A method for planning of work-flow by combined use of location-based scheduling and 4D CAD

Rogier Jongeling *, Thomas Olofsson

eBygg Center, Civil and Environmental Engineering, Luleå University of Technology, Luleå, Sweden

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Abstract

There is a great potential to improve the flow of resources through locations on construction sites, termed work-flow. Current activity-based scheduling techniques do not provide adequate support for the planning of work-flow due to practical and methodological reasons. Location-based scheduling techniques provide a promising alternative to activity-based scheduling techniques for planning of work-flow. However, neither location-based nor activity-based scheduling techniques provide users with insight in the spatial configuration of scheduled construction operations. A technique that can provide this insight is 4D CAD in which 3D CAD models are combined with data from construction schedules. This article presents a process method for the planning of work-flow by combined use of location-based scheduling and 4D CAD. We suggest that a location-based approach to 4D CAD can improve the usability of the 4D CAD models for work-flow analyses. In addition, the article suggests that 4D CAD can enhance the value of location-based schedules.

Keywords: 4D CAD; Location-based planning; Work-flow

1. Introduction

Construction planners need to carefully design a process that ensures a continuous and reliable flow of resources through different locations in a project. The flow of resources through locations, termed work-flow, and the resultant ability to control hand-over between both locations and crews, greatly empowers the management of construction from the perspective of day-to-day management of activities [1]. There is a great potential to improve the work-flow on construction sites. A major in-depth study of seven Swedish construction projects reveals that only 15–20% of a construction worker’s time is spent on direct work [2]. Approximately 45% is spent on indirect work (preparations, instructions, getting material, etc.). The remaining 35% is spent on redoing errors, waiting, disruptions, etc., i.e. a complete waste of time. We believe that managing the flow of work by improved planning methods can significantly contribute to the reduction of waste in the construction process.

The planning process in the construction industry is mainly focused on organizations and work breakdown, taking the work-flow and supply chain management more or less for granted. Today’s commonly used technique to schedule the construction process is the activity-based critical path method (CPM). Construction planners decompose a project into activities that they associate with one or more building components (e.g. casting of concrete floor 3) that make up the project. Each activity is included in a bar chart and a network that describe the proposed schedule of a project. This practice builds on the assumption that progressive subdivision of work-scope eventually turns into specification of how construction tasks should be executed [3]. Some construction planners use the CPM method to integrate the product (i.e. what is to be done) with the process (i.e. how it is done), but this leads to very detailed CPM schedules that are difficult to use and to update [4]. As a result, detailed schedules are often not updated during a construction process and thereby lose their value as an instrument to plan and control work-flow. Kenley [1] illustrates the difficulties with the manipulation of information in a detailed schedule with the following example: a 50-floor building with 10 apartments involving 50 activities necessitates
managing 25,000 individually scheduled activities. Such a schedule is possible to set up, but difficult to analyze and manipulate.

Another difficulty with the current use of the CPM scheduling method for construction planning is related to the spatial configuration of a project. Construction projects have unique spatial configurations and the spatial nature of projects is very important for planning decisions [5]. The CPM schedule does not provide enough information pertaining the spatial context and complexities of the project components [6]. Therefore, to identify the spatial aspects of a project, users must look at 2D drawings and conceptually associate the building components with the related activities from the CPM schedule. Interpreting detailed CPM schedules in combination with 2D drawings can be a cumbersome process, which limits the possibility to identify opportunities, problematic sequences or mistakes. Different project members may develop inconsistent interpretations of the schedule when viewing the CPM schedule and 2D drawings. This in turn makes effective communication among project participants difficult.

A promising approach that combines planning data and spatial data in one environment is 4D CAD. 4D modelling is a process method in which 3D CAD models are visualized in a 4-dimensional environment. 4D CAD models allow project planners to simulate and analyze what-if scenarios before commencing work execution on site [7]. Planning supported by visual analyses of 4D CAD models is considered more useful and better than traditional planning [8,9], but does not provide insight in the flow of resources through specific locations in a construction project. Research and application of 4D CAD to date has been dominated by the linkage of 3D CAD building components with activity-based planning approaches, such as CPM schedules. The difficulty of applying flow-based thinking in such models arises from the problem that the models are based around discrete activities. An additional problem is the fact that 4D CAD models often are not organized according to a location-based logic, which further constrains the application of flow-based thinking.

This article suggests that location-based scheduling provides a promising alternative to activity-based planning approaches for planning of work-flow with 4D CAD. A location-based approach to 4D CAD could also improve the usability of the 4D CAD models for work-flow analyses. In addition, the article suggests that 4D CAD can enhance the value of location-based schedules. The article first discusses location-based scheduling techniques and 4D CAD in further detail, after which results from a case study are presented in which both methods are combined. The article continues by proposing a process method for the combined use of location-based scheduling and 4D CAD. This section is followed by discussions and recommendations for further research.

2. Scheduling methods for construction

Two main methodologies for scheduling construction work can be identified: activity-based scheduling and location-based scheduling. As noted in the introduction of this article, activity-based scheduling is the dominant scheduling method in construction today and is, as a consequence, the basis for today’s 4D CAD models. Activity-based scheduling methods are well-suited for processes that are dominated by complex and sequential assemblies of pre-fabricated components, involving discrete activities on a predestined discrete location. However, many construction projects have a different character. They typically consist of large amounts of on-site fabrication, which involves continuous or repetitive work at different locations. These characteristics of construction align more closely with location-based scheduling [1].

2.1. Location-based scheduling

Location-based scheduling is not a new concept and has been a research issue for many years. Practical use in construction has been limited, mainly due to the strong tradition of activity-based planning and the absence of software packages that support location-based planning. Research and development regarding the location-based scheduling method has been carried out since the 1940s and variations of the method appear in literature under different names, such as ‘Line-of-Balance’, ‘Flowline’, ‘Construction Planning Technique’, ‘Vertical Production Method’, ‘Time–Location Matrix Model’, ‘Time–Space Scheduling Method’, ‘Disturbance Scheduling’, and ‘Horizontal and Vertical Logic Scheduling Logic for Multi-Story Projects’ [1,10,11]. In this article we adopt the Line-of-Balance scheduling technique as an example of a location-based scheduling method.

Line-of-Balance is a visual scheduling technique that allows the planner to explicitly account for flow of a project [12]. Line-of-Balance uses lines in diagrams to represent different types of work performed by various construction crews that work on specific locations in a project. Examples of Line-of-Balance diagrams that are created with the commercial software package DYNAProject are shown in Fig. 1.

Scheduling a project with Line-of-Balance begins by breaking down the project in physical sections (i.e. locations), such as for example ‘location 1’ included in ‘building A’, which is part of ‘project X’. Creating tasks in the schedule (i.e. lines) is done by using items from the bill of materials or cost estimate in a project [13]. For example, from the bill of quantity item ‘concrete floor 1’ the following tasks are derived: ‘install shoring’, ‘install formwork’, ‘install reinforcement’, ‘pour concrete’ and ‘remove formwork and shoring’. In this way a specification is directly made for the amount of work per location in a project for a construction crew. Based on these quantities and task description, the required crew size can be determined. The bill of quantity items and cost estimate define what should be done and the tasks in the Line-of-Balance schedule define how this is done. As noted in the Introduction section of this paper, this relation is often not explicitly made in CPM schedules [3] and when done so it leads to very detailed and unmanageable schedules [1,4].

Two main principles are used to minimize the deviations listed in Fig. 1 and to plan for work-flow with Line-of-Balance diagrams: synchronization and pacing.
Synchronization means that planners aim to achieve a similar production rate for all activities. A synchronized schedule can be identified by parallel lines that show a constant time–space buffer between different tasks.

Pacing means that the activities are scheduled to continue from one location to another without interruptions.

Fig. 1 shows the most common deviation types that can be identified by using Line-of-Balance diagrams. These deviation types indicate scheduling mistakes and opportunities to plan for a stable and continuous flow of work through locations of a project. Fig. 1 summarizes the deviation types in one Line-of-Balance diagram and for a more comprehensive overview of deviations we refer to Seppänen and Kankainen [12]. Identifying deviations that can affect the work-flow and manipulating the schedule to address these issues is much easier and more feasible compared to the use of activity-based scheduling methods, such as CPM.

It appears that the Line-of-Balance technique entails useful mechanisms for the planning of work-flow. However, the method does not explicitly address the spatial configuration of activities. In order to identify what building components are related to an activity, users still have to look at 2D drawings to understand the spatial implications of an activity. This process is prone to errors due to the fact that different users may develop inconsistent interpretations of how activities are related to building components shown on different 2D drawings. The locations in the Line-of-Balance diagram provide some spatial information, but these are abstract representations of the real world. Spatial configuration of a project is often much more complex than the hierarchical location structure of a Line-of-Balance diagram.

In summary, Location-based scheduling based on the Line-of-Balance technique appears to provide better characteristics to plan work-flow, compared to activity-based scheduling techniques. Combining Line-of-Balance with 4D CAD could add spatial insight in the planning of work-flow that could add to the quality of the process design. We first discuss the current practice regarding 4D CAD before combining the Line-of-Balance technique with 4D CAD.

2.2. 4D CAD models today

4D CAD models are typically created by linking building components from 3D CAD models with activities that follow from CPM schedules. Building components that are related to an activity, which is ongoing, are highlighted. The 4D CAD model provides the user with a clear and direct picture of the schedule intent and helps to quickly and clearly communicate this schedule to different stakeholders in a project. This is the main area in which 4D CAD currently is used; to communicate schedule intent, often at a macro-level, in a project.

The use of 4D CAD to plan work-flow on site is very limited. The limited use is due to several reasons. First of all, planning of work-flow with 4D CAD models that are based on CPM schedules requires detailed 4D CAD models. This implies two practical limitations. A detailed 4D CAD model requires a detailed CPM schedule, which in its turn is difficult to manipulate. The 4D CAD models themselves are also difficult to update to reflect the latest version of the schedule. Therefore most of today’s 4D CAD models are made once and not updated.

Secondly, the 3D CAD models on which most of today’s 4D CAD models are based, are limited to building components. Building components are in many cases useful and sufficient as an information carrier in a 4D CAD model that is used to communicate a master schedule. However, planning of work-
flow with a 4D CAD model requires additional objects that are not included in most of today’s 3D CAD building models. A concrete slab for example requires one 3D object for every concrete pour. In most cases the whole slab comes as one object in the 3D CAD building model thereby limiting the visualization of work-flow in 4D CAD. Further detailing is needed of the building model to suit the level of abstraction for simulation of the construction process. Research by Akbas [5] demonstrates that this process can partly be automated by defining sub-systems in a 4D model (e.g. a concrete slab) for which users define crew parameters and geometric work-locations. Triangle meshes are used to simulate and visualise the work-flow of construction crews in a 4D CAD model.

Thirdly, many aspects of construction activities are not directly related to building components, which further complicates the use of 4D CAD models for the planning of work-flow. Casting a concrete slab for example requires, among other things, temporary structures in the form of shoring and formwork. The activities in the casting process also require spaces for crews to work and to temporally store and manage materials and equipment items that are used. These aspects affect the flow of work on construction sites, but are difficult to include in 4D CAD models.

In summary: 4D CAD models provide planners with a spatial insight in the scheduling process of construction operations which is not provided by using 2D drawings in combination with CPM schedules or LoB diagrams. The possibility to plan work-flow with today’s common 4D CAD models is limited and requires a different approach to creating and managing 4D CAD models.

2.3. Summary of scheduling methods

The main advantages and limitations of today’s CPM and Line-of-Balance scheduling methods to plan work-flow are summarized in Table 1.

The combination of location-based planning by applying the Line-of-Balance technique in combination with 4D CAD could be a promising method in which the strengths of both methods could reinforce each other. To explore the possible benefits and shortcomings of this combined method a case study was set up as part of a course in Virtual Construction at Luleå University of Technology, Sweden. We worked together with a number of M.Sc. and PhD. students and experts from the industry during this course in which both methods were combined and applied in a virtual construction project. In the next section the method and main results are presented.

3. Line-of-Balance combined with 4D CAD — case study

3.1. Introduction

The case study is based on a 3D model of a planned cultural centre in the city of Luleå, Sweden, see Fig. 2. At the time of our research, there was a 3D model available from an architect and the tender for construction work was in

![Fig. 2. A 3D CAD model of the cultural centre in the city of Luleå, Sweden.](image-url)
preparation. Where possible the course work was based on actual data from the project, but most of the scheduling data and construction methods were assumed for exploratory purposes.

The building consists of a two-storey underground parking garage and a superstructure that contains, among other things, a library and a concert hall. The work was limited to scheduling with the Line-of-Balance technique and simulation with 4D CAD of the superstructure, excluding the roof. This included the scheduling and simulation of floors 3, 4, 5 and 6 of the building, shown in Fig. 2. The superstructure consists of cast-in-place concrete slabs that are supported by prefabricated concrete columns and walls. In addition to bearing walls and columns, each floor contains non-bearing walls and interior objects, such as railings, fittings, etc.

3.2. Preparation of location-based 3D CAD model

The architectural CAD model, received from the architect, was transferred from ArchiCAD to AutoCAD Architectural Desktop (ADT) via an IFC2x file [14]. The architectural model was prepared in ADT for use in combination with the Line-of-Balance diagrams and for the subsequent use in Commonpoint 4D (CP4D). CP4D is a software used to link schedule data to 3D CAD components. An important step in preparation of 3D CAD models for 4D simulation is the definition of locations. The location-hierarchy of the CAD model and the Line-of-Balance diagram had to be identical to be able to benefit from the combined use.

The casting work on each slab was divided into seven sections, shown in Fig. 3. This required the splitting of the single slab from the architectural model into seven independent objects. Other objects, such as bearing and non-bearing walls, were also divided into seven sections, but these components did not exactly follow the section boundaries that were set up for the concrete slab, due to their supplied component sizes. Certain prefabricated walls for example could not be split and, as a result, overlapped other sections. This is illustrated in Fig. 3 in which walls from Section VII overlap in Section IV and Section VI, marked by circles.

A set of CAD-layers was created in ADT according to the defined locations for the project on which all 3D CAD objects were put. A quantity take-off was made from the 3D CAD model per location, which was exported to MS Excel. In MS Excel the quantity data was prepared for import to DYNAProject in which the quantities were used as a basis for the Line-of-Balance scheduling.

3.3. Scheduling with the Line-of-Balance technique

The scheduling process in DYNAProject started with the creation of a location-hierarchy for the Line-of-Balance diagram. This diagram followed the exact same structure as the defined locations in the 3D CAD model. The quantity data from the 3D CAD model was subsequently imported to the DYNAProject after which the definition of activities started.

Table 2 includes a description of the activities related to the building framework. These activities were followed by installation of windows and non-bearing walls, after which the finishing work was scheduled, such as painting, covering floors and the installation of fittings.

Each activity is based on a quantity take-off item in which certain items can be the basis for several activities. The quantity take-off item ‘Slabs’ for example is used to define the activities for formwork, reinforcement, concreting and floor covering work.

Schedule data was exported to MS Excel after the Line-of-Balance diagram was optimized. The schedule data was then prepared for import to CP4D. The exported schedule data included one activity for every task and for every location. The work-flow which was manageable with twelve lines in the Line-of-Balance schedule resulted in a CPM schedule of over three hundred activities from which it was difficult to obtain an

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Table 2

<table>
<thead>
<tr>
<th>Task in DYNAProject</th>
<th>Layers and objects in ADT and CP 4D</th>
<th>Description and work order</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pillars and dividing walls</strong></td>
<td><strong>Columns and bearing walls</strong></td>
<td>The dividing walls (bearing walls) are part of the building framework and support the slab, together with the pillars (columns). The walls and columns are prefabricated elements.</td>
</tr>
<tr>
<td><strong>Formwork</strong></td>
<td><strong>Slab and space</strong></td>
<td>Formwork is needed to cast the slabs and is installed after the pillars and dividing walls are put in place.</td>
</tr>
<tr>
<td><strong>Reinforcement</strong></td>
<td><strong>Slab</strong></td>
<td>Reinforcement for the slabs is installed on the formwork before the slabs are cast.</td>
</tr>
<tr>
<td><strong>Concreting</strong></td>
<td><strong>Slab</strong></td>
<td>Slabs are part of the building framework and are cast after the formwork and reinforcement are installed. Slabs are supported by dividing walls (bearing walls) and pillars (columns).</td>
</tr>
</tbody>
</table>

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Fig. 3. Top view of floor 4 in the 3D CAD model of the cultural centre. The architectural slab is split into seven sections in which the slab is cast. Certain objects (e.g. bearing walls) do not exactly follow the section boundary and overlap into other sections, marked by circles in the figure.
overview while linking the activities to 3D CAD components in CP4D.

3.4. Simulation of Line-of-Balance diagrams with 4D CAD

The 3D CAD components were exported from ADT as VRML files and imported to CP4D. 4D CAD simulations could be made after the linking process was completed. However, the 4D model was not complete at this point. The 3D CAD components from the building model were not suitable or sufficient to visualize certain activities. The installation of fittings for example required different components than building components, such as walls and slabs. Other activities also required activities that could show ongoing work in a location, rather than ongoing work on a building component. For this reason space objects were created in 3D CAD for every location in the Line-of-Balance diagram that also were imported to CP4D.

The Line-of-Balance diagram was created according to a number of milestones. The diagram was subsequently optimized against the following work-flow related factors, by means of pacing and synchronization:

- Minimizing variation in resource use.
- Ensuring sufficient time and space between different trades.
- Minimizing discontinuities in the work of a trade.
- Avoiding simultaneous work of the same trade at different locations.
3.5. Results from 4D CAD simulations

The first scheduling session resulted in a Line-of-Balance diagram, of which a screen capture of a part of the diagram is included in Fig. 4. The figure shows the following sequential tasks: ‘install formwork’, ‘install reinforcement’, ‘concreting’, ‘erect pillars and walls’, ‘installation of windows’, ‘install stairs’ and ‘plasterboard walls’. The Line-of-Balance diagram shows that most tasks are continuous activities per floor, but that the work is interrupted when crews move to a higher floor. The reinforcement task shows two minor interruptions on floor 5 and was later adjusted to create a continuous flow. The concreting tasks are scheduled per section, due to the fact that the casting work cannot be executed as a continuous flow for a whole floor.

When the schedule was simulated in 4D CAD a few planning issues were identified that did not become apparent from the Line-of-Balance diagram. From the simulation it became clear that construction tasks at the beginning of week 7 in 2006 were planned with too little consideration of required work- and buffer-space between different activities. The concurrent tasks at this point in time are marked by circles in Fig. 4.

Fig. 5 includes screen captures from the 4D CAD model which shows that many different activities are concentrated around Section I–III on different floors of the building. Work on the building structure is ongoing on floor 5 in Sections I–III and windows are installed at the same time on floor 4 in Sections I and II. In addition, stairs are installed on floor 3 in Section II. This concentration of activities is not apparent in the Line-of-Balance diagram and could have disrupted the work-flow of construction crews. The use of 4D CAD in this case was beneficial as it provided a spatial insight in the Line-of-Balance diagram. After the 4D CAD simulations the tasks for the installation of windows and stairs were rescheduled to a later point in the project and evaluated by updating and simulating the 4D CAD model.

4. Proposed process method

Based on the findings from the case study and theoretical studies we propose the following process model for the planning of work-flow in construction, which includes model-based methods for cost estimation, production planning and simulation. The process model is based on the combined use of location-based scheduling and 4D CAD.

The process is described using the IDEF0 technique, see Fig. 6. IDEF0 is a structured technique that combines graphical language with text-based descriptions [15]. Each process in a system is represented with a rectangular box and the relationships of the boxes are shown by arrows. Four types of arrows can be identified: Arrows that enter a box from the left side are the inputs for a process. Arrows that leave box from the right side are the outputs of a process. Arrows that enter a box from the bottom side are the mechanisms of a process and the arrows entering a box from the top are the controls of a process.

Five main processes are identified within the planning process. The first process concerns the preparation of location-based 3D CAD models. The definition of locations is an important step in the process as it is the basis for the 3D CAD model, the Line-of-Balance diagram and 4D CAD model, but also for the location-based quantitative take-off and cost estimation. The preparation of location-based 3D CAD models also includes the modelling of space objects that can be used to represent activities in the subsequent 4D CAD model that are...
indirectly related to building components or that represent the work in certain construction zones.

The second process is the cost estimation process. Input for this process is the location-based 3D CAD model (i.e. location-based bill of quantities). The cost estimation is made by defining recipes for building components. Each recipe includes methods (i.e. a number of tasks) and resources (e.g. man hours) needed for a building component. A recipe for a cast-in-place concrete wall for example includes methods such as ‘install formwork side A’, ‘install reinforcement’, ‘install formwork side B’, ‘cast concrete’ and ‘remove formwork’. For each of these tasks it is known, based in historic data, how much resources are required. The output of the cost estimation process is a location-based 3D CAD model with recipes specified for each 3D CAD object. This model is the input for the third process, which is the planning process with the Line-of-Balance technique.

The third process involves the definition of tasks in the Line-of-Balance diagram by using the methods that are defined in the 3D CAD model during the cost estimation process. The Line-of-Balance diagram is structured according to the exact same location-hierarchy as the 3D CAD model and cost estimation. By using the Line-of-Balance technique planners can optimize the flow of resources through locations in a project by synchronizing and pacing the scheduled tasks in the diagram.

The results of the third process are used in the fourth process in which 4D CAD models are created. The 4D modelling process includes linking of tasks from the schedule to building objects and spaces from the 3D CAD model. This process can be automated with appropriate mechanisms as each task is associated in the schedule with objects from the 3D CAD model. The 4D modelling process results in 4D simulations and 4D content. 4D content is defined as quantitative data extracted from 4D models to support 4D-based-analysis of construction planning information [16].

Visual and quantitative analyses are made of the 4D CAD model in the fifth process which can result in suggestions for improvement for the 3D CAD model or the Line-of-Balance diagram. This is an iterative process in which processes one to five are repeated until a construction schedule emerges that ensures a continuous and reliable flow of resources through different locations in a project.

5. Discussion and further research

The case study shows that the combined use of location-based scheduling and 4D CAD is a promising mechanism to plan for work-flow. The specific planning decisions and structure of the 3D CAD model and Line-of-Balance diagram of the presented case study are hypothetical, but show a planning process that does not occur in today’s construction planning. Reasoning, such as analyzing distances between different tasks and rerouting tasks, is done in actual production where there is a limited opportunity to change construction execution strategies, especially in cases where much of the work is handed out to subcontractors. This leads to waste in the form of waiting by crews, rework and disruptions. We believe that managing the flow of work by combining 4D CAD with location-based scheduling methods can significantly contribute to the reduction of waste in the construction process.

The Line-of-Balance technique allows planners to quickly gain insight in the flow of resources through locations in projects. The visual representation of scheduled tasks requires minimal effort to manipulate a schedule, when for example the work of a crew has to be rerouted through different locations of a project. Compared to activity-based methods, such as CPM, the Line-of-Balance method facilitates the planning for work-flow. The method can also be a good basis for the planning of work-flow with a 4D CAD model as a result of the integration of schedule data and 3D CAD object data. This tight integration addresses some of the current limitations related to the creation and manipulation of a 4D CAD model and facilitates the process of rescheduling and updating a 4D CAD model.

The 4D CAD model is a valuable supplement to the Line-of-Balance diagram as it allows users to quickly and clearly gain insight in the spatial configuration of scheduled activities. The 4D CAD model of the case study showed for example the concentration of different activities in one corner of the building on multiple floors, resulting in a lack of work-space and hazardous conditions for crews to perform safe and productive work. This concentration did not become apparent from the Line-of-Balance diagram, but could be detected by using the 4D CAD model that was based on the Line-of-Balance diagram. The case study also showed that the use of a 4D CAD model provides insight in the relation between the location-hierarchy and building components from the 4D CAD model. Certain types of building objects partially overlapped multiple locations. This insight could not be gained from the Line-of-Balance diagram, but became clear from the 4D CAD model. The combined use of location-based planning and 4D CAD reinforces both methods and forms a promising toolset to plan for a reliable and continuous flow of resources through locations in a project.

The proposed planning method is best initiated in the early stages of a project. Project actors have to agree at this stage on a hierarchical decomposition of the project into locations by which the 3D CAD models, cost estimation, construction planning and 4D CAD models will be structured. Furthermore, a tighter integration between design and production planning in the early stages of a project creates opportunities for constructability analysis, prefabrication of components and selection of proper work methods with regard to the available work space. Early definition of these locations can also facilitate the data transfer between different types of systems that are used in the design, cost estimation and planning process. The case study showed that the proposed method can be implemented by using a number file transfers between different commercial software systems. The data transfer- and data modelling process can be streamlined and automated by standardizing the data content and by using the same source data, such a shared project database. We believe that dedicated software packages for a number of different professionals (i.e. CAD consultants, cost estimators, construction planners, 4D modellers, etc) should be
integrated, rather than developing a single software system to perform all tasks.

Although the Line-of-Balance method is a mechanism to plan how a construction task will be performed, it does not provide the user with a clear picture whether a task can be performed. Examples of prerequisites for successful execution of a task are [17]: the availability of information, equipment, space, material and labour. It is also important that the work by the previous crew is completed. Managing these conditions implies continuous monitoring and manipulation of schedules and 4D CAD models. Mechanisms should also be available that allow planners and crews to manage the prerequisites for an activity throughout the combined use of location-based scheduling and 4D CAD models. The presented case study is limited to the planning for work-flow and does not address the control of work-flow. Further research is required in which the principles and criteria for efficient and effective work-flow management are studied, as for example suggested by Koskela [17], in relation to the use of location-based scheduling and 4D CAD. Kenley [1] suggest the use of Line-of-Balance schedules for micro-management of work-flow on site by explicitly addressing the requirements from the site personnel. It is suggested to further explore the concept of micro-management based on Line-of-Balance schedules in relation to the use of 4D CAD models.

The results from a 4D CAD model are currently mainly used for graphical analyses. When construction planners visually evaluate the 4D CAD model, they may or may not detect constructability issues, such as time-space conflicts, that can jeopardize the work-flow. Planning supported by visual analyses of 4D CAD models is considered more useful and better than traditional planning methods, but does not take advantage of the qualitative data contained in 4D CAD models [16]. Further research is required to study what 4D content can be extracted from 4D CAD models and how this can be used for quantitative analyses in the planning and control process for work-flow. One obvious extension is the management of the supply chain to the building site. Since the proposed production planning process connects the building objects with location and time, material delivery schedules can be automatically produced. These schedules can be used for procurement and call orders from suppliers of components and material to the building site to get a better integration of the supply chain of materials with the work-flow at the building site.

In the case study it was illustrated how an architectural 3D CAD model can be prepared for the simulation of construction operations in 4D CAD. The preparation process entailed the definition of locations and the modelling of objects to represent locations. The locations were subsequently used to represent tasks with an indirect relation to building components, such as the installation of formwork. Although the use of space objects is considered a promising technique to represent the location of a task, it is not clear what type of space is represented. The space usage on construction sites can be classified into different types of spaces. Akinci et al. [18] identify for example the following different types of spaces and models these space-types in a 4D CAD model: building component space, material space, labour space, equipment space, space for temporary structures and hazardous space. We believe that the management of work-flow should include the management of different space-types, in addition to the management of resource-flow through locations in a project. Space is in this respect considered as a resource that is related to a location and a task in a project. Currently, Line-of-Balance schedules concentrate on the scheduling of crew locations and do not specify the types of space that a location includes (e.g. equipment space, labour space and material space) or how the use of one location results in space requirements for another location. An activity on a floor might for example create a hazardous situation for the execution of construction work in a location on a floor beneath. We suggest further research to study the use of the Line-of-Balance technique in combination with 4D CAD to plan and manage space use as part of the work-flow management on construction sites. The work-flow management should not be limited to avoiding discontinuities and time–space problems that can negatively affect the work-flow, but should also include the identification of scheduling opportunities that can benefit the work-flow.

References


