Construction Analysis during the Design Process

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Abstract: 4D CAD systems are used by contractors for visually checking the construction process. To enable simulation of the construction process, the construction planner links building components from a CAD model with the activities from a project planning. In this paper we describe a method to generate a project planning directly from a CAD model using basic construction knowledge. A case study is discussed briefly to show the current results and the shortcomings. Finally an outlook is presented on a more advanced implementation that is (also) useful for designers.

1 INTRODUCTION

Traditionally, construction planning is a critical factor in building management. The construction planner, employed by a building contractor is a person with much experience in building construction that knows how to estimate the required labour and equipment from a building design. Using this knowledge a construction planning is created as the leading schedule for other derived plans such as transport, measurement, safety, etc. Project plans are constructed completely manually or using a specific tool like MS project or Primavera.

Due to its critical factor, many research efforts have been directed to simulation of the building process using the planning, to visually or computationally search for conflicts or errors (Dawood et al. 2003, Mckinney and Fisher 1998). From this research, 4D CAD systems have emerged, like InVizn®, Navisworks® and 4D Suite®. These systems support the planner by relating building components from a 3D CAD system with construction activities from a project planning system, using a graphical interface. The construction process can then be simulated by executing the planning and the user can visually check how the process proceeds. 4D CAD systems can by used for construction analysis and communication. Experiences in practice by Mark Clayton and Marcel Broekmaat have learned that 4D CAD reduces the number of activities on the critical path, distributes the equipment more evenly, allows for more flexibility in time and reduces planning mistakes (Clayton et al. 2002, Vries and Broekmaat 2003).

Even when using 4D CAD systems, the planning expert still plays a crucial role. It is him who manually relates building components to construction activities and who visually tests whether problems occur during the construction process. 4D CAD systems don't bear any knowledge about the construction process itself. More advanced systems support collision detection, but there is no mechanism for expressing constraints and dependencies, and to test whether they are violated in the construction process.

In our research project we took up the challenge to automate the planning process, being well aware that a completely automated procedure is probably not feasible. However, this proposition allows us to investigate which construction knowledge can be derived from common sense or physical laws, which knowledge is construction method dependent, which knowledge is building component dependent and which knowledge cannot be described by the previous methods and thus remains. For knowledge representation we initially follow a computational approach to research how far this method can bring us in producing a reliable planning. A limited pilot study is executed to test the results against current planning practice. In this paper we report on the construction algorithms we investigated and how well they performed in the pilot study. Finally we will discuss which deviations were found and how we think we can extend our system to produce a more reliable planning.

2 CONSTRUCTION ALGORITHMS

A construction algorithm encapsulates construction knowledge. Construction knowledge can be divided in knowledge about structural behaviour and knowledge about construction methods. Structural behaviour is determined by physical laws, construction methods are determined by the building products and the construction equipment. For now, we assume that the construction method is fixed, which does not mean that our automated planning can only handle only one construction method. We will come back to this issue in discussion section. Provided the construction method, yet multiple construction processes or in that case, construction orderings are possible. In this section we will discuss which computation methods are available for calculating the construction order of building components and how these methods perform. An excellent overview of ordering methods is presented by Johnson et al. (2004). They discriminate between ordering by element type, by elevation, by joint configuration, and by tracing from foundation. The authors were not able to identify an algorithm that worked in a consistent, generalized manner. The methods flawed for special cases. They conclude that only Finite Element Analyses can solve this problem. Different form their research however, we do not aim at an abstraction for structural analysis, but for construction analysis. Therefore we have researched algorithms that analyze the topology of a building construction. Before that we will briefly discuss the basic principles for 3D geometry representation of building components, since this representation strongly affects the algorithmic approaches.

2.1 3D Representations

In building practice line drawings are still widely used. Recognition of building components from line drawings is in its infantry and is not considered in this research. Increasingly, architectural and engineering offices produce 3D models using surface modelling and/or solid modelling. With solid modelling structural properties like inertia and volume are ready available. CAAD systems typically contain a library of building components that can be adjusted to the designer’s needs. Building components (e.g. wall) can provide additional (e.g. material) and derived data (e.g. surface area).

2.2 Object Topology Analysis

Instead of calculating the vertical load distribution to find out which component bears another component, it is also possible to use the geometric data of the model. More specifically the topology of the building can tell which component is on top of or next to another component. Under the assumption that a 3D CAD model is available, we investigated two approaches for topology analysis, namely 3D box representation and 3D solid representation. The results of the analysis should be a directed graph, stored in a log file. In this graph the nodes represent the building components and from each node the edges point at components that are underneath or besides.

2.2.1 3D Box Representation

The original 3D model is subdivided into a 3D grid. Building components represented as boxes, can occupy one or more grid cells. A useful grid size is 20 cm. (Bax 1976), because the dimensions of many structural components as they are delivered on the building site can be approximated without obtaining incorrect results with the ordering algorithm. First, the algorithm will test each component if any of the grid cells is vertically adjacent in one direction to other grid cells of other components. If so, these vertical relationships will be registered in the log file. Secondly, for those components whose grid cells don’t have any vertical adjacent neighbours, it will search for horizontal adjacent components in all four directions. These horizontal relationships are also registered in the log file.

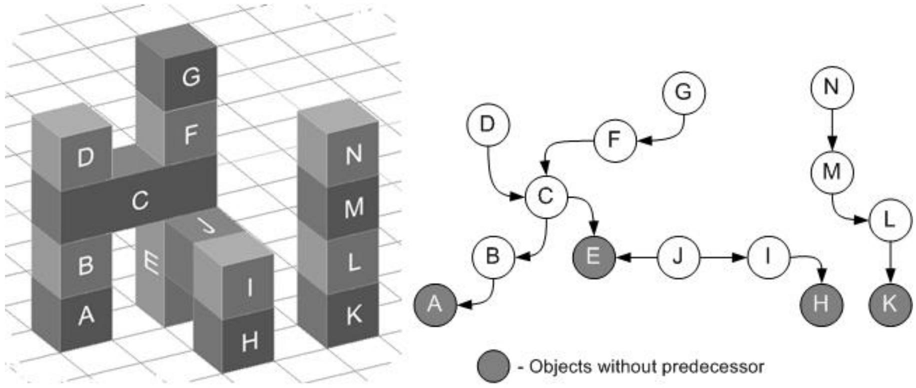

Figure 1 3D grid and Graph schema

Although, this is a very elegant method that can process any 3D CAD model, it causes serious problems in terms of memory management. The minimal data needed are the cell centre coordinates for the occupied grid cells. Even a computer with a big RAM will fall short due to the memory demand of millions of grid cells for an average building model. External storage could solve this problem, but will slow down the computation process dramatically.

2.2.2 3D Solid Representation

The original 3D model is converted into a solid model. First, each solid component is displaced vertically over a short distance (10 cm.) in the negative direction. After a displacement the Constructive Solid Geometry (CSG) intersection operation is used to find out which other component are intersected. Secondly, those components that did not vertically intersect any other component, they are displaced horizontally in all four directions. Again, the intersection operation is executed to find out what the neighbouring components are. From these results, like with the 3D grid, the vertical and horizontal adjacency relationships are stored in a file for each component.

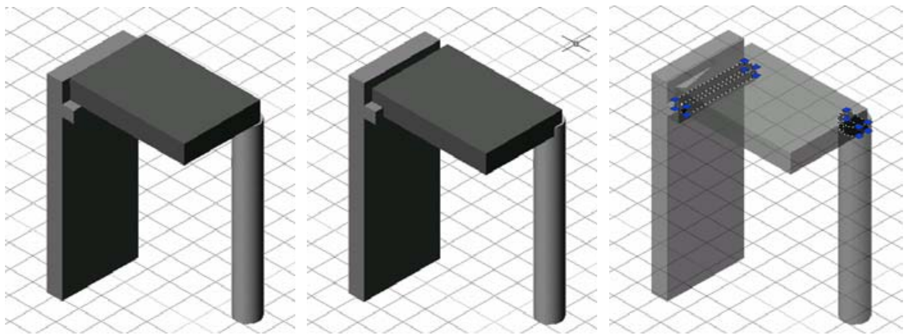

Figure 2 3D solid displacement and intersection

This approach requires significantly less storage capacity and computing power, but is only applicable if a conversion to a CSG model is supported by the CAD program. Unfortunately this is not always true, often even not for all drawing entities within one CAD program.

3 IMPLEMENTATION

The construction analysis is preceded by the creation of a 3D model using a CAD program (e.g. Autocad/ADT). The construction analysis program imports the 3D model and calculates the vertical and horizontal relationship between the building components as described in the previous section. At the same time it must also calculate the duration for the construction of a component. Therefore it uses a database of available equipment and labour, and formulas for the duration calculation expressed in XML. Identification of the construction component type is established in the current implementation by placing a component on a CAD layer with the right component type name. In the generated log we find for each building component, its name, the duration of the construction and a list of components that it is horizontally or vertically related to. A project planning program (e.g. MS project) is used to import the log file and create a planning schema from it, i.e. all components will be ordered subsequently and the appropriate recourses (equipment and labour) will be allocated. The project planning program is also used to create PERT diagrams and for the calculation of the critical path.

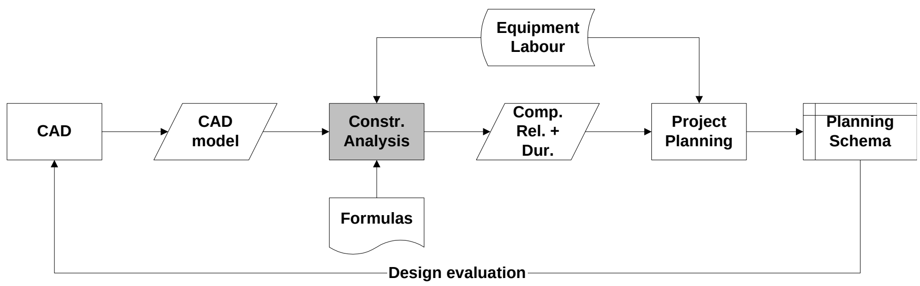

Figure 3 Process model

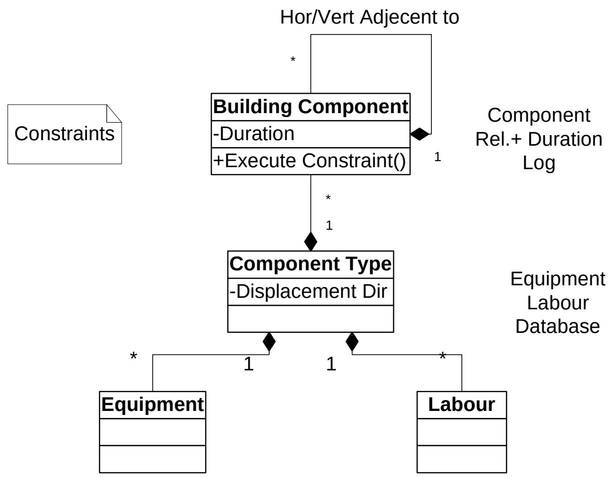

Figure 4 Data model

For the calculation of the construction duration of a component, available literature resources are used that contain reference data about construction time as a function of component volume, applied equipment and applied labour capacity (Misset 2003). The volume is calculated using the CSG function from the CAD system. The calculation formula is described as constraints using XML. External storage of this construction knowledge and reference data allows for adjustment to the needs and experiences of the users.

The construction analysis program (Figure 3), implemented in Autocad-Visual Basic for Applications (VBA), generates horizontal and vertical relationships using the 3D solid representation method in the current implementation as described in Section 2.2.2. A building component can occur in three situations: (i) only vertical relationships (e.g. walls, floors), (ii) only horizontal relationships (e.g. balconies) and (ii) vertical and horizontal relationship (e.g. stairs). To reduce the number of displacements during the construction order analysis, each component type is labelled with a displacement-direction attribute, indicating which displacement is appropriate.

4 PILOT STUDY

The case study (Figure 5) is the construction on an office building for the municipality in Amsterdam. From this project the 3D CAD drawings and the construction planning were available. The construction is combination of prefabricated components (e.g. beam) and in-situ construction components (e.g. the facades).

Figure 5 Building for Case Study

4.1 3D CAD Model Preparation

Despite the availability of 3D drawings, created with Autocad - Architectural DeskTop (ADT), the CAD model was not ready for use in our construction analysis system. The ADT component type classification (see Figure 4) is not appropriate for linkage with the equipment and labour reference database. Therefore all ADT components (i.e. Autocad-objects) are transferred to a layer with appropriate component type name (i.e. Autocad-layer). Two additional computer programs were developed for model preparation. The first program converts the ADT components (e.g. wall, floor, etc.) into solids. Objects that are drawn using functions outside the ADT library will be lost. The second program detects clashes between 3D solid components (Figure 6). Inaccurate drawing of building components will produce incorrect results of the construction analysis program. The clash detection program will generate a list of building components that intersect and thus that must be adjusted to prevent this error.

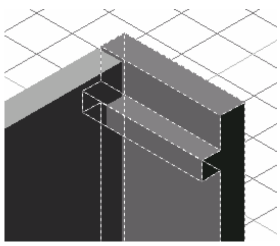

Figure 6 Clash-example

4.2 Planning Generation

After preparation of the CAD model, the generation of the planning is straightforward as described in Section 3. For the case study the equipment and labour database is prepared in XML, listing for each component type the required resources per volume unit. In this test case these data were fixed for each building component. Consequently the system cannot search for construction alternatives. We will come back on this issue in the discussion section. Execution of the Autocad-VBA construction analyses script takes approx. 1 hour for the test case on a standard PC.

4.3 Planning Comparison

For obvious reasons we present here only a small part the whole construction process. A comparison is made between the real planning (Figure 7) and the generated planning (Figure 8) of the concrete construction of the ground floor level.

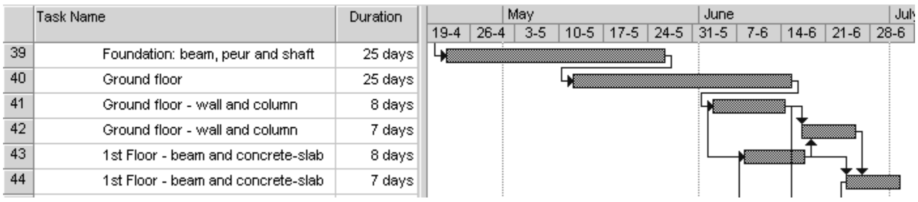

Figure 7 Part of the real planning

First of all we notice that in the generated planning, the construction activities for all individual building components are grouped into bigger tasks. A group is defined as a collection of building components that are constructed subsequently and that share the same resources (equipment and labour). The original, real planning uses a slightly different grouping strategy, based upon experience, to identify the bigger tasks without detailing into subtasks.

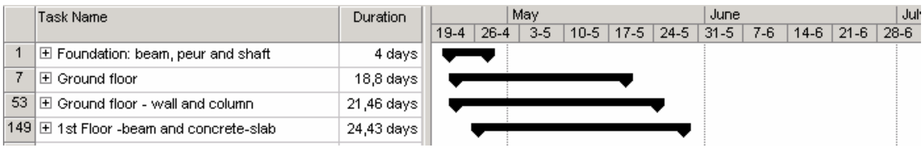

Figure 8 Part of the generated planning

There is a striking difference between the generated duration of the foundation task and the really planned duration. This difference can be explained by two factors: (i) in the generated planning all foundation construction activities can be executed concurrently because of unlimited resources, and (ii) the contractor applied a different foundation technique then the one selected from the resources database.

Another interesting result is that in the generated planning, the construction of the walls and columns of the ground floor starts at the same time as the construction of the ground floor slab. The reason is that the floor slabs are supported by the foundation within the walls and thus a wall component can be put in place before the floor is constructed. Walls and columns construction are completely independent from the floor construction (Figure 9).

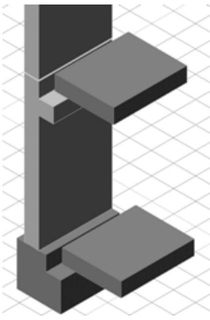

Figure 9 Slab position

Finally, we conclude that the construction order is correct. First the foundation is constructed, then the ground floor and the walls and columns. Shortly after the construction of the ground floor walls and columns, the construction of the first floor can start.

5 DISCUSSION

The current system lacks construction knowledge. The construction analysis program will execute a construction activity as soon as this is feasible. There is no knowledge of equipment and labour capacity, equipment and labour availability, costs, material storage capacity and location, temporary constructions, preferences of the contractor, etc. However, we anticipate that much of this additional contractor specific knowledge can be expressed as constraints in XML.

The outcome of the generated planning sometimes raises questions about the traditional construction method, such as the case of the ground floor slab (in the previous section). This result can be a planning flaw because of lack of construction knowledge (e.g. the floor slabs are required for the craftsmen to position the wall and columns) but it can also reveal new options for concurrent building that we have been unaware of (e.g. wall and column positioning by construction cranes or robots).

Most importantly, the proposed system supports the evaluation of alternative construction methods. After a first analysis using the building components layout as designed and default construction capacity values for equipment and labour, the resulting planning schema can be investigated. In the following evaluation runs all variables (building components, equipment, labour) can be varied to study the effect in time, and required resources (equipment, labour). This is represented by the design evaluation loop back cycle in Figure 3. Even one step further this evaluation process can be extended using optimisation methods from operations research (e.g. linear programming and genetic algorithms). As such the system becomes a construction analysis tool not only for construction planning experts, but for designer also, that want to study the various effects of constructive solutions as part of the design process.

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