QUANTITATIVE ANALYSES USING 4D MODELS – AN EXPLORATIVE STUDY

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ABSTRACT : 4D models help construction planners to develop and evaluate construction plans. However, current analyses using 4D models are mainly visual and limit the quantitative comparison of construction alternatives. This paper explores the usefulness of extracting quantitative information from 4D models to support time-space analyses. We use two 4D models of an industry test case to illustrate how to analyze 4D content quantitatively (i.e., work space areas and distances between concurrent activities). This paper shows how these two types of 4D content can be extracted from 4D models to support 4D-based-analysis and novel presentation of construction planning information. We suggest further research to formalize the content of 4D models to enable comparative quantitative analyses of construction planning alternatives. Formalized 4D content will enable the development of reasoning mechanisms that automate 4D-model-based analyses and provide the information content for informative presentations of construction planning information.

Key words : 4D CAD, construction planning, time-space buffer

1. INTRODUCTION

The application of 4D CAD models is a promising approach to help introduce construction innovations and to evaluate construction alternatives. Simulating production options with multiple 4D CAD models from different perspectives allows project stakeholders to compare construction alternatives. However, today these analyses are mainly based on visual analyses where experienced practitioners may or may not detect constructability issues, such as time-space conflicts, that make certain alternatives more or less feasible. Planning supported by visual analyses of 4D CAD models is considered more useful and better than traditional planning [1-4], but does not take advantage of the quantitative data contained in 4D CAD models.

In this paper we show the value of extracting data from 4D CAD models to enable quantitative analyses of 4D CAD models. Our starting point is the 4D CAD model and not the underlying planning and modeling method for these models, such as the Critical Path Method (CPM), Line-of-Balance diagram [5] or Geometry-based Process Method simulation [6]. This paper first introduces 4D CAD models of an industry test case that we use as the case example. Then, the paper describes two quantitative analyses of the 4D CAD models, in which we analyze workflow and resource use and costs. In addition to these two analyses, we perform a combined analysis in which we join the two quantitative analyses to show the relation between different types of data. The paper concludes by suggesting research directions for development of 4D CAD systems that support quantitative analyses of 4D CAD models.

2. INDUSTRY CASE EXAMPLE

In an effort to adequately support the introduction and evaluation of construction innovations (i.e., prefabricated reinforcement, permanent formwork, self-compacting concrete, etc.) Betongindustri AB, a Swedish ready mix concrete supplier [7]initiated a pilot study using 4D CAD simulations to evaluate two construction alternatives of a residential construction project. The concrete supplier conducted the experiments after the actual construction of the project was finished. The experiments are realistic and, where possible, are based on actual site data, but had no direct impact on the construction process performed by the contractor. The 4D CAD simulations by the concrete supplier include construction operations related to concrete walls and slabs, but the analyses of these models performed in this study are limited to analyses of simulated construction operations related to the casting process of concrete slabs.

The first alternative, the traditional scenario, represents today's common practice for cast-in-place concrete construction. The objective of this scenario is to represent a typical set of construction activities that are related to casting of concrete. The second alternative provides an industrialized approach to cast-in-place concrete construction utilizing permanent formwork systems in combination with the use of prefabricated carpets of reinforcement and self-compacting concrete. The objective of the pilot study by the concrete supplier was to visualize the potential for such an industrialized construction method.

2.1 4D CAD Models of the Case Study

The concrete supplier used an architectural 3D CAD model as the base model for the 4D CAD simulations. The 3D CAD objects of this model were not detailed enough to be used for representation of specific construction operations. The concrete supplier therefore transformed the architectural model into a model suitable for simulation of construction operations by adding detail to the 3D model. The concrete slab, for example, is modeled as one object in the architectural model, but is poured in several sections. The supplier, therefore, split the slab into separate casting objects.

The complete 3D model consists of four 3D CAD models that are based on the architectural model and represent four successive construction trades:

- Shoring to support formwork elements
- Formwork elements on which reinforcement is installed and concrete is poured
- Reinforcement bars
- Pouring of concrete sections

In addition to the 3D CAD models, the concrete supplier created detailed schedules for both alternatives, resulting in CPM schedules with 111 activities for a single slab of 60 meters in length and 15 meters in width. We linked these activities with the components in the 3D model to make the 4D models. Planners at the concrete supplier detailed and grouped all activities in the CPM schedules in four two-hour work packages per day. The concrete supplier defined casting sequences for concrete work by splitting the 3D CAD model into a number of sections. The supplier planned two scenarios per construction alternative. Figure 1 shows a scenario in which the slab is cast in three sections. Table 1 includes all the simulated construction alternatives.

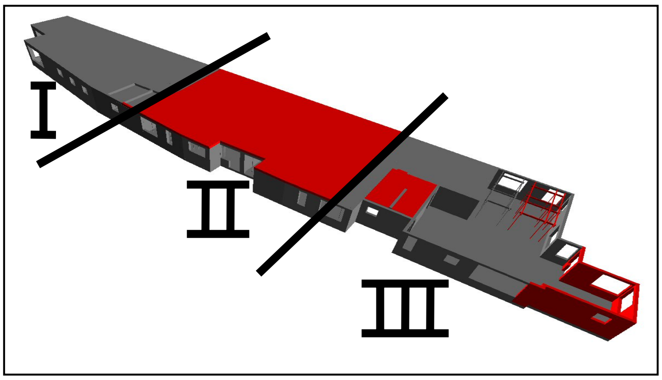

Figure 1. Snapshots of a 4D CAD simulation of a traditional construction alternative, cast in three sections.

Red elements are ongoing at the time of the snapshot.

Table 1. Simulated construction alternatives in 4D CAD

Alternative	Two sections	Three sections
Traditional	Traditional II	Traditional III
Industrialized	Industrialized II	Industrialized III

3. ANALYSES OF 4D CAD MODELS

We conducted two types of analyses to study and illustrate the potential of 4D CAD beyond visual analyses. The first analysis originated from recognizing the spatial nature of construction work and the way in which the work moves over a construction site during construction. Secondly, we analyzed the resource use and cost during the construction to explore relations between resource and cost information, and 4D content. We define 4D content as information present in a 4D CAD model such as distances between concurrent activities. The analyses of resource use and costs helped us to illustrate potential impacts of spatial constraints on the project's performance.

As a basis for our analyses, we manually inspected the 4D models and collected the required data in spreadsheets for every two hours of construction time simulated in the 4D CAD models and added cost and resource data. As an example of such a spreadsheet Table 2 shows data from the industrialized construction alternative on days 3 and 4. We performed the data collection and data analyses manually to understand the data thoroughly, but this process could be automated with appropriate mechanisms. We joined the spatial analysis and the resource use and cost analysis in a combined analysis to explore the relation of spatial data and productivity of crews. These examples of 4D-model-based analyses of construction alternatives exemplify the data that can be available in 4D models and show how such explicit 4D content could support automated analyses of construction alternatives. These analyses enable the generation of novel and informative presentations of information about construction alternatives, which, in turn, can lead to new insights into the performance of construction activities.

Table 2. Example of collected data in spread sheets from the 4D model of the Industrialized III alternative.

Time	Used work space area (m2)				
	Shoring	Form	Rebar	Concrete	Total
Day 3					
08-10	0	50	40	0	90
10-12	20	40	0	80	140
13-15	15	15	0	80	110
15-17	55	45	55	0	155
Day 4					
08-10	0	40	45	0	85
10-12	0	50	40	0	90
13-15	0	40	35	0	75
15-17	0	45	45	0	90

3.1 Spatial Analyses

We extracted the following data from the 4D models:

- Workspace areas used per construction trade
- Distances between concurrent activities of different trades

Workspace areas are measured from CAD components in the 4D CAD model. Figure 2 presents the used workspace in square meters (Y-axis) per trade in two hour intervals per construction day (X-axis) for the industrialized construction alternative that is cast in three sections (industrialized III). Figure 2 shows that the industrialized III alternative has a widely varying workspace usage. Workspace used by shoring activities during the first two days is around 40 to 60m^2 after which it drops to 0m^2 on day 3. Formwork and reinforcement activities have similar space use patterns. This 4D CAD model does not show production problems on day 3 of construction for the Industrialized III alternative, such as workspace conflicts. However, the concrete supplier experienced difficulties in planning space buffers between the successive trades and needed a number of iterations to create a 4D CAD model without time-space conflicts.

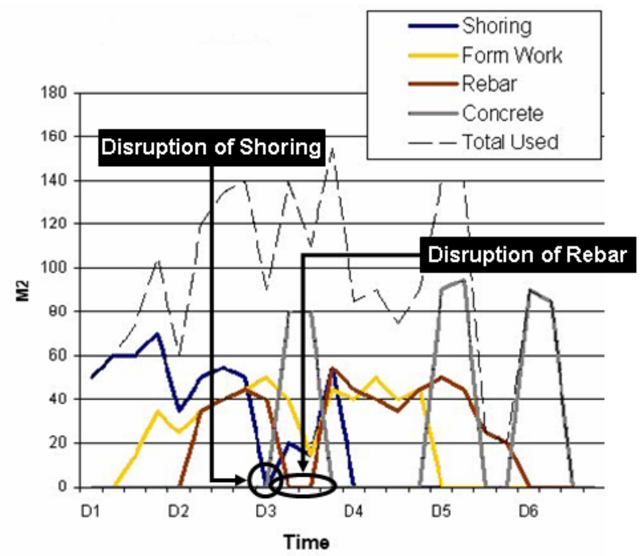

Figure 2. Used workspace extracted from the 4D CAD model of the Industrialized III alternative.

The following planning decisions and planning rationale led to such disruptions in the workflow:

Planners at the concrete supplier assumed that the laborers needed for casting concrete on day 3 could be used from the shoring activities. As a result, shoring activities were halted during the first 2 hours on day 3.

The initial time-space buffer between the successive trades was too small. A short stop in the shoring activities resulted in a lack of available workspace for formwork, which in turn limited the reinforcement installation activities.

The focus was on planning each trade individually instead of planning the overall project. The activity start was prioritized in the planning process, with too little consideration for the total activity duration and time-space status of these activities. The 4D CAD model was used to filter out severe time-space conflicts between different activities, but was not used to optimize the workflow.

In summary, the planning of the industrialized construction alternative was sub-optimized by trade, due to the fact that the planners focused on one trade at the time. The planners did not make explicit consideration of the time-space status of activities resulting in disruption in workflow. These disruptions did not become directly clear from the CPM schedule or from the 4D CAD model, but became obvious from representation of the used workspaces of different trades in time, as shown in Figure 2.

In addition to workspace used, we analyzed distances between concurrent activities of different construction trades. These distances indicate the amount of space buffers that are allocated by planners between different activities. These data can possibly be useful for planners in allocating sufficient workspace for construction crews. Allocating too much space distances activities too much and lengthens project duration. Allocating too little space reduces productivity, which also lengthens project duration.

Figure 3 shows the distances between the formwork and reinforcement activities for the traditional alternative. We measured two types of distances for every construction day per two hour interval (X-axis): distances between the activities' centers and the closest distances between two trades (Y-axis).

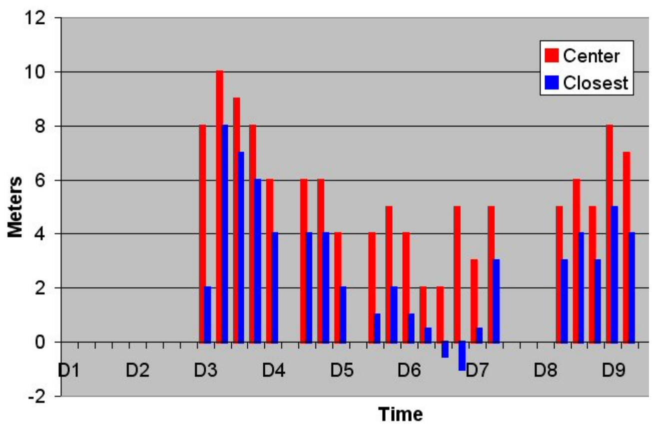

Figure 3. Distances between formwork and reinforcement trades for the Traditional III construction alternative.

The formwork and reinforcement activities are close to each other during days 3, 4, 5 and 6. On day 6 the activities overlap, as shown by the negative distance between the two construction trades. This overlap, or time-space conflict, was overlooked in the 4D CAD model, but became immediately obvious in the graph showing the distances between trades.

The analyses of used workspace and distances between trades illustrate that not all spatial data of 4D CAD models become explicit in the typical form of 4D snapshots or 4D movies. These analyses show that additional representations and presentations of 4D CAD model information, such as graphs, are needed to efficiently allocate work space and space buffers between concurrent activities for productive work by construction crews.

3.2 Cost and Resource Analyses

Currently, costs and resources are not part of 4D CAD models. Therefore these aspects of different construction alternatives are assumed similar, or just ignored in 4D simulations.

In this section we illustrate how changes in the construction schedule affect cost and resource use, although current 4D methodology does not reflect that relation in 4D simulations. For example, a construction strategy 'A' might visually seem to be better than strategy 'B', but may turn out to be more expensive and less effective in terms of resource use than strategy 'B'. Users of 4D CAD models are not able to clearly visualize this potential consequence due to the absence of interrelations between 4D CAD models and cost and resource information. In the combined analysis presented below, we exemplify how certain spatial data contained in 4D CAD models (e.g. distances between trades) could lead to variations in resource use, productivity, and finally cost.

We calculated the material cost by taking off the quantities from the 3D CAD models. Then, we combined these quantities from the 3D CAD models with cost and productivity information obtained from industry professionals, such as planners and cost estimators. Cost estimation and quantity take-off in two-hour chunks is not very realistic. Since the productivity data is based on mean values over much longer periods, we decided to take off the quantities per work day in the analysis.

Figure 4 shows the distribution of total costs, which includes material and labor costs, for each construction alternative. Figure 4 shows that the industrialized alternative is more expensive than the traditional alternative. There are some small variations for the two and three-section scenarios of each alternative although the final cost is the same for both scenarios in each alternative. These small variations are due to differences in the schedules. However, the amount of work and productivities are the same, and consequently the final cost is the same as well. Figure 4 also shows the difference in duration between both alternatives: the industrialized alternative takes six days whereas the traditional alternative takes ten days. This information is generally available from sources other than 4D models (such as scheduling and cost estimating software), but it is disseminated in different pieces of information, what makes time consuming the process of putting it all together.

Having that information available within the 4D models would be of use for planners to decide between construction alternatives. Identifying relations between cost and resource information and 4D contents that affects this information will greatly improve the understanding of the construction alternatives enabling planners to make better informed decisions. In the next section we discuss a combined analysis of spatial data and cost and resources.

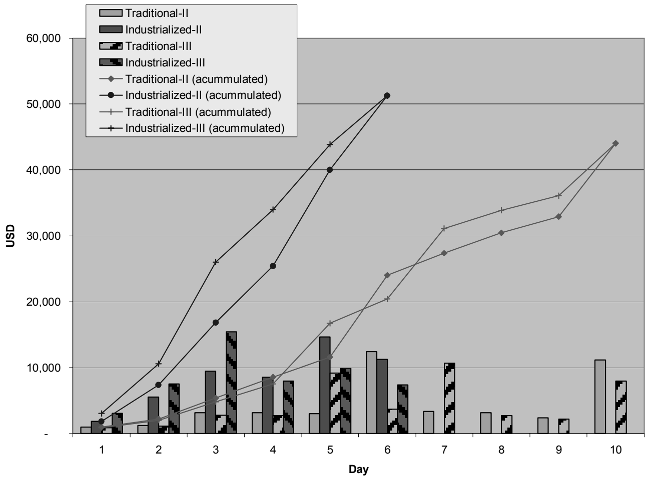

Figure 4. Total cost (material and labor) per day and accumulated for all the construction alternatives

3.4 Combined Analysis

To illustrate a possible combined analysis of 4D content we defined and analyzed distances between trades in relation to trade productivity, which consequently leads to cost. In this combined analysis we focus on the detected conflict between the formwork and reinforcement trade, as shown in Figure 3.

As explained in previous sections, we measured the distances between trades directly in the 4D models, and we obtained the productivity rates from planners and cost estimators. These productivity estimates were considered constant for each trade during the project. However, productivities are usually not constant, and available workspace is one of the factors affecting productivity.

To estimate the impact of the detected conflict between trades, we established a relation between trade distances (a specific 4D content) and trade productivities, summarized in 오류! 참조 원본을 찾을 수 없습니다.~~오류! 참조 원본을 찾을 수 없습니다.~~ 3. We established this relation for illustrative purposes by assuming impacts on productivity based on the distance between trades. We considered the trades separately: a predecessor and a successor. In this case example the reinforcement trade is a successor to the formwork trade and is dependent on the outcome of formwork activities.

Table 3. Relation between the productivities of construction trades and the distance between formwork and reinforcement trades.

Distance between trades	Assumed productivity of successor trade	Assumed productivity of predecessor trade
> 2m	100%	100%
1-2m	50%	75%
0-1m	25%	50%
< 0m	(cannot work) 0%	100%

Like in other prototype 4D modeling systems [6] we adjusted the productivities that were given by planners and technology providers for the specific trade conflict as noted in Figure 3 based on the relation between distances and productivities. Table 4 shows the adjusted productivity percentages for the reinforcement and formwork trades for day 6. The productivities represent two-hour intervals of work for the construction day on which the trade conflict occurs. At the bottom of the last two columns in Table 4, we calculated the average productivity of the day.

Table 4. Modifications of assumed productivities based on trade distances.

Time Day 6	Assumed productivity	Closest distance between trades (m)	Productivity of formwork crew	Productivity of rebar crew
08-10	100%	1.0	75%	50%
10-12	100%	0.5	50%	25%
13-15	100%	(conflict) -0.5	100%	0%
15-17	100%	(conflict) -1.0	100%	0%
Average	100%		81%	19%

The conflict between the two trades results in lower average productivity (lower daily production) on day 6 for both trades (resp. 81% and 19%) than the assumed productivity (100%). Extra work is needed for formwork and reinforcement installation on days 7 and 8 to compensate for the lower productivity on day 6. This extra work results in higher resource use and consequently higher costs, compared to the original planning and cost estimation.

Figure 5 shows the difference in labor costs due to the conflict between trades on construction day 6 for the traditional III construction alternative. This extra labor cost corresponds to the labor cost of the extra time needed to finish the units that could not be done on day 6 due to the lower productivity. This extra cost is approximately 7% of the total labor cost (shoring, formwork, reinforcement, and concrete) of the slab construction.

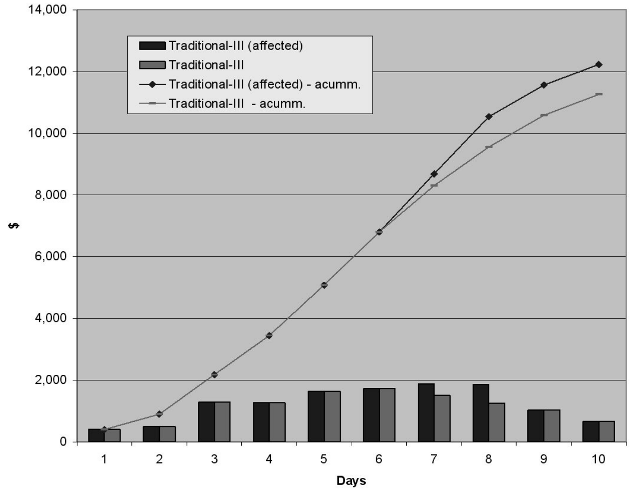

Figure 5. Effect of distance between formwork and reinforcement trades on labor costs.

4. DISCUSSION AND FURTHER RESEARCH

The specific numeric results of the presented analyses are hypothetical, but show a type of reasoning or analysis that does not occur in today's 4D CAD simulations. Reasoning, such as analyzing distances between trades and re-routing formwork trades, is done in actual production where there is a limited opportunity to change construction execution strategies. The distance between different types of work is an important factor in safe and productive execution of work. This paper showed that early analyses of 4D content can limit the risk for time-space conflicts in production. In addition to minimizing risks, there is also a potential to use analyses of 4D content to improve construction processes on aspects such as workspace usage and resource usage. The analyses of 4D contents that were performed in this study showed, for example, disruptions in workspace usage that did not become clear from CPM schedules or from 4D CAD models. Representation of workspaces of different trades in a graph made these disruptions explicit and illustrated the usefulness of extracting data from 4D CAD models.

In the process of manually extracting the 4D content we made certain assumptions about how to measure, for example, distances between trades. We measured distances in the horizontal (XY) plane and did not consider differences in height. In addition, we assumed that the 3D CAD components represented the workspace used by crews, but in reality the workspace used by crews is not limited to these components [9]. Representation and interpretation of extracted 4D content calls for an accompanying 4D CAD model to understand the meaning of these data and to put the data in a spatial context that the 4D CAD model provides.

4D CAD models come in different levels of detail and with different contents. Certain 4D CAD models are, for example, workspace loaded [9], and other 4D CAD models contain a temporary structure plan. How to extract 4D content from a 4D CAD model therefore depends on the type of 4D CAD model that is available. As a result, the process of querying 4D content is currently not a straightforward database query in time, since there is no agreed upon standard for defining and managing 4D content of 4D CAD models. To illustrate this, 4D CAD objects that represent shoring in the 4D CAD models of the industry case study have the same definition as objects that represent formwork. The lack of specific definitions for these objects requires custom-built reasoning mechanisms to extract 4D content such as distances between trades automatically from a 4D model.

Certain 4D CAD software tools [10] offer functionality to specify the type of activity in 4D CAD models (i.e., activity types), which works in a similar way as CAD layers in 3D CAD tools. Using activity types can be one way of defining specific 4D contents, which in turn could enable the automatic extraction of these contents. However, activity types are not always used in 4D CAD models by modelers, nor are they available in all 4D CAD software tools [10]. In the 4D CAD software tools that support activity types there is currently no functionality available to query the 4D CAD model for specific type of activity. The technical challenges of developing such functionality are minimal. However, the process to input 4D content and to extract this content requires further research.

In this paper we illustrated a number of 4D contents, with different analyses, but there are most probably more 4D contents that can be of interest for the design, planning and control of the construction process. We suggest further research where different types of 4D content are extracted and analyzed from 4D CAD models. Combined, these studies can eventually result in sets of standard 4D contents, reasoning mechanisms, and information presentations that are standardized for different types of analyses. The standard 4D contents and subsequent analyses can be expressed as a set of metrics that can provide planners with a basis to compare construction planning alternatives on different aspects.

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