level 4D models to deal with design and schedule changes including issues of scale, and makes it prohibitive to build operations-level 4D models. Our approach addresses this challenge by providing a more general way of linking the product models on both the CAD and scheduling sides. Essentially we link objects at the class level rather than the instance level and through the different product models rather than linking CAD objects and activities directly. This type of linking mechanism minimizes the number of links that need to
be made, and eliminates the need to manually re-link CAD objects and activities as the design and schedule change.

For the example project, we are scaling the building up from 6 to 15 stories so the issue is creating the links to these new CAD objects on the nine new stories with the new schedule activities. Because we already have the general mappings set up between existing CAD styles and associated schedule activities, we only need to link CAD objects for new styles that are unique to a particular story. In high-rise construction, most stories are repetitive so this is often not an issue. For a project-level 4D model, the 6-story example project required 24 CAD styles so we only had to make approximately 125 links, including links between the two product models and between the scheduling system product and process models. When scaling up the model to the 15-story building, the 3D model did not contain any new styles and therefore, no additional linking was required for the project-level 4D model (compared to over 1350 links using traditional 4D tools). For an operations-level 4D model, the 6-story example project contained 50 CAD styles so we had to make approximately 150 links to set up the model. Again, since no new styles were required when scaling up to 15 stories, no additional links were required for the operations-level 4D model, compared to the almost 4400 links required for traditional tools. Thus, the number of links is invariant to changes in project scale when no new CAD styles are required either at the project-level or the operations-level.

It is also worth noting that the process of linking the product and process models is significantly different in our approach. In traditional tools, users have to go into the models and select the 3D components to create the links. This can be an onerous process as it requires the user to search for the appropriate elements in 3D space, which is particularly tedious in an operations-level model that can have hundreds of elements (e.g., studs, drywall, etc.). In contrast, our approach allows users to create links by using the semantics of the component classes in the PCBs on the scheduling side and in the Styles on the CAD side to make general associations for classes of components.

Table 2 summarizes the key functionality required to create and maintain 4D linkages and critiques our approach in comparison with current 4D modeling approaches. As illustrated in the table, the general linking mechanism offered in our approach makes it significantly easier to create and maintain links as new CAD objects and activities are added or changed.

### 5.4. Creating 4D images to complement 4D models

Our approach allows for significant power in creating customized, rendered 4D images to complement traditional 4D models. By working with the native 3D CAD model we were able to: (i) manipulate and render the 4D images in unique ways; (ii) group similar elements to show work in progress and communicate the spatial relationships between different activities; and, (iii) adjust the transparency of elements and create exploded views and sections to visualize interior work and communicate the progression of the crew and potential conflicts of crew work spaces. We were also able to apply materials, adjust the colors and transparency, and change the lighting to enhance the realism of the model. Many of these manipulations are not possible with current 4D tools. In our current implementation, however, these manipulations are performed manually. Ideally, these 4D images would be created dynamically through direct interactions with the scheduling environment.

### 5.5. Creating Linked Visualizations

A variety of visualizations were needed to facilitate the process of exploring multiple construction strategies. Each type of visualization contributed something unique to the analysis. For example, congestion plots were particularly useful in identifying congestion problems in interior work which are difficult to identify in a 4D visualization where there is limited visibility. Ideally, we want to be able to juxtapose a number of images on a single screen — e.g. multiple schedule representations, which can be done now, plus resource usage diagrams, pictures of the site, etc. However, what are missing are linkages between the different visualizations and the ability to interact with the different visualizations to further explore the options and create other customized views on the fly.

Fig. 11 shows a mock-up of such a visualization environment. Although not fully implemented, it illustrates key functionality that is needed. The figure shows a particular time frame selected in the LP chart with the relevant activities highlighted. These same activities are shown in the related 4D visualization. The resource histogram and congestion plot are re-configured to isolate these specific activities. Additional 3D and 4D visualizations are created to better show the interior work affected. A discussion of human computer interaction (HCI) features is beyond the scope of this paper, but properly designed, a good interface can place enormous power in the hands of the user in terms of being able to navigate the time-space domain, zoom in and out, filter, highlight, overlay, compare, juxtapose other visual images, and change one or more of production rates, location sequences, logic, and space buffers. Although many of these visualization techniques are not new, they have yet to be realized in an integrated environment. We feel that our approach has the potential to provide this type of functionality as it addresses many of the modeling issues associated with integrating product and process views.

### 6. Conclusions

In this paper, we have described selected aspects of our work directed at formulating a dynamic visualization environment that links 3D CAD and a generalized implementation of CPM which embraces linear planning to create custom 4D images. Requirements of such an environment include quickness, treating scale, working at multiple levels of detail, dealing with design variability, and realistic representation of the work. This work shows how various visual
representations of a project’s schedule and associated information (e.g. congestion plots) combined with visual representations of the project in progress (i.e. 4D CAD) can assist greatly with the evaluation of alternative construction strategies for shortening project duration.

The ability to represent dual product models on the CAD and scheduling sides is novel and central to our approach. It enables a more general way of linking product and process models. Essentially it enables objects to be linked at the class level rather than the instance level and through the different product models rather than linking CAD objects and activities directly. This type of linking mechanism resolves many of the difficulties associated with linking/re-linking product and process models, which often limits the availability of these models in practice. We have found that these efficiencies are necessary for treating issues of scale, and for developing operations-level 4D models, enabling the exploration of multiple construction strategies. It also provides considerable power in that the completeness and consistency of each of the product models can now be easily validated.

A variety of modeling issues must be confronted to develop models useful for the evaluation of construction strategies. In particular, the level of detail was a particular concern as it prompted the question, for realism, how far do you go? Based on our work to date, we suggest the following guiding principle — include intermediate detail or states for a component when successor activities for non-related work are dependent on partial completion of the component. This principle suggests that 4D visualizations must represent multiple levels of detail simultaneously to support the needs of construction professionals.

Ongoing work is focused on modeling the spatial context in both the vertical and horizontal directions including zoning, treatment of work direction, and site layout issues. Additional modeling is also necessary to adequately represent temporary facilities and equipment. We will also further develop the visualization environment to provide the functionality discussed, including combining information from more than one project view and more than one representation (e.g. importing data from CAD), operations on data from product, process (e.g. congestion plot), as-built views (e.g. compare as-planned and as-built, and tie in with digital images from field), etc. Finally, we will continue to investigate product modeling issues and the potential for hierarchical modeling of both the process and product views, which deals with issues of inheritance and aggregation, including upward aggregation of associations between the two views.

References


