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Quantitative analysis of workflow, temporary structure usage, and productivity using 4D models

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ABSTRACT

This paper presents time–space analyses of construction operations supported by quantitative information extracted from 4D CAD models. The application of 4D models is a promising approach to help introduce construction innovations and to evaluate construction alternatives. Current analyses of 4D models are mainly visual and provide project stakeholders with a clear, but limited, insight of construction planning information. This practice does not take advantage of the quantitative data contained in 4D models. We use two 4D models of an industry test case to illustrate how to analyze, compare, and present 4D content quantitatively (i.e., workspace areas, work locations, and distances between concurrent activities). This paper shows how different types of 4D content can be extracted from 4D models to support 4D-content-based analyses and novel presentation of construction planning information. We suggest further research aimed at formalizing the contents in 4D models to enable comparative quantitative analyses of construction planning alternatives. Formalized 4D content can enable the development of reasoning mechanisms that automate 4D-model-based analyses and provide the data content for presentations of construction planning information.

1. Introduction

The application of 4D CAD models is a promising approach to help introduce construction innovations and to evaluate construction alternatives. 4D modeling combines schedule data and spatial data. The method visualizes 3D CAD models in a 4-dimensional environment (i.e., time–space environment), facilitating analyses of different production strategies before work on site is initiated [1]. 4D models are typically created by linking building components from 3D CAD models with activities from activity-based scheduling methods, such as the Critical Path Method (CPM) [2]. Building components that are related to an ongoing activity are highlighted, providing users with spatial and temporal insights of the construction process. 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. It is relatively easy to spot potential time–space conflicts through visual inspections, and some 4D modeling tools provide automated time–space conflict analysis, i.e., they alert the user if two activities are scheduled to use (part of) the same space at the same time. However, it is more difficult to identify opportunities to improve workflow on site and improve space usage and productivity through purely visual inspection or analysis of 4D models. Nevertheless, planning supported by visual analysis of 4D CAD models is considered more useful and better than traditional planning [3–6]. However, visual analysis does not take advantage of the quantitative data contained in 4D CAD models.

We present three types of analyses to illustrate the usefulness of quantitative analyses from 4D CAD models for planning of construction operations. The first analysis addresses workflow, workspaces and space buffers. The second analysis concentrates on the planning of temporary structures. The third analysis focuses on crew productivity and production costs. These three analyses are based on temporal and spatial data extracted from 4D models.

1.1. Planning time and space buffers for construction operations

Planning workspace for crews or trades and space between different crews (i.e., space buffers) is a challenging task. Construction planners need to carefully design time–space buffers between activities so that on one hand the productivity for each crew is not slowed by time–space conflicts and lack of workspace and on the other hand the overall schedule is not lengthened due to excessive use of time–space buffers. This planning task is particularly challenging because the space usage on construction sites changes dynamically. Different crews move across the site from one work location to another. To execute their work, construction crews use, among other things, temporary structures. Temporary structures are one of the important factors in planning workspace and time–space buffers as

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they occupy space, but also provide workspace depending on the stage of a construction project. The productivity and therefore the output of crews is strongly dependent on available workspace and affects the progress on projects, and ultimately the project cost. Traditional scheduling techniques, such as the Critical Path Method (CPM), used in combination with 2D drawings, do not provide planners with the spatial insight that is required for the planning of efficient workspace use and allocation of optimal time–space buffers. In the traditional approach using CPM and 2D drawings users are required to look at 2D drawings to conceptually associate building components with the related activities [5]. Different actors may develop inconsistent interpretations of the relations between activities in a schedule and project components. This practice is prone to errors and limits the understanding of the spatial context of the flow of construction work on projects.

Virtual environments, such as virtual reality (VR) and 4D CAD, promote improved understanding of construction operations [7]. Akinci et al. [8] formalize and model space usage for construction activities in 4D CAD models, resulting in space-loaded 4D CAD models. The formalization and modeling methods provide insight into various types of spaces that are related to specific types of construction activities and potential conflicts (e.g., material space, labor space, building component space, etc.), but do not provide insight into the efficiency of designed time–space buffers between different activities. The Line-of-Balance (LoB) method [9], also known as Location-based Scheduling (LBS), provides spatial insight into the planning of time–space buffers and workspaces in the construction process. This technique uses lines to represent the production of crews over time in diagrams. LoB diagrams are based on a well-defined spatial subsystem, such as a floor consisting of apartments, divided into rooms. This type of static spatial hierarchy of workspaces is not present during all stages of the construction process. The distribution of and boundaries between workspaces are generally much more complex and less clear. Projects can have complex workflow directions of crews as a result of variations in the spatial configuration of a project [10]. Akbas [11] proposes a geometry-based process model (GPM) that uses geometric models to model and simulate workflows and work locations. This method provides spatial insight into the planning of workspaces and space buffers for repetitive crew activities, but has not been applied for quantitative analyses of 4D CAD models. It has rather been used as a simulation method for workflow and work locations with detailed 4D CAD models as an output.

1.2. Quantitative analyses using 4D models

In this paper we show the value and method of extracting data from 4D CAD models to enable quantitative analyses of 4D CAD models. The basis for analysis is the 4D CAD model and not the underlying scheduling and modeling method for these models, such as the CPM schedule, LoB diagram, or GPM simulation.

This paper first introduces 4D CAD models of an industry test case that we use as a case example. Then, the paper describes quantitative analyses of the 4D CAD models, in which we analyze workflow and planning of temporary structures. In addition, we perform an analysis in which we relate crew productivity and production costs to extracted data from the 4D CAD models. The paper concludes by suggesting research, including determining the content of 4D models needed for quantitative analyses, standardizing the representation of that content, and formalizing automated methods for quantitative analyses of construction concerns on the basis of 4D models.

2. Industry case example

In an effort to adequately support the introduction and evaluation of innovations in the construction process (i.e., prefabricated reinforcement, permanent formwork, self-compacting concrete, etc.) Betongindustri AB, a Swedish ready mix concrete supplier [12] 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. Such a combination of innovative production technologies had not been applied previously on actual projects in Sweden.

The concrete supplier used the 4D simulations in seminars in which a variety of construction professionals were invited. The 4D models provided the professionals from different disciplines an integrated visual impression of the two construction alternatives (Fig. 1), but were limited in the sense that it was not possible to extract

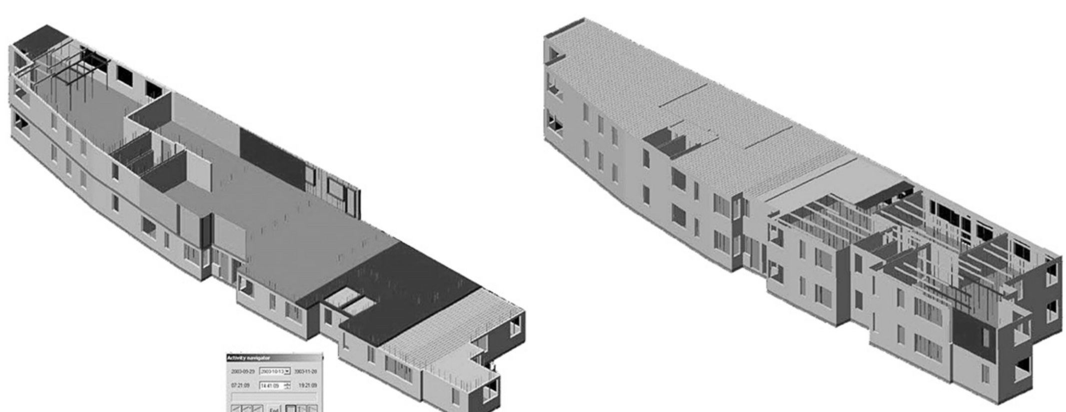

Fig. 1. Snapshots of the 4D models of two construction alternatives. Dark grey elements are ongoing at the time of the snapshot. Left: the traditional construction alternative. Right: the industrialized construction alternative. The industrialized construction alternative shows higher progress compared to the traditional construction alternative.