30 FORMALIZING DOMAIN KNOWLEDGE FOR CONSTRUCTION ZONE GENERATION

Ragip Akbas, Martin Fischer, John Kunz, Benedict Schwegler

Ragip Akbas
Stanford University Center for Integrated Facilitiy Engineering M:4020 Stanford, CA, USA 94305-4020 - rakbas@stanford.edu

Martin Fischer
Construction Engineering and Management Program Terman Engineering Center, Room 292 Stanford, CA 94305-4020 - fischer@cive.stanford.edu

John Kunz
Stanford University Center for Integrated Facilitiy Engineering M:4020 Stanford, CA, USA 94305-4020 - kunz@cive.stanford.edu

Benedict Schwegler
Walt Disney Imagineering 1401 Flower St. Glendale, CA, USA 91221 - ben@disney.com

Abstract

This paper describes the formal domain knowledge necessary for generation of construction zones. This is a part of our layered approach for automated generation of construction zones from 3D CAD models for construction planning and scheduling. The existence of 3D models and product models provides an opportunity for planners and schedulers to consider zoning alternatives and represent and visualize production information in detail. Construction zones are spaces, or groups of spaces, which serve as units of work in the construction planning process. Failure to define construction zones properly may increase overall project duration and impact workflow adversely. Today, zone definitions are generally ad-hoc. Formal definitions and mechanisms to generate construction zone information in the context of 4D models are not available. We have defined a three-layer computational framework to automate the generation of detailed information about construction zones. The framework separates the construction-based information from the product model representation and geometric information. Each layer is extensible and testable without the other layers. The highest layer contains domain knowledge about zones, i.e., types of zones and factors or constraints affecting construction zone definition. The other two layers manage the changes in the product and process models and manage geometry respectively. The main contribution of this paper is the definition of types and factors affecting construction zones and the use of that knowledge for zone generation.

Keywords: *Zone Generation, Product Models, Geometric Reasoning*

INTRODUCTION

Motivation

To be useful in practice, a construction planning and visualization system with realistic analysis capability requires well-defined construction zones. The crucial problems are the lack of formal zone definitions; the lack of automated zone generation mechanisms and the lack of mechanisms to manage changes in construction zones over time during the project.

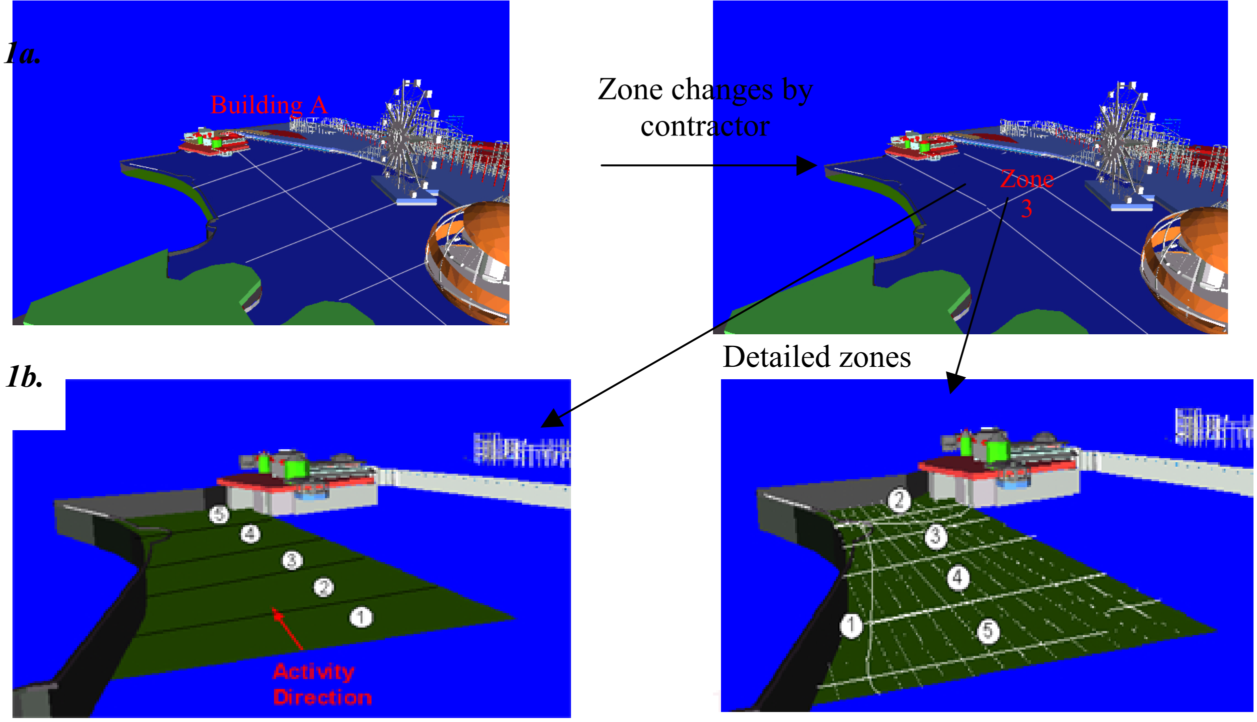
We will illustrate these issues using a sample case from a construction project in Southern California, which used 3D CAD models in their work processes. The project includes a water-reservoir lagoon in the center of the project area. The construction of this lagoon is a challenge because many buildings, which are under construction at the same time, surround it. Additionally, construction of the lagoon is on the critical path of the project because the lagoon needs to be filled with water before some of the facilities surrounding the lagoon can be tested.

Figure 1 shows views of the lagoon during different phases of the project and with different levels of detail. The construction schedule for the lagoon evolved considerably through the different phases of the project. The owner suggested a plan with rectangular zones, starting from one corner, to continue all around the lagoon. However, the construction means and methods were not well defined at this stage. After the bid stage, the contractor decided on the methods of construction for the lagoon by considering the space availability and other constraints around the lagoon. This resulted in the lagoon construction activities in the master schedule, which has six zones defined for the lagoon. Each zone has in turn five activities acting on it.

When construction of the lagoon approached, there was a need for a more detailed schedule for the lagoon. Three-week look-ahead schedules were developed taking resource and space availability and other constraints into account. An example of these constraints is that the steel erection for a nearby building (Building A) requires scaffolding. The construction of the lagoon in that area cannot start until that scaffolding is removed. Many CPM schedules include, of course, these types of constraints. However, we found that some of these detailed production constraints, which often depend on the specific site conditions and geometry of the design, get sometimes overlooked when designs, schedules, and construction methods change. In our experience, visualization of the detailed planned construction progress helps the project team identify missed or misplaced constructions (Haymaker and Fischer, 2001).

The contractor wanted to accelerate the lagoon construction, to make up previous delays. However, this is not as simple as increasing the production rate to decrease the activity durations in the master schedule. There are complex spatial arrangements and constraints that affect the decision. In the master CPM schedule, there was a finish to start sequence relationship between the steel erection of Building A and the lagoon excavation, the first activity of lagoon construction. However, in practice, the *excavation* activity can start from the middle of Zone 3, and continue on close to the location where the scaffolding exists, before the scaffolding is dismantled. This is not obvious in the CPM schedule. So, there needs to be a more detailed representation for work zones for activities.

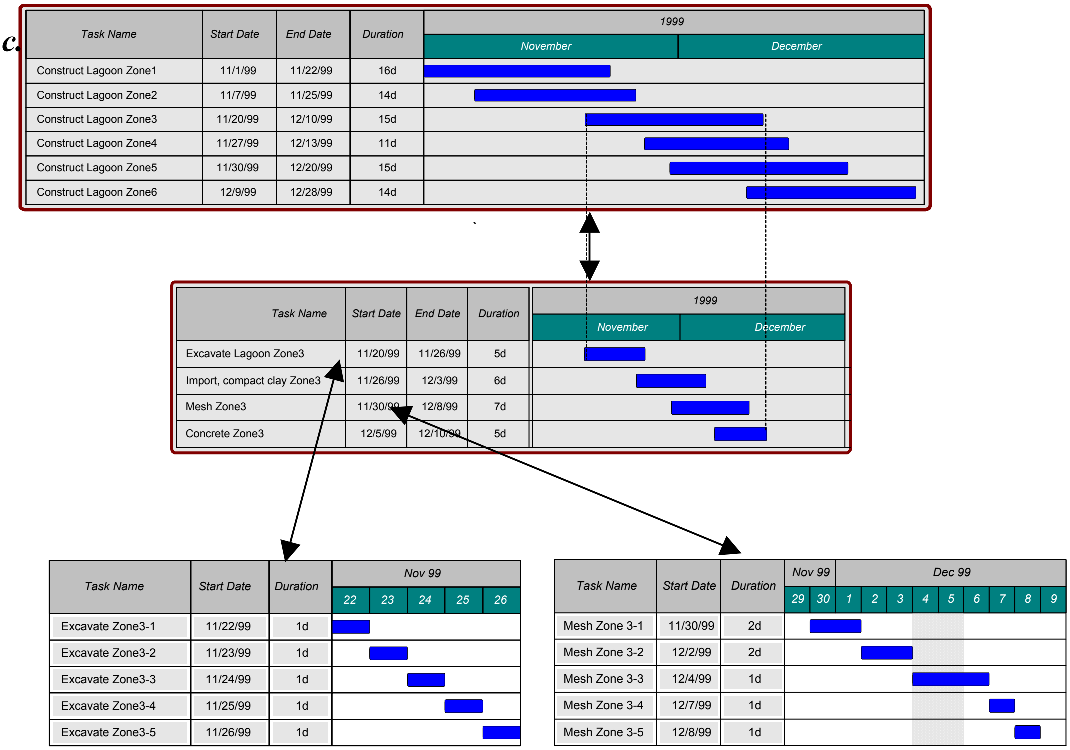
The *Install reinforcing mesh* activity that follows the *excavation* activity has a different construction pattern than the excavation. The activity is performed around the edges first, then moving to the center. The production rate for the activity is slower in areas where the lagoon surface is sloped. The mesh cages come to the site prefabricated to a unit size. These mesh units are to be combined in a way to define daily work zones considering the production rate and the geometry of the final component. Meshing and the other activities that follow excavation can start before the excavation for the whole zone finishes, provided that there is enough buffer preventing conflicts between activities. The contractor at this stage needs a way to compare different alternatives and discuss them with related other contractors. There is no easy way to test different crew compositions and corresponding production rates, activity directions, etc. to come up with a successful detailed schedule that considers site and project-specific geometric constraints.



Related schedules

Related schedules

1c.



Task Name	Start Date	End Date	Duration
Construct Lagoon Zone1	11/1/99	11/22/99	16d
Construct Lagoon Zone2	11/7/99	11/25/99	14d
Construct Lagoon Zone3	11/20/99	12/10/99	15d
Construct Lagoon Zone4	11/27/99	12/13/99	11d
Construct Lagoon Zone5	11/30/99	12/20/99	15d
Construct Lagoon Zone6	12/9/99	12/28/99	14d

Task Name	Start Date	End Date	Duration
Excavate Lagoon Zone3	11/20/99	11/26/99	5d
Import, compact clay Zone3	11/26/99	12/3/99	6d
Mesh Zone3	11/30/99	12/8/99	7d
Concrete Zone3	12/5/99	12/10/99	5d

Task Name	Start Date	Duration
Excavate Zone3-1	11/22/99	1d
Excavate Zone3-2	11/23/99	1d
Excavate Zone3-3	11/24/99	1d
Excavate Zone3-4	11/25/99	1d
Excavate Zone3-5	11/26/99	1d

Task Name	Start Date	Duration
Mesh Zone 3-1	11/30/99	2d
Mesh Zone 3-2	12/2/99	2d
Mesh Zone 3-3	12/4/99	1d
Mesh Zone 3-4	12/7/99	1d
Mesh Zone 3-5	12/8/99	1d

Figure 1*. The construction zones for the lagoon at different phases of the project.*
Figure 1a. shows the phasing plan for the lagoon before (left) and after (right) the mobilization of the contractor
*Figure 1b****.*** *shows the actual construction progress for the Excavate and Mesh activities.*
Figure 1c. shows the schedule for the activities acting on the zones at different levels of detail.

Current Practice

Similar issues exist on many types of projects. In construction projects, there are methodologies to model the process, such as CPM schedules and line of balance diagrams. On the other hand, there are also models to represent the product. A common requirement during planning and scheduling is to match the product and process, i.e., units of work to the work tasks. 4D CAD models provide ways to visualize the construction progress by linking units of work to the work tasks at a certain level of detail (Koo and Fischer, 2000). However, any change in the level of detail of schedule or the geometry requires time-consuming manual updates to the 4D model and the links between 3D components and activities. Therefore it is impractical to consider many alternatives. Nevertheless, the detailed spatial information about the production can be instrumental for communication and analysis.

The definition of activities in a construction schedule does not represent the attributes of component installation, nor has it spatial information, such as the direction of activities or the desired spatial buffers between activities. Because of the lack of techniques that automate some of the model manipulation tasks, it would be impractical today to maintain a construction schedule that contains all the details of a construction site.

A common industry practice to overcome the shortcomings of CPM schedules is to use *look-ahead* schedules to show near-term activities in more detail than the overall schedule. The purpose is to coordinate various resources in a short period of time, e.g., coordinate subcontractors, prevent conflicts, and control material delivery. The activities in these schedules typically relate to specific zones. Several previous research efforts have identified the value and the need for look-ahead schedules. However, they still do not convey any spatial information and the consistency between the overall schedule and the three-week look-ahead schedules is very limited(Ballard, 1997, Hinze, 1998). Site personnel stick to hand-colored blueprints to explain actual or planned work progress. The missing link is the formal and flexible zone definition for each of the work tasks. Construction zone information needs to be generated using method and means knowledge of the contractor. This is a time consuming and error prone task when performed manually. This complex task is further complicated by the need for planning and scheduling at several levels of detail.

A further challenge is that look-ahead schedules are done shortly before the construction, so the opportunities to proactively consider possible problems early are limited. If professionals had a way to generate detailed 4D models rapidly and early on in the construction planning process they might be able to explore production approaches more proactively.

Overall Approach

Our research addresses the issues in the sample case as follows. It works in a 4D CAD environment, where the product model (components with 3D shape representations) is linked to the process model (schedule activities). The lagoon in the sample case is part of the product model received from design as a single building element, with its 3D shape representation. The zone generation mechanisms (*decompose* and *aggregate)* are interactively available to the user. The user can also change the parameters for zone generation, i.e., factors affecting zones. For the excavation activity, in Zone 3, the planner specifies that the activity progresses linearly in 5 sub-zones. The *decompose* operator has multiple effects in the project model. It transforms the lagoon component into lagoon subcomponents and initiates geometric algorithms that subdivide the shape representation of the lagoon. It also acts on the activities in the process model to decompose work tasks for lagoon construction.

For the reinforcing mesh activity, the planner first specifies the unit work size of reinforcing meshes to generate shape representations for groups of meshes based on the geometric representation of the lagoon. Then he uses the production rate and direction of the activity within each zone to manage *aggregation* of reinforcements to get work units of specified duration. The production rate changes locally when the lagoon surface is sloped. Then, the user can visualize the construction process in any level of detail, arrange for material deliveries, or simulate the construction process to explore scenarios with respect to resources, cost, etc.

Next, we define construction zones and zone generation, followed by types and factors.

CONSTRUCTION ZONES

Definition

Construction zones are spaces, or groups of spaces, which serve as autonomic units in the construction planning process (Shaked and Warszawski 1995). We approach zones as a particular reorganization, aggregation or decomposition, of components that relate to a construction process. There is no unified understanding of construction zones in the research literature. However, formal definitions of zones will be increasingly necessary for construction planning as product models are more widely used. Spatial analysis of cost, space conflicts, etc. in 3D, as well as actual progress information requires knowledge of zones.

Several papers have addressed the topic of construction zones. Shaked and Warszawski (1995) defined zones in high rise buildings by their nature, designation and location. *Nature* is the direction of flow, e.g., horizontal or vertical. *Designation* is the function or future use of the zone, e.g., lobby, elevator shaft, mechanical room. Our definitions below extend their definitions. *The nature* definition is a special case of direction of workflow in our research. *Designation* is a special case for zones for phasing plans. Just using the designation is limiting for construction planning purposes, since there might be zones with multiple functions in the final product. For example, Riley and Sanvido (1995), in their research for space planning in multistory buildings, defined work-area patterns to describe the directions for and locations of units of work completed for different activities and materials. These patterns are similar to the activity progress representations in our research.

Zone Generation

We refer to the process of changing the level of detail of the geometry as *zone generation*. There are two possible approaches for zone generation. The first, called *top-down approach*, is concerned with allowing the user to manually define each zone or applying geometric criteria for generation of the zones. An example is the subdivision of space into grids or linear zones. The second is the *bottom-up approach*, which uses construction knowledge and geometry to generate zones automatically. This approach has the ability to consider local geometric factors and interactions.

Some researchers have tackled the zone generation problem before. They were mostly for automated planning and required the user to specify the zones in a top-down fashion. Thabet and Beliveau (1994) defined zones for aggregating components in their KNOW-PLAN geometry-based automated planner. The purpose of their zones is to simplify the planning process by creating sub-networks of activities and constraints within zones. Zones are planned individually in sub-networks, and combined to generate the final plan. The same authors extended this idea in ScaRC (Thabet and Beliveau, 1997) by a hierarchy of work-block structure for zones. However both systems require users to manually specify volumes that form the zones.

Winstanley and Hoshi (1992) use an automated aggregation approach within a model-based planning system, OARPLAN, to create construction zones. They suggest that aggregation should be possible on the basis of physical zones, trades, resource availability, costs and major milestones. Their ZonePlanner system uses the 3D CAD model and productivity and cost data to search for an optimal zoning plan. It considers predefined building blocks to generate the zoning combinations and checks all of these cases for the selection of the most efficient set of zones, by evaluating them with cost and duration criteria. Their system suffers from the necessity to define building blocks for each case a priori and from the combinatorial complexity of testing all the alternatives.

AbouRizk and Mather (2000) use concepts of benches and subgrids to break up the geometry for earthwork operations into equally sized grid pieces. They then attach properties to set the order and the construction method for each subgrid and use this information in an earthwork simulation system. However, there is little flexibility in definition and the order of the grids.

Types of Zones

There are different purposes for construction zone generation such as visualizing detailed progress, defining areas for construction method assignment and making phasing plans. The zoning typology varies for each purpose (Figure 2). We will first explain these types and then discuss the factors that affect the definition of zones.

Zones for activity progress representations

At the micro-level, construction components are generally installed in discrete increments. Component representations need to be broken up into representations for distinct time phases to reflect the installation sequence. This makes it possible to simulate the construction progress and analyze resource allocation and conflicts in more detail. Although there are a great variety of component installations for different construction activities, it is possible to classify activity progress representations using a few criteria.

Zones for construction method or resource assignments

Multiple construction methods can act on a single construction component to define different zones on it. This generally occurs when the geometric features or spatial constraints have variations at different locations of the component. For example, on the Experience Music Project in Seattle, WA, the complexity of the skin surface required the contractor to apply several methods of construction in different areas during shotcrete operation (Akbas and Fischer, 1999). Construction methods affected the zones needed, which, in turn, affected the resource requirements.

Zones for phasing plans

This is an aggregation of components within a space. This space might simply be a bounded area defined during design (e.g., a room) or might be partitioned specifically for construction to balance activity duration and resource allocation in each zone. The initial lagoon zones in the case study are an example of zones having multiple activities. Similarly, it is a common practice to group steel elements to define activities, build sequences, and track the actual progress of detailing, fabrication and erection.

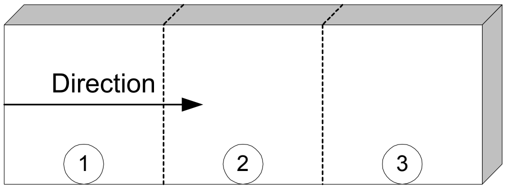


Figure 2a. *Zones for activity progress representations of a wall. Each number corresponds to the order in which the part of the component will be installed.*

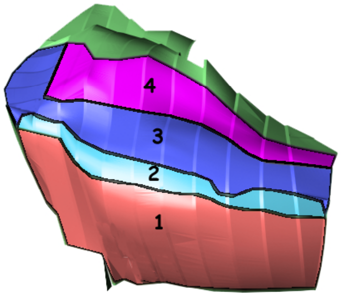


Figure 2b*. Zones defined by assignment of construction methods on a component. Shotcreting the structure requires different methods depending on the height, curvature and distance to scaffolding* (Akbas and Fischer, 1999).

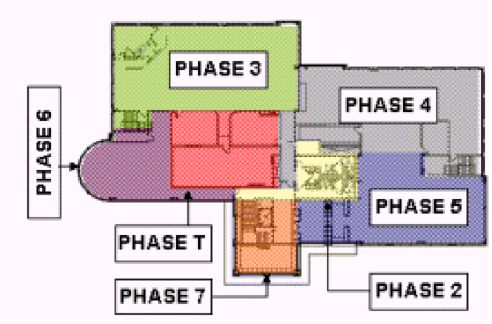


Figure 2c*. A floor plan of an office building, showing the stages of construction* (Koo and Fischer, 2000). *Zones for phasing plans contain every component of a certain type within a space or area.*

Figure 2. *Types of Construction Zones*

Factors Affecting Zone Definitions

Based on the types and definitions of zones, the next step is to define how they are used in practice. Our purpose is to classify these factors so that we can use them together with the 3D geometry to generate the zones. Table 1 summarizes our classification for factors affecting zone definitions. The flow of work, combined with the production rate is an important determinant of zones. The design information, i.e., the shape representation of the product and properties of parts that compose the product also affect the definitions. Spatial relationships between components and the capacity and availability of resources are the other factors. One or more of these factors are used to determine the actual zones.

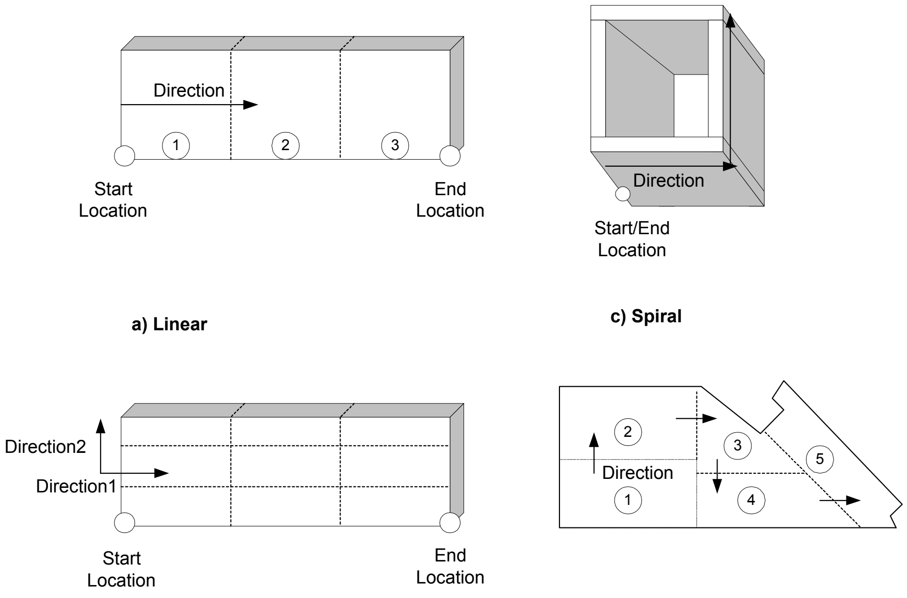
TABLE 1. Factors affecting construction zone definitions

Category	**Factor**
Construction Method Information	Direction of workflow Baseline production rate Shape factors
Design-based information	Building element type Unit size of constituents Shape complexity Joint locations
Spatial relationship information	Distance to other components
Material/Resource availability	Capacity

Construction process based factors

The size and shape of zones can vary widely with the construction method. Trades usually have a specific direction of workflow, which is typically not captured explicitly in production models or documents generated with the current planning process. The direction for component installation can have different meanings depending on the direction type. To formalize the decomposition of construction components, it is imperative to classify the directional information of installation. So far, based on the literature (Riley and Sanvido, 1995) and on our personal experience, we have defined the following types as the most common directional types (Figure 3):

- Parallel to an axis (linear): horizontal, vertical, inclined, e.g., installation of stud walls or slab forms. This type can be applied to components having linear progress, following similar patterns throughout the activity.
- Along two axes (grid): e.g., construction of a slab-on-grade or of exterior panels. This type proceeds in two directions at the same time.
- Spiral: e.g., masonry walls. This type has the same starting and ending location. The direction of flow covers a loop, coming back to the same point.\
- Alternating axes (complex 3D shapes): e.g., excavation of the lagoon in Figure 1. The axes of the component change during the construction.



a) Linear

c) Spiral

b) Grid

d) Alternating Axes

Figure 3. *Activity Direction Types*

Obviously, productivity of crews is an important factor for the zone definition, i.e., factors affecting the productivity also affect the zone definitions. We will explain our productivity model for our study in more detail in the next section. We are mostly concerned with the local variations of production rate because of the shape of component. The effect of a shape on productivity can be different for different construction methods.

Shape of component

The geometry of a component is another important factor. Thomas and Zavrski (1999) have shown that the productivity is a function of the geometric complexity of the design. Some examples of design complexity are the complex edges of concrete slabs, or extreme curvatures of a component. For example, in the motivating case, the production rate of the concrete activity is lower where the lagoon is sloped.

Several research efforts analyzed geometric factors that effect labor production rates (Sanders and Thomas, 1991, Thomas et al., 1990, Thomas and Zavrski, 1999). These research efforts have defined certain design features that can affect the productivity, e.g., masonary walls with corners that are not perpendicular, and have assigned a shape factor (also called *work content*) using statistical methods. However, these research efforts do not take the shape variations within a component into account, instead they assign a bulk factor for the whole component. In our approach, the shape is used in conjunction with the shape factors to change the local productivity value for construction of the component. We are not aware of previous research analyzing the effect of micro-level geometric factors on a construction activity.

Construction components with predefined unit sizes and prefabricated components such as steel and pipe elements are considered differently from continuous elements such as concrete slabs. For example, the reinforcing mesh in the lagoon case is formed by 4" by 4" prefabricated unit meshes. The zone generation process needs to consider these unit sizes. Prefabricated components cannot be decomposed, since their design representation is similar to the representation needed for construction. However they might be aggregated like the reinforcing mesh in the case.

Joint locations are also important in zoning decisions as they can create the boundary for the work done during a certain period. For example, the concrete activity has construction joints in the lagoon case.

Spatial relationships to other components

Components have relations to other components, e.g., height from ground, distance to scaffolding, which affect how an activity is performed. This could also be the proximity to a nearby ongoing activity. Previous researchers commonly used support relations to determine the activity sequences, which is also a spatial relation type(Zozaya-Gorostiza et al., 1989).

One variant of the spatial relationship is the distance to the edges of the same component. For example, during installation of the reinforcing mesh in the case, the construction method dictates installing the edges first. Furthermore, the productivity is slower near the edges. Again, we use shape factors to capture the effect of these relations on the production rate.

Material/Resource availability

The amount of resources used is limited because of cost considerations, the status of the job market, material availability, or space limitation. For example, the number of concrete pump trucks that can enter a site limits the amount of concrete to be poured in a day. Some of these constraints are implicit in the baseline productivity value. We consider these resource constraints using shape factors.

The availability of space and prevention of spatial conflicts are also important for the definition of zones because they limit the available area of work. However, the analysis of space resource constraints is out of scope of this research. Space planning methodologies analyze this problem in detail (Akinci and Fischer, 1998). We limit our interest in this category to material availability.

Productivity Model for Zone Generation

We use a factor-based productivity model (Thomas et al., 1990), which measures productivity as a function of output and focuses on the crew as the basic work unit, rather than individual crew members. Our model also allows the production rate to be calculated at any location on the component geometry, rather than assigning a bulk value for the component.

We use shape factors to incorporate local productivity variations on a component. We define shape factors as functions representing the effect of a certain property of local geometry on the productivity of the crew when using a particular construction method. The shape factor functions applied to a shape give shape factor coefficients at any location of the surface of the geometry. Shape factor coefficients vary from 0 to 1. A value of 0 means there is no work possible at a certain location, and value of 1 means that the unconstrained production capacity can be reached. Assuming each shape factor is independent, we combine multiple shape factors by multiplying the shape factor coefficients at that location. Therefore at any location:

$$\text{Production rate} = sf * \text{Production Capacity} \qquad (1)$$

$$sf = sf_1 * sf_2 * \ldots * sf_n \qquad (2)$$

where definitions are from (Tommelein et al., 1999):

Production rate: Actual number of trade-specific work units per unit of time a crew is able to finish given constraints on their work.

Production capacity: Number of trade specific work units per unit of time a crew is technically able to finish given their work is unconstrained.
sf: Shape factor value.

We exclude factors such as organizational structure, management, environmental site conditions, since we will not consider these factors within shape factors. These factors need to be calculated beforehand within the production capacity. Currently, we have used four shape factors. These are height, slope, distance to edge, distance to component. Shape factors can also be time-dependent. For example, the distance to another component can be relevant when that component is under construction. Furthermore, distance to a temporary structure such as scaffolding can impose a construction method, thus changing the productivity.

Our purpose is not to make a comprehensive study of these shape factor values. We define the factors and formalize mechanisms that allow users to enter these factors as a function of the geometric properties and distances and use the factors to modify the production capacity at a certain location.

MECHANISMS FOR ZONE GENERATION

Here, we briefly outline how we represent the changes in product and process models and how we perform the operations in the 3D model. We have defined a set of product model transformations between design and construction planning. In this paper, the focus is the mechanisms for generation of zones, namely *decompose* and *aggregate*. These mechanisms can act simultaneously on the building elements and the activities.

Any representation in a product model is composed of some semantic information about the building element and its geometric representation. The shape representation can be in many different forms. We prefer to use triangular meshes in this research. This fits our analysis requirements, because it is easy to obtain local geometric properties, refine or decompose the mesh. Additionally, it is possible to convert from any geometric representation to a triangular mesh representation. There is a wealth of literature in geometric modeling and mesh generation domains that deals with manipulation and analysis of polygonal meshes (Möller and Haines, 1999).

The input for the geometric reasoning for zone generation is a hierarchical product model with each of the building element representations referring to an unconnected set of triangles for shape representation. The geometric reasoning step also requires either an initial productivity estimate or a schedule activity linked to the building element. The properties related to the construction method (direction of activity, productivity, shape factors) are encapsulated. Then a set of geometric algorithms is applied on the triangular mesh.

Decomposition

The *decomposition* mechanism creates construction zones by subdividing the geometric representations of the product. Construction process planners use *elaboration* mechanisms to generate a detailed plan from a high level plan (Zozaya-Gorostiza et al., 1989), making use of the organization of the design-based product model. *The elaboration* mechanism stops when the most detailed representation in the design-based product model is reached. Decomposition mechanisms are necessary to adequately represent construction units of work.

We have implemented a set of algorithms to achieve top-down and bottom up decomposition. We will summarize here the *bottom-up decomposition*, which makes use of the topology of the shape and the productivity information to simulate construction activity progress. The criteria specified as *shape factor functions* define how construction productivity is affected during an activity or interaction of activities. The algorithm, then, modifies the productivity of the activity locally on a component and generates construction zones at the level of detail specified by the user. We assume that an activity on a component starts at a certain location, and progresses in a connected way, i.e., no two unconnected parts of a component are under progress at a certain time. The implementation can be summarized as follows:

- generating the topology for the mesh,
- determining shape factor coefficient for all triangles in the mesh,
- traversing the mesh,
- refining the mesh if necessary, and
- breaking up the geometry.

Aggregation

One can start from the other extreme, from the design representation that has all the details of the model. For example, if all the reinforcing mesh representation is included in the model, the schedule activities should refer to different levels of aggregations of individual elements, thus components should be aggregated. Aggregation is crucial for planning when there are many tasks for the project. Aggregation algorithms in our research are used to perform spatial search of components using spatial or temporal criteria, e.g., find all the activities that affect a region within a certain period and define an aggregation for the components related to these activities.

CONCLUSIONS

This paper describes domain knowledge necessary for zone generation. Using the domain knowledge together with the transformation mechanisms and the geometric algorithms, users can refine a high level plan for construction together with the corresponding geometric representation as the project progresses.

Our research provides tools for more detailed visualizations of construction processes. 4D models with construction zones that represent work progress with daily or similar increments can be very valuable to the people managing the actual construction in the field. The zones can help maintain consistency between multiple schedules by using the product model as a basis. Once zones are generated, many types of detailed analysis can be performed on the model, such as time-space conflicts, discrete-event-simulation, etc.

From a research standpoint, this zone generation approach is built on an extensible framework. This approach provides flexibility in several ways. First of all, the level of detail of the product model can be automatically adjusted to the planning requirements. Second, the organization of the product model is flexible during design and construction. Third, the change in the level of detail is done using a group of user-defined parameters. We don't have hard constraints for our reasoning steps. Instead, we use user defined quantitative factors.

More work is needed for determining the shape factor values and their interactions for different construction activities. Another possible research is using the zone generation mechanisms as a basis for simulating the construction to determine the problem areas beforehand and modify a design accordingly.

REFERENCES

AbouRizk, S. and Mather, K. 2000, 'Simplifying Simulation Modeling through Integration with 3D CAD', *Journal of Construction Engineering and Management,* Vol. 126, no. 6, pp. 475-483.

Akbas, R. and Fischer, M. 1999, 'Examples of Product Model Transformations', *Information Technology in Construction, CIB W78 Workshop,* Vancouver, BC, pp. 2737-2746.

Akinci, B. and Fischer, M. 1998, 'Time-space conflict analysis based on 4D production models', *1998 International Computing Congress on Computing in Civil Engineering,* Boston, MA, USA, pp. 342-353.

Ballard, G. 1997, 'Lookahead Planning: The Missing Link in Production Control', *Proceedings of the 5th Annual Conference of the International Group for Lean Construction,* Griffith University, Gold Coast, Australia.

Haymaker, J. and Fischer, M. 2001, 'Challenges and Benefits of 4D Modeling on the Walt Disney Concert Hall Project', CIFE Working Paper Nr. 64, CIFE, Stanford, CA

Hinze, J. W. 1998, *Construction Planning and Scheduling,* Prentice-Hall Inc, New Jersey.

Koo, B. and Fischer, M. 2000, 'Feasibility Study of 4D CAD in Commercial Construction', *Journal of Construction Engineering and Management,* Vol. 126, no. 4, pp. 251-260.

Möller, T. and Haines, E. 1999, *Real-time rendering,* A K Peters, Natick, Mass.

Riley, D. R. and Sanvido, V. E. 1995, 'Patterns of Construction-Space in Multistory Buildings', *Journal of Construction Engineering and Management,* Vol. 121, no. 4, pp. 464-473.

Sanders, S. R. and Thomas, H. R. 1991, 'Factors affecting masonry-labor productivity', *Journal of Construction Engineering and Management,* Vol. 117, no. 4, pp. 626-644.

Shaked, O. and Warszawski, A. 1995, 'Knowledge-based system for construction planning of high-rise buildings', *Journal of Construction Engineering and Management,* Vol. 121, no. 2, pp. 172-182.

Thabet, W. Y. and Beliveau, Y. J. 1994, 'HVLS: horizontal and vertical logic scheduling for multistory projects', *Journal of Construction Engineering and Management,* Vol. 120, no. 4, pp. 875-892.

Thabet, W. Y. and Beliveau, Y. 1997, 'SCaRC: Space-Constrained Resource-Constrained scheduling system', *Journal of Computing in Civil Engineering,* Vol.2, no.1, pp.48-59.

Thomas, H. R., Maloney, W. F., Horner, R. M. W., Smith, G. R., Handa, V. K. and Sanders, S. R. 1990, 'Modeling construction labor productivity', *Journal of Construction Engineering and Management,* Vol. 116, no. 4, pp. 705-726.

Thomas, H. R. and Zavrski, I. 1999, 'Construction baseline productivity: Theory and practice', *Journal of Construction Engineering and Management,* Vol. 125, no. 5, pp. 295-303.

Tommelein, I. D., Riley, D. R. and Howell, G. A. 1999, 'Parade Game: Impact of work flow variability on trade performance', *Journal of Construction Engineering and Management,* Vol. 125, no. 5, pp. 304-310.

Winstanley, G. and Hoshi, K. 1992 'Model-Based Planning Utilizing Activity Aggregation Based on Zones' CIFE Technical Report Nr. 69, CIFE, Stanford, CA.

Zozaya-Gorostiza, C., Hendrickson, C. and Rehak, D. R. 1989, *Knowledge-Based Process Planning for Construction and Manufacturing,* Academic Press Inc., San Diego, CA.