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Geometry-Based Modeling and Simulation of Construction Processes

By

Ragıp Akbaş

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If you would like to contact the authors, please write to:

c/o CIFE, Civil and Environmental Engineering Dept.,
Stanford University
Terman Engineering Center
Mail Code: 4020
Stanford, CA 94305-4020

GEOMETRY-BASED MODELING AND SIMULATION OF CONSTRUCTION PROCESSES

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Ragıp Akbaş

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ABSTRACT

I describe a new approach for modeling and simulation of construction processes based on geometric models and techniques. Currently, there is an inadequate support for modeling the spatial aspects of construction operations, evaluation of alternative process plans and visualizing the results directly. Critical Path Method networks do not describe how a project is built. 4D models provide visualizations for the construction process, but they have limited support for analysis. Existing discrete event simulation techniques do not use the spatial aspects in model definition and evaluation of results. Using geometric techniques to generalize and increase applicability of the conceptual process models, this research contributes a process modeling and simulation approach and the geometric techniques to support it.

This process modeling and simulation approach, called GPM, models the conversions in construction processes as sequences of crews acting on geometric work locations. It uses a simple process description: work locations are processed by crews. It describes a crew model that includes a workflow strategy and a production rate function. The workflow strategy specifies in what order crews plan to perform their scope of work. The production rate function specifies at what rate crews can perform work at a specific work location at a specific time instant.

A set of crews acting on work locations in a bounded space defines a subsystem. Subsystems use formal approaches to modeling and simulation, such as state management, for their definition. GPM describes three interaction types between subsystems as activity ordering, spatial crew ordering and nearby work. Coupling of a set of subsystems and considering the interactions describes the complete process model.

GPM reduces each subsystem into queueing networks for simulation purposes and uses discrete event simulation to obtain state trajectories for the geometric model and the crews performing work on the project. The system states provide automatic 4D and crew performance visualizations.

In GPM, geometry is not a static representational element, but an integral part of the process model. The geometric model, represented as triangle meshes, is a source for automated extraction of a number of constraints and interactions. The geometric techniques manipulate, reorganize and analyze the geometric model. I categorized the geometric techniques to support GPM as geometry tessellation, geometry sorting, geometry analysis and hierarchical space decomposition. I adopt, extend and implement geometric algorithms for each category.

GSim is an implementation prototype for GPM. It implements the elements of the modeling and simulation approach, including the geometric techniques. It also provides user interfaces for parameter entry and visualizes the simulation results. Users can utilize 3D models to define subsystems interactively and evaluate alternatives easily by changing parameters and observing the results directly. I tested the research contributions on three construction projects.

The research results provide improved modeling and simulation techniques for construction operations and more effective use of geometry for construction practice and research.

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INTRODUCTION

This research is on understanding the construction process from a geometry oriented modeling and simulation perspective. The purpose is better design of operations by making the geometric model an integral element of the planning process and using formal techniques for modeling and simulation.

Construction projects have unique spatial configurations and the spatial nature of projects is very important for planning decisions. A quick glance at existing models for construction processes shows that when models accurately represent the construction operations, the model complexity increases significantly. Consequently, the effort required to create and maintain these models increases. This is partially because planners must manually include the spatial factors that are already in the geometric model in the construction process models they build in support of construction planning. For example, activities and sequencing relationships in Critical Path Method (CPM) networks only implicitly consider geometry and spatial factors. The same is true for simulations of construction processes.

Because of this complexity, construction managers develop aggregate plans that may oversimplify the effect of the project's geometric configuration on the construction process. Instead of accurate and in depth process analysis early in the project, the common practice is keeping the process plan at a macro level and creating a detailed plan for shorter intervals as the project proceeds. This prevents earlier consideration of problems on site and evaluation of alternatives.

Can the modeling effort be simplified with reasonable assumptions while maintaining or increasing the power of the resulting models? Intuitively the modeling of operations can be simplified by basing models on the spatial configuration and making effective use of geometry. By managing spatial effects effectively, allowing various manipulations, transformations and analysis on geometry, construction operations can better utilize process modeling and simulation approaches for other man-made systems, such as manufacturing, communication, electrical systems.

One limitation until recently was that 2D drawings are the predominant representation of the finished facility. Availability of 3D geometric models for project management opens up new possibilities. However, effective use of these geometric models requires renewed understanding of construction processes with geometry in mind.

1.1. Motivations

I introduce three ways to use geometric models as an important and effective element for construction process design and analysis: work balancing in 3D, zone generation and process decomposition. They highlight important limitations of existing planning techniques and consequently have theoretical and practical importance. In summary, it is a challenge on every project to build a flexible and general process model while considering the spatial characteristics of the project.

1.1.1. Work balancing in 3D

Activities on projects such as high-rise buildings, multi-unit housing, highways and tunnels exhibit repetitive characteristics, where the same unit is repeated several times. These activities resemble assembly line processes of manufacturing with sets of tasks in repeated sequences. For such activities, it is necessary to balance work so that each crew can progress from one unit to the next in an orderly way, i.e., to provide a rhythm to the process. The crews should move through the project in a continuous manner, without interruption, to get the efficiency of repetitive work. To achieve continuity in all repetitive units, planners adjust the production rates (speeds), mobilization dates and sequences for the activities.

Line-of-balance (LOB) or linear scheduling techniques provide ways to satisfy this need (O'Brien 1975; Stradal and Cacha 1982). These techniques use lines to represent the production of crews over time. They can represent crew sequences in a single diagram and detect interferences by intersection of lines. However, these techniques assume repetitive units, linear direction, and constant production rates, which fall short of supporting complexities of realistic project cases with complex crew workflow directions and variations in production rate due to variations in the spatial configuration of the project.

By making effective use of 3D geometric models of the project, the intuition behind these techniques could be extended to balance a wider range of construction processes. Instead of using lines to represent crews, a computer application could capture the order of work performed on geometry. Similarly, instead of using a constant production rate for a crew, the user could describe the changes in the crew production rate using a set of parameters. At the same time, the application could give users an interface similar to LOB diagrams to interactively define and modify mobilization dates, production capacities, and sequences of crews by manipulating lines for each crew. The user could also interactively define the directional workflow for crews on the geometry. Simulating the construction process on the geometry, the application could predict how the crews will perform over time. Additionally, it could detect interferences between crews automatically, support work continuity and overlay the results on the same LOB diagram.

The process elements to support such a computer application are lacking: representation and simulation of spatial characteristics for crews on 3D geometry, various geometry-related effects on production rate, management of crew interactions and conflicts during simulation are necessary.

1.1.2. Zone generation

Construction crews need space to perform work productively. When crews share space, one or both crews cannot proceed efficiently until the other has finished and moved to another location. Consequently, construction managers should predict space requirements and allocate spaces for crews to minimize congestion and interference (Riley and Sanvido 1995). Currently, a common practice is to use colored blueprints to define, visualize, and update space allocations. Why not use the geometric model to assist with space allocation?

A computer application could simulate the construction process on geometry and use the simulation results to determine where each crew should work on the project at a particular time period (i.e., define the *work area zones*). Planners could evaluate different processes to consider alternative zones. When changes occur, they could create a new zoning plan accommodating the changes.

Having a geometric model for the finished facility does not directly amount to its productive use for planning purposes. Modelers build 3D geometry by making decisions on factors such as how the geometric model is organized, what components are modeled, and in what detail. However, the structure of the geometric model is irrelevant from a crew's or planner's perspective. General and automated geometric techniques are necessary to manipulate, reorganize and analyze geometric models to relate geometry to the operations, i.e., to define geometric units of modeling and simulation. This way, the simulation results on the geometry can relate back to the process, describing the work area zones over time.

The next application, process decomposition, combines and relates these perspectives. It is possible to partition (or decompose) construction operations as sets of crews following each other in a sequence. Each set of processes has interactions with others and cannot be considered in isolation. Using geometry is essential to manage this decomposition.

1.1.3. Process decomposition

Construction projects are complex undertakings, involving multiple participants and requiring a large amount of effort to plan and manage. The focus of the project management team varies depending on the levels and areas of responsibility and on the project phase. At the same time, the construction decision processes are effectively decentralized, each subcontractor planning and optimizing their own process in detail. To support this complexity, flexible techniques to decompose the construction process are necessary so that the individual processes can be optimized in the context of a well-coordinated overall plan that considers the spatial and production particularities of a project.

Current project management methods use work breakdown structures to provide a fixed hierarchical breakdown of a project into work packages. Work packages then describe activities for project planning and control purposes using network based project planning techniques (e.g., CPM), where the activities become the basic unit of analysis. The interactions in the construction process are represented using precedence relationships between activities. Increasing the number of activities leads to a model that is more precise and realistic but makes the definition and management of a schedule harder.

A computer application could use the geometric model with flexible spatial structures, and information about the finished facility, process, and organization to decompose the construction process into subsystems. Then it could consider each subsystem separately and relate subsystems using a set of interactions. It could, for example for a specific foundation in a building, balance work using *work balancing in 3D* and allocate spaces to crews using *zone generation*.

Unlike CPM activities, these subsystems could contain detailed process information. Unlike precedence relationships between CPM activities, the interactions between subsystems could consider spatial relationships and space conflicts from another subsystem. At the same time, one could use the simulation results to obtain activities and relationships for CPM if necessary.

The challenges to support such an application are describing the content and behavior of each subsystem, formalizing interactions between subsystems, and developing flexible ways to modularize the construction process using geometry.

Process decomposition, therefore, provides a system perspective for the processes on the project. In fact, all are related and complementary. *Work balancing in 3D* takes the process perspective, *zone generation* provides the spatial perspective and *process decomposition* uses the systems perspective.

Through a formal process model based on geometry, this research provides a formal basis to relate and support these applications. These applications all call for process modeling and simulation to support evaluation of alternatives, visualizing the results and using geometric techniques.

1.2. Summary of the requirements for the research

Overall, there is a theoretical and practical need for integrated planning, simulation and visualization, bringing existing modeling techniques to use in a systematic framework and developing a foundation for new techniques. The modeling and simulation approach should support the description of the process plan easily and parametrically, and simulate and visualize its results during planning.

A geometry-based process model should capture the basic parameters for how and at what rate crews should perform work. It should detect crew conflicts on geometry to make sure that at most one crew is scheduled to work at a location at any time.

The process model should support easy evaluation of alternatives. The modeling parameters should be easy to change and the process model, once defined, should support simulation with little effort from the user. Focusing on each subsystem, the users should be able to improve specific elements of the process and see the effect on the overall system. 4D visualization of the process and description of crew performance should be a direct result of simulation.

The approach needs to work with common 3D geometric models for projects and support geometric techniques that keep planning parameters independent of the specifics of the geometric representation, i.e., decouple modeling and simulation techniques from geometric techniques. A unit of analysis based on geometry is necessary. The geometric techniques should be able to decompose the process in flexible ways and manipulate, reorganize, and analyze geometric models to support the approach.

1.3. Research Questions

This research asks two formal research questions. The first question is on describing a process modeling and simulation approach on geometry and the second question is on the geometric techniques to support the approach. These two questions are interrelated; the process modeling and simulation approach should be designed to take advantage of geometric techniques, and geometric techniques should support the process model and its simulation. The following paragraphs state the research questions.

1. What is a geometry-based process modeling and simulation technique that is appropriate for construction planning and visualization?

The discrete event simulation techniques for construction can model the operations in detail, but they do not consider spatial issues directly, model definition is time consuming and not intuitive, and the results are not related to geometry. On the other hand, 4D CAD relates geometric models with CPM activities to provide visualizations of construction operations at a high level. This research asks for a modeling basis to formally relate this range of techniques.

The modeling and simulation approach should be general to support many types construction activities and physical components, scalable to support complex construction projects, and flexible to allow consideration of alternatives and future improvements.

This research question has three parts:

a) What are the basic construction process elements to leverage geometric models?

Birrell (1980) described construction processes as composed of work locations, crew workflow paths and sequence of work locations that the crews pass through. However, his model is conceptual and does not use geometric models. Using his intuition, this question seeks a general description and formalization of crew behavior and work locations sufficient to support a process model on geometric models.

These process elements should be such that, given a geometric model of the finished facility and parameters describing each crew, it should be possible to simulate the model and visualize the results directly. However, the process elements should not depend on a specific geometric representation.

b) How can the construction process be decomposed into subsystems to consider project parameters and interactions? What are appropriate input parameters and internal structure for each subsystem?

Defining the process elements is not sufficient for a good process modeling and simulation approach. Construction processes involve complex interactions between crews, equipment, and materials and are subject to multiple management, control and design objectives. Projects use work breakdown structures and work packaging techniques to manage this complexity. However, these structures are fixed throughout the project. Project participants need to be able to analyze flexible decompositions of the process and consider interactions between each.

Systems theory and formal modeling and simulation approaches (Cassandras and Lafortune 1999; Zeigler et al. 2000) provide techniques to manage complexity by decomposing the system of interest into modular components and using state management techniques to describe the behavior of model components. I apply these methodologies for geometry-based modeling and simulation.

The answers to this question should provide formal, state-based encapsulation of physical conversion processes on geometry as subsystems. The interactions between subsystems should support common relationships between construction activities and extended relationships that are directly related to geometry. The interactions should also support ways to determine conflicts between crews within and among subsystems.

c) How can this model be simulated and analyzed using discrete-event-simulation?

Discrete event simulation is the primary method of analysis in this research. Construction process models contain many constraints, reflecting the nature of the operations. Ashley (1980) described a queueing theory approach to simulate repetitive unit construction using queueing networks, since repetitive processes resemble assembly lines. Nevertheless, this can only work for certain types of construction and describing the simulation model is time consuming. Besides, existing construction process simulation techniques provide detailed statistical reports and charts for simulation results but they lack intuitive visualizations of these results.

The answer to this question should reduce the process model into an abstraction using queues to describe a simulation model. Furthermore, it should describe methods to visualize the results after the simulation.

The need to support this process modeling and simulation approach on geometry leads to the second research question.

2. What geometric techniques are needed to describe and analyze such a system?

This question seeks geometric techniques that support the model and simulation technique for the first research question. A wide variety of geometric techniques is available from various geometry related fields. However, their application to construction processes is limited apart from visualization. Geometric models are not directly usable for process modeling and simulation because they are not modeled with the construction process in mind.

The answers for this research questions should adopt, extend, categorize, and implement the geometric representations and algorithms sufficient to support the process model and its simulation. The geometry should not be a static representational element, but an integral part of the process model. Specifically, the techniques should support process modeling and simulation using geometry manipulation, triangulation (Shewchuk 1996), vector fields on surfaces and sorting geometry (Turk 2001), distance and shape evaluations, and hierarchical space decomposition (Foley et al. 1995). The representations and algorithms should use triangle meshes.

The geometric techniques should be general to support many component and activity types in the construction process, transparent to decouple geometry from the process modeling approach, extensible to allow for future extensions, and they should be able to support complex geometry and large numbers of components in construction projects.

A computer implementation prototype should demonstrate the modeling and simulation approach and the geometric techniques. The prototype should be able to use 3D models and CPM activities as a basis to build models with intuitive user interfaces and visualize the results.

1.4. Properties of the process modeling and analysis approach

To support the research questions, I describe a process modeling and simulation technique for construction process planning that builds on geometry. I call it GPM, for **g**eometry-based **p**rocess **m**odel. This section introduces the important properties of this process model, including the process of interest, the modeling methodology and its elements, and analysis and visualization techniques.

Figure 1-1 summarizes the modeling and simulation approach. Physical conversions in construction processes are the system to be modeled, or the process of interest. The 3D geometric model of the finished facility and a set of production parameters are used to model the process of interest. To manage the complexity, the approach decomposes the whole construction process into subsystems. Each subsystem contains crew parameters, geometric work locations and interactions. The approach then reduces this process model into queueing networks and simulates the process. Each of these steps uses geometric techniques.

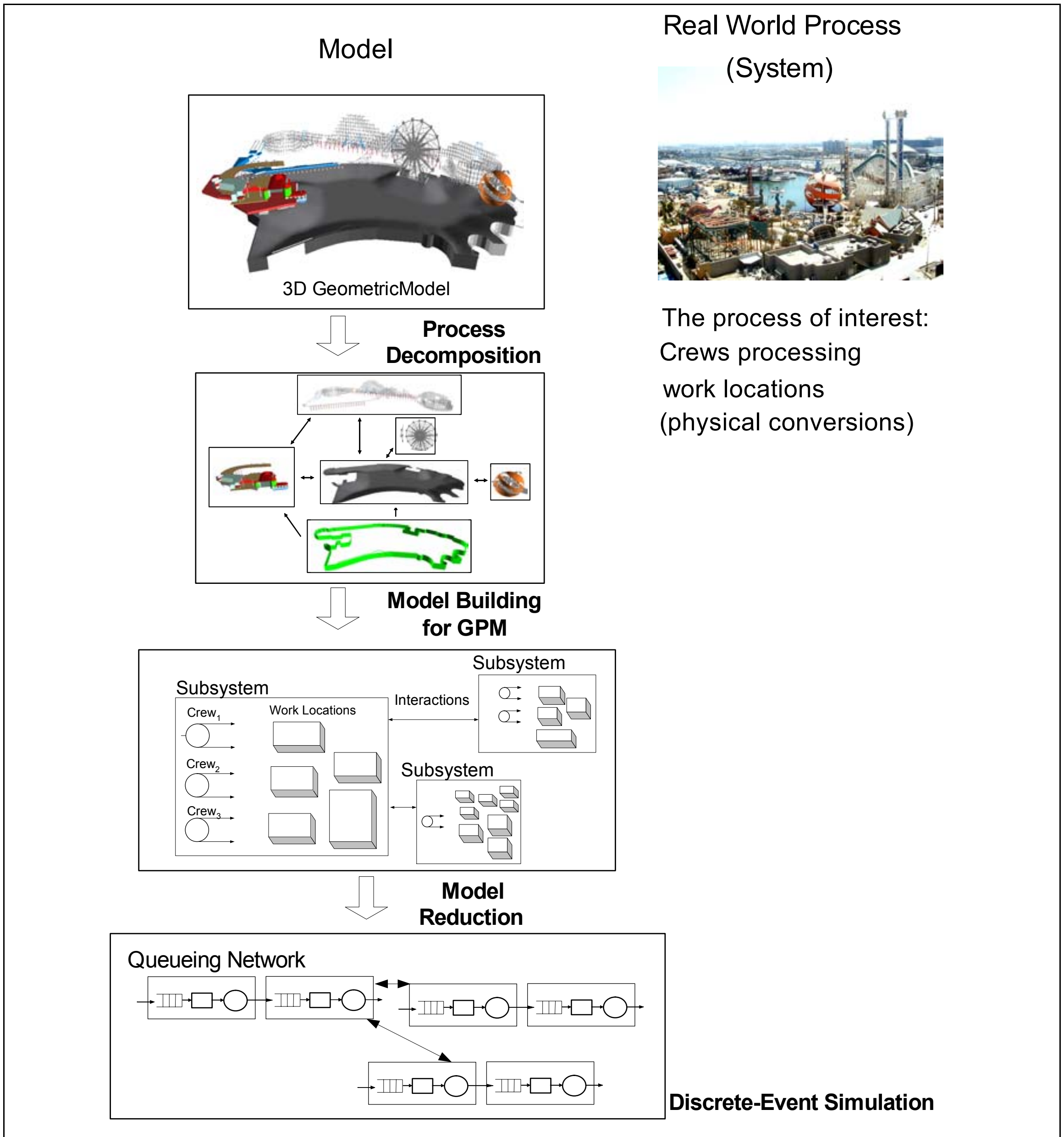


Figure 1-1. Overall view of the modeling and simulation approach.

1.4.1. Process of interest

The construction process is a complex system. Instead of trying to model the complete process, I focus on the readily observable and measurable processes which can be related to a geometric model. Therefore, I select the process of interest as spatio-temporal aspects of crews installing work at its final location (erection, placement, assembly and installation activities). Different terms are used in the literature to describe this process of interest, e.g., physical conversions, transformations, production or site assembly activities. I use the term physical conversions for this purpose, and the term *process* refers to physical conversion processes unless otherwise stated.

Within the conversion processes, GPM focuses on the behavior of crews and locations. Crews are the basic production units. Instead of modeling the behavior of each individual crew member, the crew model considers the crew in its entirety. The basic process is conversion of work locations by crews.

The modeling purpose is to describe construction operations, synthesize better process designs by evaluating process alternatives from the individual and the overall construction process perspective, and visualizing and analyzing production. Modeling important aspects such as cost, materials management and safety issues are not within the scope. Similarly, the modeling approach does not directly model architectural, engineering design or inspection activities. Chapter 2 describes how this research relates to previous work.

1.4.2. Modeling techniques

The physical outcome, i.e., the terminating condition, for the construction process is the finished facility. It can spatially be represented as a 3D geometric model, for which I will use the term *geometric model* throughout this document. The geometric model is an approximation for spatial content of the building elements; combined with geometric techniques, it provides a valuable basis to support simulation.

To leverage existing geometric techniques and to easily obtain geometric input, GPM uses geometric models consisting of triangle meshes. The geometric model provides the basis for derivation of various information related to a crew’s production rate, direction of workflow, crew interference and spatial organization.

GPM describes a crew model that captures the planning decisions as parameters of crews performing work on locations: the workflow strategy, production rates, and mobilization date. It defines the geometric units of work as work locations and associates them with the process using the production rate. The production rate and the quantity of the work location are the sole determinants for how long it will take to construct work locations.

The complete project is complex for analysis in its entirety. GPM describes flexible ways to decompose the construction system into subsystems. Each subsystem can be analyzed separately and coupled to form the system, incorporating the *interactions* (or *couplings*) between each subsystem.

GPM considers the physical conversions in construction processes as a system (Bertalanffy 1969; Lin 1999; Skyttner 2001). It adopts *discrete event systems* as the modeling approach (Cassandras and Lafortune 1999; Zeigler et al. 2000). For modeling purposes, the only function of the construction process is the physical conversion of work locations. The input parameters for the system are crew parameters and sequences. Outputs are the simulation results for the crews and the work locations. GPM uses discrete installation states for every work location, starting from "not started" and ending with "complete". Similarly, the crews have states. Every state change is a result of a discrete event, for example start of a crew on a work location and mobilization of crews.

Chapter 3 describes this process modeling approach in detail.

1.4.3. Simulation and analysis of results

Discrete event simulation is the main analysis technique for GPM. I describe a technique to reduce the model described in the previous section into a *queueing network* model. This provides a direct and automatic discrete event simulation model for crews and locations based on geometry. Each crew in a subsystem forms a *server*, whereas work locations enter *queues* and get processed by servers. Work locations move from server to server.

Once every crew in the system is simulated, the state of any crew and location over time is known. Visualization of installation states is automatic, since installation states are built on the geometric model. The crew state trajectory provides the history of the crew performance. Installation state trajectory on work locations provides 4D visualizations and work area zones. The user is able to dynamically change model parameters and re-simulate the process model to consider what-if scenarios. Chapter 4 explains the simulation and analysis of the model in detail.

1.4.4. Geometric techniques

Geometric techniques are one of the main enablers for this approach. Elements of production rate, workflow strategy, interactions between subsystems have geometric aspects which are hard to consider otherwise. Support for the model requires manipulation, transformation and analysis of geometry. I formulate tessellation, geometry sorting, geometry analysis and hierarchical space decomposition problems that complement the modeling methodology. I then, adapt and extend existing geometric representations and algorithms to support these formulations. I organize and use the geometric model in a general way that relates to and works concurrently with the dominant models used for construction planning and control. Chapter 5 describes the geometric techniques in depth.

1.4.5. Research scope

Building projects are the primary domain of this research is. Building projects have a large variety of types of work and geometric shapes for building elements. The test cases and validation use building projects. In particular, I have tested earthworks, structural components, foundation, concrete works, piling and exterior construction. However, the basic elements for this process model should be applicable to any construction project.

To limit the scope, this research has some limitations. GPM is deterministic, therefore ignores the elements of the process with random nature. Stochastic simulation for construction operations is common, because construction is usually subject to variations and interruptions due to the nature of the construction environment (AbouRizk 1990). Similarly any optimization of process parameters is outside the scope. Additionally, GPM is not an automated process planner. Instead of generating the activities, work methods and sequences automatically, GPM relies on the user to define the crew parameters and sequences and generates the activities and simulates the process given these parameters.

1.5. Test case

I use a sample case throughout this dissertation to illustrate the limitations of current modeling techniques and to describe the modeling and simulation approach, implementation, and validation. This case is a construction project in Southern California: Disney's California Adventure (DCA). The areas of attention in this project are a water-reservoir lagoon and a nearby restaurant building. The construction of the lagoon requires complex workflow directions, variable production rates and complex interactions with the other parts of the project. The nearby restaurant is a two floor building with many crews and subcontractors.

The construction of this lagoon is a challenge because many buildings, which are under construction at the same time, surround it. These constraints create pressure to delay construction of the lagoon. Most of the surrounding buildings need to be accessed from the lagoon during construction. Additionally, construction of the lagoon is critical because the lagoon needs to be filled with water before some of the facilities surrounding the lagoon can be tested. These constraints create pressure to accelerate the construction of the lagoon.

The restaurant construction has constrained work spaces, and there are many interactions among crews. It is also on the critical path and more than 20 subcontractors are involved in its construction. Moreover, the restaurant affects the lagoon construction in multiple ways.

1.5.1. Process modeling techniques

As many other construction projects, this part of the DCA project used various techniques for planning, scheduling, and progress monitoring. To determine and manage milestones, allocate resources and attain criticality of work, there is a CPM master schedule. For detailed operations planning, the planners used three-week look-ahead schedules. Another planning tool for the project was a 4D CAD model for visualization, obtained by associating the project 3D model with the master schedule.

The construction plan and the schedule for the lagoon evolved considerably through the different phases of the project. An initial plan developed by the owner, without the construction means and methods, shows lagoon construction progressing in equal size rectangular areas.

After the bid stage, the contractor decided on the method to construct the lagoon. The method used four primary activities: excavation, import and compact clay, install reinforcing mesh and place concrete. To manage the large number of constraints for the lagoon in the master schedule, the construction management team defined six separate zones on the lagoon, considering the interactions between the lagoon work and the neighboring facilities. These activities must follow each other in the given order in each zone. These zones are helpful in defining and managing earliest and latest times for activities via their relationships with their neighboring facilities and other regions. However, they do not reflect how the activities are actually performed, and it is difficult to model and manage the interactions between the zones and the surrounding buildings under construction.

The decision parameters for the construction process are not modeled in CPM. The CPM schedule represents the relationships between the activities as a start-to-start relationship with a lag, describing that the successor activities are able to start some time after its predecessor starts. For example, activities that follow excavation can start before the excavation finishes, provided that there is enough buffer that prevents conflicts between activities. The decision parameters are how each activity will be performed, their production rates at any time and location, constraints caused by the other work at site, and availability of space, resources and access.

Three-week look-ahead schedules for the lagoon take the resource and space availability and other constraints into account. However, even they do not describe the locations where the crews are working over time. For every day, the general contractor needs to allocate spaces for the crews.

The contractor needs a way to compare different alternatives. This is a tough task without considering the spatial issues, even when the resource availability and cost implications are ignored. There are complex spatial arrangements and constraints that affect the activities. There is no easy way to test different crew compositions and corresponding production rates, activity directions, etc. to come up with a detailed schedule.

The earthworks subcontractor could model its processes using discrete event simulation. It would improve the efficiency of earthwork operations. However, it must know where it can act considering other work and space availability. The interactions between the earthworks subcontractor and the other work are difficult and time consuming to model with existing approaches.

The master schedule for the restaurant building has hundreds of activities and precedence relationships, which need to be manually defined and managed. Many of the precedence relationships represent the workflow of crews among zones and crews that follow each other in the same zone. To define, maintain and update these relationships over time is challenging.

Section 7.2 describes the modeling and simulation of this test case for validation.

1.6. Prototype implementation

I implemented a software prototype for the core properties of this geometric process model, called GSim (**G**eometry-based **Sim**ulator). Users can model the construction process interactively by defining subsystems, crews and their parameters. The simulation and visualization is automatic given these parameters. After any simulation, the users can evaluate the results and consider what-if planning scenarios with respect to crew sequences, workflow patterns, the production rates and interactions between subsystems.

Figure 1-2 summarizes the inputs and outputs and the main steps of GSim. The input is the 3D geometric model, crew parameters and sequences, and the hierarchical spatial structure. The geometric model represents the physical components in the finished facility and contains the type information for each component. Each crew has parameters (workflow strategy and production rate function) and known activity types. GSim can import the crew mobilization dates, average production rates and crew sequences from CPM schedules. The outputs are the state trajectories for crews and work locations visualized in different ways. Geometric techniques are a part of the implementation and they support the steps of GSim.

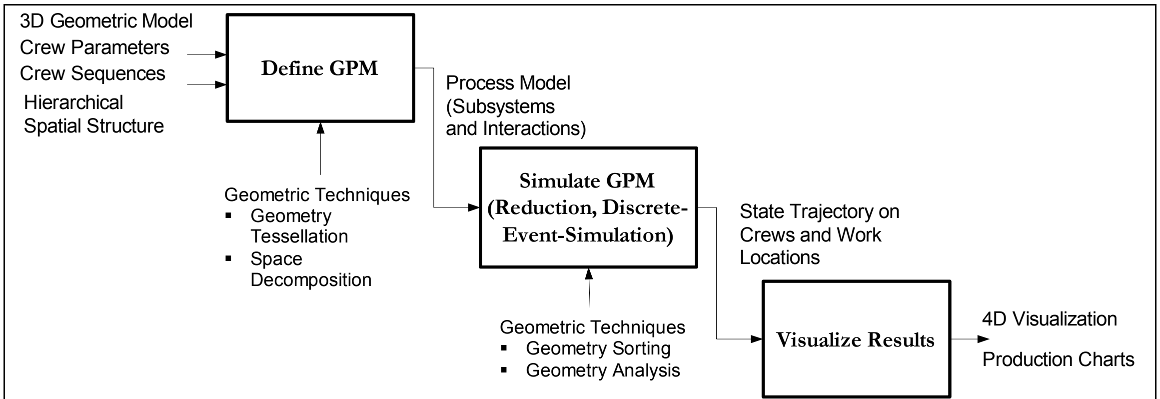


Figure 1-2. The inputs, the outputs and the main steps for GSim.

GSim is developed in C++ and contains around 20,000 lines of code specifically for the implementation of the GPM approach. The basic functionalities of GSim are:

(1) Support organization of the project geometry using a hierarchical spatial structure. Use that structure and component types to decompose the construction process into subsystems.

(2) Support the interactive assignment of crews to subsystems and definition of production rate and workflow strategy parameters for crews.

(3) Simulate the construction process automatically using the input parameters.

(4) Implement the geometric representation and algorithms to support modeling and simulation.

(5) Depict the results of the simulation as 4D visualization and crew performances over time.

(6) Import 3D geometry and crew parameters.

(7) Support work balancing in 3D and zone generation.

Chapter 6 explains the implementation in detail. I conclude this chapter by describing the history and methodology of this research.

1.7. Research History and Methodology

The primary steps for this research have been defining the research questions, theory and model building, case studies, prototype development, and validation in an iterative fashion. Overall, I followed three main cycles of these steps during this research.

To define the research questions and perform the research, three main areas provided knowledge sources and inspiration. The first is construction management related: observations at construction sites, interviews with construction professionals, as well as analysis of existing construction planning, scheduling and simulation techniques. The second main area is various fields in computer science: geometry related fields such as geometric algorithms, geometric modeling, computer graphics and other related fields such as computer vision, data structures, and automata theory. The third main area is formal theories on modeling and simulation.

The first phase of my PhD research was on the broad research question of how the 3D geometry can be used to improve construction planning. I had practical experience with 3D modeling for various projects and observed that the contribution of geometric models to the construction planning process is very limited. My personal interest in computer graphics and geometric techniques and construction project management combined with existing 4D CAD research provided a good fit. During this first phase, the initial research question was the formalization and automation of product model transformations from design to construction planning.

An internship at the Experience Music Project construction in Seattle, WA provided me an early test case on complex geometry related planning problems at construction sites (Akbas and Fischer 1999). The project used a 3D model as the primary construction document. The construction was challenging with complex building shapes, limited access and work spaces, and even a monorail operating within the job site. After this experience, I developed prototype algorithms based on CAD software to manipulate the geometry for construction needs.

The start of the second phase and my next practical experience was an internship at Walt Disney Imagineering Research and Development. During this phase, my research questions were on construction zone generation. I was lucky enough to approach the problem from both the software development and construction management perspective. I developed software code related to 4D CAD, explored different geometric representations and algorithms and implemented appropriate techniques on triangle meshes.

The main outcome of the second phase was definition of various types of zones, factors effecting zone generation, and a set of mechanisms to generate zones (Akbas and Fischer 2002). Each mechanism used geometric algorithms to manipulate component geometry and schedule activities. These mechanisms allowed me to demonstrate the basic ideas and get valuable feedback from researchers and practitioners. I described the construction planning knowledge necessary for zone generation on geometric models, such as crew production rates, production rate modifiers such as shape factors and the crew workflow direction. Additionally, I defined a hierarchical spatial structure to automatically generate the physical project organization. This spatial structure allowed decomposition of the construction process and description of construction process parameters.

During the second phase, I extended my construction case studies at Disney's California Adventure project and the Disney Concert Hall project. Disney's California Adventure became the main test case for this research. The case study on the Disney Concert Hall revealed the value of state management for multiple crews working in the same area and representation of direction of workflow on general and complex surfaces.

This dissertation reflects the last phase of the research formulation. It provides an overall modeling and simulation framework for my studies, utilizing the test cases, practical experience and various outcomes from the previous phases. Zone generation became one application of the research. I reused the geometric techniques from previous phases under new geometric formulations. I generalized the workflow strategy and production rate function to describe subsystems and formalized techniques for simulation. I extended GSim to support the theoretical improvements in this phase. The Emeryville Bay Street project provided additional data for validation in this last phase.

1.8. Reader's Guide for the Dissertation

In this chapter, I presented an overview of this research, including the practical and theoretical motivation, overall purpose and the domain, introduction to the test case and the implementation. The following chapters proceed in the manner of previous work, model definition, analysis, geometric techniques, implementation, validation and contributions.

Chapter 2 describes the previous work on and related to construction process models and the theoretical basis for modeling and simulation.

Chapter 3 formally introduces and defines the process modeling approach.

Chapter 4 is on the simulation and evaluation of process alternatives using the process model.

Chapter 5 explains the geometric techniques necessary for the process modeling and simulation.

Chapter 6 presents the implementation of the GPM approach.

Chapter 7 describes the validation for the research contributions.

Chapter 8 is the contributions and future work chapter.

CHAPTER 2

BASIS FOR THE PROCESS MODEL

The construction process, by its multiple-participant and multiple-trade nature, is modeled with a number of existing approaches at various levels of detail and for various purposes. Inevitably, there are different perspectives and overlaps among these approaches. The primary purpose for GPM (Geometry-based Process Model in this research) encompasses construction process design, analysis, and control. It models and simulates the production and spatial characteristics for construction crews on geometry in various ways.

This chapter introduces the related background for this research. It starts by framing this research among other construction process modeling approaches. Then, the chapter summarizes the related work on construction planning/scheduling, construction process modeling, simulation and visualization using this framework. It also gives a short introduction on related formal modeling concepts using systems theory.

2.1. Categorization of previous work on construction process modeling

This research embraces a process modeling and simulation perspective based on geometry. Models for other project aspects such as project organization, cost estimating and control, material supply chains, or information management are out of scrutiny.

This section provides a framework to categorize various aspects of related work. It uses analysis type (or modeling purpose) as the main differentiator among previous work. Spatial content and reasoning and level of detail are the other important parameters. Using this framework, Figure 2-1 categorizes some of the related work mentioned later in the chapter.

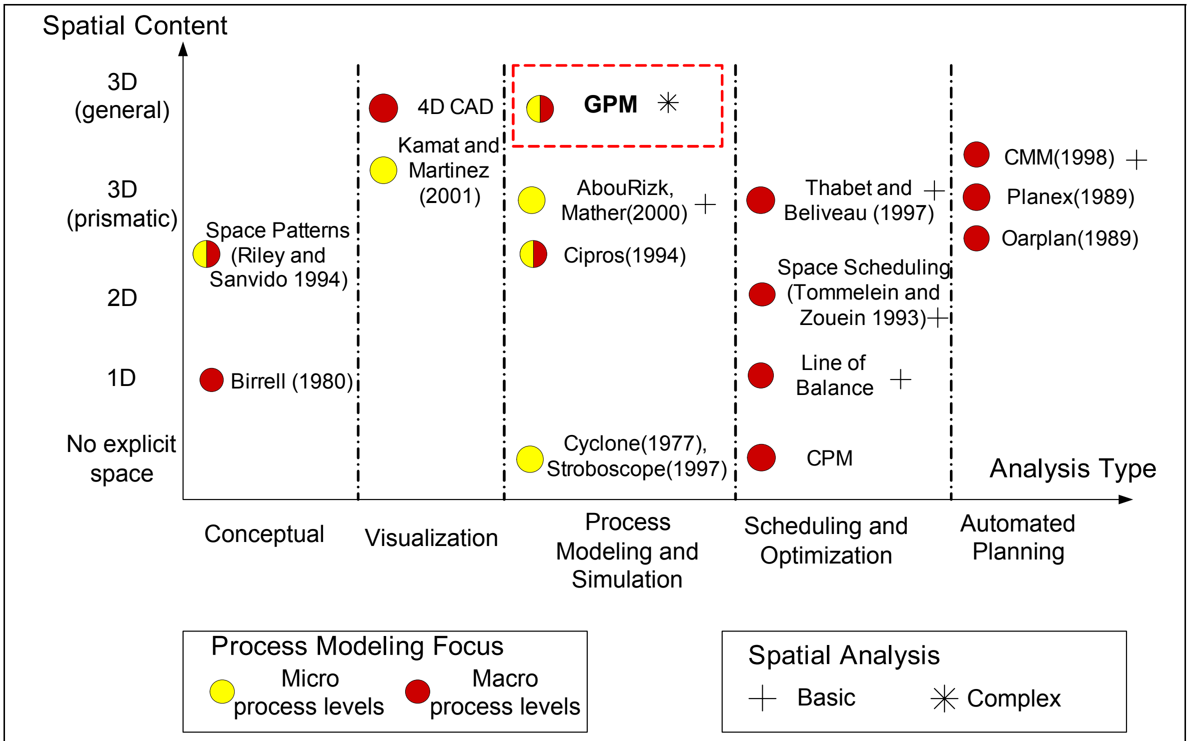


Figure 2-1. Categorization of related work for GPM.

2.1.1. Process analysis type

One way to categorize process modeling techniques is by their analysis type or their purpose. Ordered by increasing level of automation, the categories relevant to this research are conceptual, visualization, simulation, scheduling and optimization, and automated planning models. This categorization reflects the perspective of GPM and the distinctions between these categories are not always clear-cut.

Conceptual models describe their process of interest with limited effort to formalize and implement the model contents. The models for *visualization* focus on visually conveying information by transforming data and rely on the user to evaluate the model. Models for *simulation* focus on evaluating their process of interest for various model parameters. Models for *scheduling and optimization* and *automated planning* models define schedules and generate plans for the construction process.

2.1.2. Spatial content and analysis

Using geometric techniques to represent and reason about spatial content of a project is an important characteristic of this research. Characteristics such as space interactions and space use patterns can affect construction planning significantly. The spatial content for a process modeling technique ranges from no explicit space representation to 1D, 2D, prismatic 3D and general 3D models. The flexibility and accuracy of geometric representations can be different (see Section 5.3).

Another aspect of the spatial content is the existence and complexity of spatial analysis based on geometric techniques. Use of geometric models does not always point to effective spatial analysis. The spatial analysis in a process modeling technique can range from no explicit space analysis and basic spatial analysis to complex spatial analysis. Detection of crew interferences using intersection of lines, distance calculations, and checking if a component is within a space are all examples of basic spatial analysis. Complex spatial analysis includes geometric algorithms for manipulation and reorganization of geometric models, as well as using geometry as a way to describe construction process aspects.

2.1.3. Process level of detail

Process planning for construction projects is performed at multiple levels. The level of detail of planning and scheduling is highly variable depending on the individual project and who will be using the information (Clough et al. 2000). Section 2.2 discusses the need and approaches for project planning at multiple levels. There is no consensus on the definition of these levels. Halpin and Riggs (1992) describe a multi-level hierarchy for operations in construction management. The levels include project, activity, operation, processes and work task in increasing detail. An activity is for time and cost scheduling and control purposes. A construction operation results in the placement of a definable piece of construction. Work processes have a technological sequence focus. Work tasks are the elemental works in the construction process.

For evaluating previous work, I use *macro* and *micro* levels as a simpler categorization for the process levels. A macro level is any level higher than the operations level (project and construction activity). Micro level corresponds to *operations, work process*, and *work task* levels.

2.1.4. Summary of GPM

Within this framework, GPM is a process modeling and simulation approach that can work in both macro and micro levels, uses general 3D spatial content and supports complex geometric analysis. It makes use of various conceptual models to formalize its approach (Birrell 1980, Riley and Sanvido 1994). It adopts 4D CAD to visualize the construction process, and bases the visualization on simulation results. Unlike the other construction process simulation techniques, GPM includes 3D spatial content in its description of the simulation model and performs complex geometric analysis. However, unlike most other simulation approaches, the simulation of GPM is currently deterministic and the work task level is not considered. GPM is not a scheduling technique or an automated process planner, but can help with various aspects of the planning and scheduling process.

I start the following sections by explaining the existing construction planning, scheduling and control techniques. I then describe conceptual models built for better understanding of the construction process. This description includes how every aspect of the process interacts and how conversion activities are located within the overall construction process and portrays the properties of related aspects such as space use patterns and production rate. Subsequently, I point out related process design and analysis techniques, primarily construction process simulation.

2.2. Models for project planning/scheduling/control

The basic planning and scheduling tasks for construction projects are defining work breakdown structures, defining activities, estimating durations and sequencing activities. Work breakdown structures (WBS) define the project scope in manageable pieces. This structure is hierarchical and organized in different forms depending on the project. Various coding structures exist to organize (or decompose) the building facility elements. The Masterformat (Institute 1992) provides the most widely used standard for coding of building facility elements.

The pieces at the lowest level of a WBS are the work packages. A work package is "a deliverable-oriented grouping of project elements that organizes and defines the total scope of the project" (Project Management Institute. 2000). Halpin (1985) states that "a work package is a sub-element of a construction project on which both cost and time data are collected for project status reporting. All work packages combined constitute a project's work breakdown structure".

The work packages are the basis for the definition of the activities in construction master schedules. Halpin and Riggs (1992) define an activity as "a time and resource consuming element of a project normally defined for the purpose of time and cost control by a planner, estimator, scheduler or cost engineer. Activities are aggregation of operations or processes that contribute to the completion of a physical component of the structure or the performance of a support service."

Master schedules depict the work performed at a macro level and are used to plan major work assignments to all crews and coordinate off-site activities, equipment and manpower acquisitions for construction projects. Network based models (CPM) are the most common method to describe and manage master schedules. In master schedules, a rough range for average activity duration is between 5-10 working days. The work packages and activities are also used in project controls to relate the feedback from the site and update the design for the operations.

In contrast, techniques for operation (or production) planning coordinate various resources in a shorter time period, e.g., coordinate subcontractors, prevent conflicts, and control material and delivery. Operation planning is usually performed on site by site superintendents and specialty subcontractors. Consequently, there is often a disconnect between master schedules and production planning.

2.2.1. Network based models (CPM)

Currently, the most common technique used in practice for macro-level construction planning and scheduling is the critical path method (CPM), a network based project scheduling technique. Many existing software products such as Primavera Project Planner (2000) and Microsoft Project (2003) use CPM techniques for project scheduling. CPM schedules are typically used to provide an overall view of the project, activity durations, sequences, milestones and criticality of activities.

The CPM model contains activities and precedence relationships. The CPM algorithm defines the path(s) (sequence of activities) that provides the shortest project duration among all possible paths. The main outputs are the range of possible activity times, critical activities and floats (flexibility in performing activities), and cost and resource information related to activities.

The CPM technique is mainly useful for master scheduling. The main limitations of CPM for operations management are as follows:

- CPM schedules, when used for operations planning, become hard to manage, maintain and track because of the increased number of activities and relationships. Increasing the number of sequencing relationships opens the schedule for inconsistencies.
- Activities do not represent production characteristics for installation. The CPM activities are the basic unit of analysis for the schedule and are aggregations of a set of construction processes, lacking information about ways to perform these processes.
- Activities and their sequences do not represent spatial characteristics of the work performed, such as the crew workflow directions or the desired spatial buffers between activities. To support such characteristics would require many activities and spatial characteristics implicitly represented via precedence relationships, which makes the definition and maintenance of such a schedule hard. Spatial locations and physical components are not directly related to activities.
- CPM networks do not model work continuity for activities that are part of a wider workflow. LOB techniques aim to resolve this for linear or repetitive activities.

The geometric nature of GPM provides ways to overcome some of these limitations. Although GPM is not a scheduling technique, it can describe spatial characteristics of crews, relate production at multiple levels using geometric information, decrease necessary precedence relationships and support work continuity requirements between crews.

2.2.2. Look-ahead schedules

A common industry practice to overcome the shortcomings of CPM schedules for operations planning is to use *look-ahead* or *short-interval* schedules to show near-term activities (commonly a two or three week range) in more detail than the master schedule. Several previous research efforts have identified the value and the need for look-ahead schedules (Ballard 1997; Hinze 1998). However, look-ahead schedules are prepared manually or using a set of heuristics from the master schedule and resource input. Therefore, the consistency between the master schedule and look-ahead schedules is limited.

Similar to the CPM networks, look-ahead schedules do not explicitly relate to the spatial aspects of a project. In areas where spatial interactions are critical, site personnel develop hand-colored blueprints to evaluate and explain actual or planned work progress. In addition, look-ahead schedules are done shortly before the construction, so the opportunities to identify possible problems and proactively consider alternative workflows are limited.

An even more detailed approach is weekly work plans, developed by foremen of crews who will actually perform the work (Gil et al. 2000). In two related systems, Last Planner (Ballard 2000) defines a methodology to generate assignments for look-ahead schedules and weekly work plans, and WorkPlan (Choo 2003) describes ways to coordinate these plans among project participants. Again, the connections to the master schedule are limited at this detail and there is no link to the geometric model of the project.

2.2.3. Linear scheduling models

Another group of scheduling techniques, mainly for linear and repetitive activities, is linear scheduling or line-of-balance (LOB) techniques. The purpose of these techniques is to ensure that each resource can progress from one activity to the next in an orderly way, and provide continuous utilization of resources if necessary. The diagrams for these techniques represent the progress information linearly or unit by unit, so they are limited for linear or repetitive tasks in construction (Kavanagh et al. 1985; O'Brien 1975; Selinger 1980; Stradal and Cacha 1982).

This technique, originally developed for industrial production planning (Lumsden 1968), analyzes the required rate of finished products and builds up the necessary production rates of all assemblies feeding into the finished product, back to the ordering of materials.

In building construction, trades move from location to location in 3D around installed components and complete the work that is prerequisite for the following trade. Furthermore, LOB, in a diagram form, can only present a limited amount of information. Many extensions are needed for these techniques to support construction work in general (Arditi et al. 2002). GPM supports general crew workflow representation on geometry, a production rate function supporting variations in production rates, and detection of interferences between crews to improve LOB methods.

There are various efforts to combine CPM and LOB (Perera 1982; Russell and Wong 1993; Suhail and Neale 1994). GPM takes a different path, modeling the process using detailed work locations based on geometry. Using this approach, the differences between these techniques decrease significantly.

As an extension of LOB methods using 3D geometric models, Thabet and Beliveau (1997) describe a planning and scheduling technique based on space use of activities for multistory building construction. They consider space as a consumable resource and describe space consumption of each crew over time. They abstract activities into different classes based on space requirements and consider the workflow direction for each crew as either horizontal or vertical. They decompose the project geometric models into structure grid blocks and analyze each space separately. The spatial information that drives the scheduling process is the enclosed space of the grids, instead of components enclosed in the space. Additionally, their technique supports only basic spatial analysis. GPM makes more general use of crew workflow directions and incorporates more geometric techniques to increase the applicability of LOB methods.

2.3. Conceptual process models

Existing conceptual models are informative to provide a theoretical basis for GPM. This section gives a brief overview of the conceptual construction models to position the physical conversions within the other aspects of the construction process. Next, related conceptual models that describe how construction professionals design the work processes are summarized. GPM describes how crews perform work as a workflow strategy and at what rate they perform work using the production rate function. It also combines crews to describe subsystems. Therefore, other related models are for spatial characteristics for crews, production rates of crews and relationships between activities.

2.3.1. Construction system overview models

Construction is a combination of many interconnected dynamic processes categorized by different types of trades. System overview models provide a general description for construction processes to better understand and describe them. Sanvido (1988) describes a conceptual model for site management activities to support work-face processes. Figure 2-2 shows the scope of GPM within this model and how other site processes can be related to it. Sanvido's model contains two kinds of management inputs: resource controls and work plans by which physical inputs will be converted to outputs. Resource controls include acquiring services and resources, transporting to site, storing and distributing resources. A work plan describes how to convert inputs to outputs. The basic model in GPM focuses on the work plan.

Koskela (1992) conceptualizes the construction process as composed of conversions (or transformations) and flows and extends this conceptualization to transformation, flow and value in Koskela (2000). The flow processes are material, information and work flows. He suggests that traditional network planning fails to support the planning of work flows of teams or material flows and may lead to suboptimal flows. In GPM, the conversion processes are the focus of the model. However, work flows for crews are incorporated as a part of workflow strategy and material flows can be input to the process model as a part of the production rate function. In other words, in GPM material flows and work flows are not separately modeled as processes, but used as inputs to the process model.

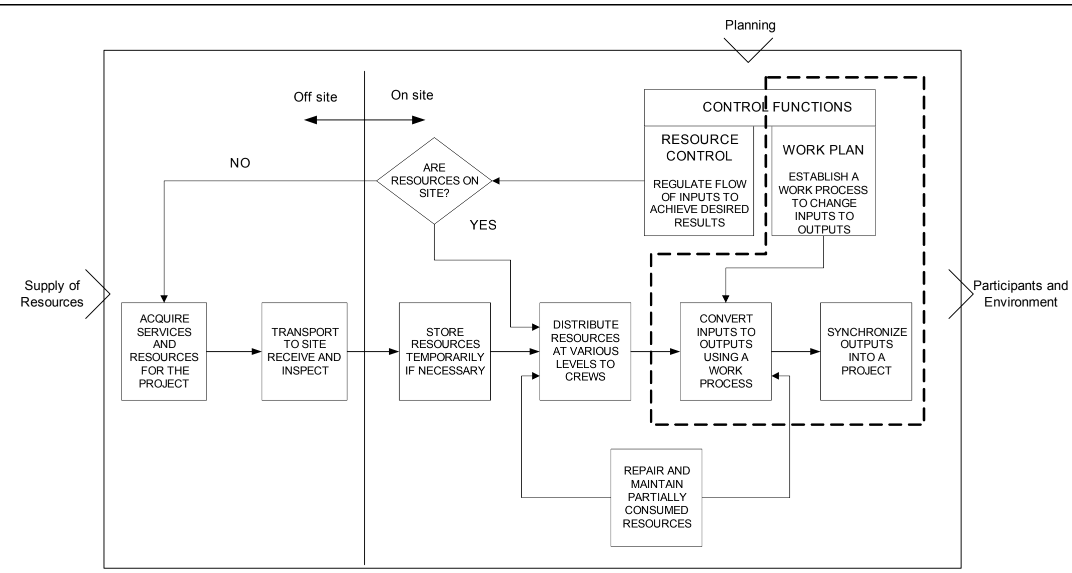


Figure 2-2. The focus of GPM within site management activities. Figure adapted from Sanvido (1988).

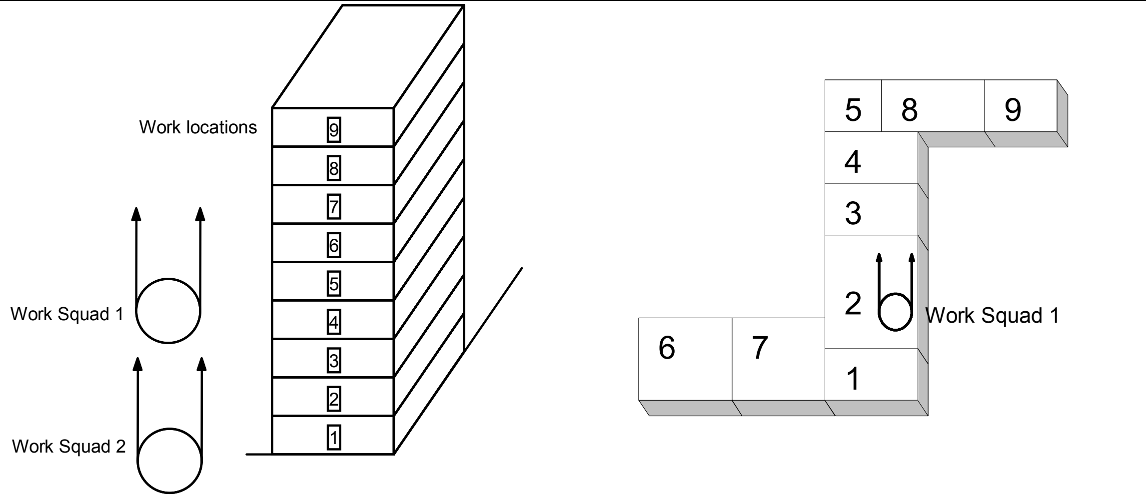


Figure 2-3. Basic elements of Birrell's model (Birrell 1980). Work squads sequentially process work locations. Work locations are at the macro-level (floors or housing units).

2.3.2. Conceptual planning models

One of the conceptual bases for GPM is Birrell's model. Birrell (1980) presents a conceptual, heuristic construction process model that is derived from actual practices and existing theories on construction planning (Figure 2-3). He suggests that the superintendent decides on the work locations and the flow and sequences of crews performing work on locations, placing a space buffer between crews if necessary. Examples of work locations are floors in buildings or individual housing units in a housing project. Accordingly, one of the main goals of construction process design is to provide the rhythm in the process. He considers each type of work at a work location as a work package. He suggests the use of queueing theory with work locations as customers and crews as servers as a modeling technique to support such a conceptual model. Other suggestions are using discrete event simulation to analyze such a system, and he suggests that this model can be combined with cost and schedule control.

Other significant aspects of Birrell's model are viewing construction projects as an aggregation of smaller projects and his suggestion of using work locations to decompose a project into sub-projects. He adds that a contractor cannot impose construction methods and use of resources on every subcontractor.

However, Birrell's model description lacks support for a geometric model and spatial analysis. The work locations are simplistic, manually defined, at the macro level and should be identical for all crews. Additionally, all crews are assumed to follow the same work location sequence. The interactions between crews at separate work locations are not formalized. I provide a general, computational model extending the basic ideas in this viewpoint. Processing of work locations in Birrell's model corresponds to subsystems in GPM.

2.3.3. Models for spatial characteristics of construction work

If crews share space while performing work, they may interfere with each other's work. One crew generally cannot proceed efficiently until the other finishes and moves to another location. Therefore, for planning purposes, modeling the direction of workflow for construction crews is crucial. CPM does not capture this information (Birrell 1980, 1986). Linear scheduling techniques conceptualize space use as a fixed direction for directional workflow, for example horizontal to north, vertical up. Other research also models space as a fixed linear direction, e.g., Thabet and Beliveau (1997).

Riley and Sanvido (1995) summarize the work-space planning literature as falling into three categories: site-layout techniques, spatial characteristics of construction work, and methods to quantify space need. GPM uses spatial characteristics of construction work, specifically work area patterns.

Riley and Sanvido (1995) describe a conceptual model for the space use in multistory building construction, describing patterns for various space types. They find that work area patterns for multistory building construction are linear, horizontal units, vertical, spiral, building face and random. Different types of activities in multistory building construction (enclosure, interior and core) use different patterns. For example, enclosure activities tend to follow each other to wrap the space they belong to. Workflow strategy formalization in GPM provides a general representational framework for workflow direction capable of representing these patterns and types of activities.

Akinci et al. (2002) determine the micro-space requirements of activities computationally, given the construction method and component geometry. They also analyze time-space conflicts based on this model, with the assumption that the work locations are correctly defined at the micro level. However, they do not computationally represent the crew flows and do not use work area patterns in analysis.

2.3.4. Models for crew production rates

Section 3.2.2 describes a simple production rate model for GPM, in which the crews are the processing units on geometry and various factors such as shape effects and resource availability are considered. Several previous efforts consider factors on production rates.

In construction, the estimation of production rates is mostly at the activity level and effects on production rate are described as a factor. 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 production rate, e.g. masonry walls with corners that are not perpendicular, and have assigned a factor (called *work content*) to describe effects of shape on production rate. However, these research efforts do not consider shape variations within a component; instead they assign a bulk factor for the whole component. Other research efforts use a linear combination of several factors to model effects on the production rate. For example, O'Brien (1998) considers modifiers for shared site resources, access paths, site cleanliness and work area availability. GPM can represent the effect of shape on production rate locally. Additionally, it can consider effects of nearby work, resource availability and the work progress of a crew.

2.4. Process modeling and simulation

A good process design requires understanding and description of the nature and prediction of the behavior of the actual system. Simulation, specifically discrete event simulation, is a commonly used technique in construction research for design and analysis of construction processes. It was introduced to construction processes with the development of the CYCLONE modeling methodology (Halpin 1977). Since then, it has been a basis for various construction simulation systems, e.g., INSIGHT (Paulson 1978), STROBOSCOPE (Martinez and Ioannou 1999). The state-of-the-art construction simulation tools allow flexible and detailed modeling of construction operations. They can provide information about resource utilization, idleness, operation bottlenecks, and production rates.

However, simulation models have limited successful applications in construction practice, mainly because of complexities involved in constructing a model and the resultant time required (Shi and AbouRizk 1997). Their main use tends to be for processes with repetitive or cyclic nature at the work task level. Accurate representation of processes requires detailed simulation models with considerable effort required to build these simulation models. In addition, the focus generally is on a particular type of work, with the simulation model considering only limited amounts of interactions with other work performed on site. Once the simulation parameters are defined, they are kept constant during simulation. Additionally, construction planners are reluctant to base their decisions solely on statistical and chart reports.

Techniques to reduce the necessary simulation modeling effort concentrate on model reusability and graphical modeling interfaces. Sawhney and AbouRizk (1995) explored modularity and hierarchy concepts to define basic simulation building blocks to support separate queue types, various types of variability and interactions between process elements.

Construction simulation models usually do not have specific reference to geometry. Consequently, the changing in space requirements and spatial effects are not considered in most simulation models.

Ashley (1980) applies simulation to repetitive unit construction with crews as the servers, and work locations as the customers waiting to be served. User can change decision variables such as equipment usage, crew size and allocation of crews to different tasks. Then, the user can explore the impacts of changing the variables by comparing values such as crew utilization and waiting time. However, the input of the simulation model requires the time-consuming use of a low-level language. The suggested duration to build and use a network of 10 activities and 8 different alternatives is one man-week. The lack of a geometric model limits its use in several ways: model building is time consuming, it works at a macro level and interpretation of simulation results is hard. The approach in GPM simplifies the input using geometry and the results of the simulation can easily be visualized.

CIPROS (Tommelein et al. 1994) uses the CPM network, some semantic information about components, method information and available resources to describe a simulation network. The method information is defined in terms of elemental simulation networks with CYCLONE style primitives. CIPROS creates elemental networks for each CPM activity in the schedule. Assembly of these elemental networks provides the simulation model, which is then simulated. As a result defining an intermediate simulation model based on CPM activities, the model size and interactions between modeling primitives can be excessive. In contrast, GPM generates the simulation model directly, once the process model is built. CIPROS also does not use a geometric model for deriving parameters, interactions, and visualization.

AbouRizk and Mather (2000) simulate earthwork operations by relating the simulation model to geometric models in an external CAD software. They decompose 3D CAD geometry into pieces defined by a structured grid and manually assign the order and construction method for each grid element. Each grid element becomes a submodel of the original simulation model. The spatial content is externally linked to the simulation model, the spatial analysis is basic, and the technique is earthworks specific.

Overall, the purpose of GPM is similar to the previous work on simulation, namely to evaluate alternatives by changing different parameters to design better operations. In GPM, once the construction process system is described, there is no need for a separate simulation model. The modeling parameters directly reduce into a simulation model. Users can dynamically update the input variables during simulation. The generated state trajectories directly support visualization.

2.5. Visualization and automated process planning

2.5.1. Visualization models

This section is interested in visualization models for construction processes that use geometric models to describe the spatial aspects. Effective navigation and animation tools for construction projects are available. However, models built solely for visualization purposes lack support for effective analysis methods.

Data and information visualization aims for visually conveying some information using graphical representation of data and concepts. Visualization is a graphical representation of data and concepts (Ware 2000). It provides ways to convey information derived from a model, relying on users for interpretation and pattern detection.

4D CAD (or 4D) is a geometry-based construction process visualization technique (Koo and Fischer 2000). Its basic goal is the time-lapse visualization of a construction process by association of components and CPM schedule activities. It visualizes the installation states (the start and finish dates of activities) for the 3D geometry of the finished facility using the color-coding of the associated activity types. 4D models use a discrete-time scale; changing project time gives a visualization of project states at that time instant. Various extensions are available for 4D CAD to enhance its use with extended semantic content, provide better visualization and use it for planning.

4D CAD is an effective means for communicating temporal and spatial information to project participants. It can support accurate spatial content depending on the geometric model. However, 4D CAD is typically more useful at a macro level. Its basis on CPM networks and input 3D geometry limits its utilization for operations planning. It carries over some limitations of CPM; it assumes the production rate is constant for the duration of an activity, and it does not capture or visualize the reasons behind an existing plan or any geometric planning parameters, such as workflow directions.

For 4D CAD, matching the geometric representation with the process description requires manipulating input geometry and the schedule activities and associating the resulting elements. However, this approach is time consuming, error prone and it makes no explicit use of construction process information for geometry and activity manipulation. Whenever a change occurs in the plan, the 4D model needs manual updates. Therefore, it is impractical to consider many alternatives with 4D models.

Some researchers describe techniques to visualize the results of discrete event simulation of construction processes based on 2D or 3D. Ioannou et al. (1996) create a text file during simulation to drive a 2D visualization software and animate the simulation results by changing the position, shape, and color of icons to represent resources on 2D drawings. Kamat and Martinez (2001) extend this idea to 3D visualization tools, generating a text file as an output from STROBOSCOPE to graphically illustrate the construction operations as simulated in 3D. However, the spatial content in the 3D models are not part of the simulation, and the geometric models still need to be manipulated for visualization purposes.

GPM combines various styles of visualization to convey process information. For spatio-temporal visualization, 4D CAD is the approach of choice. GPM can use data input from 4D CAD. Use of geometry manipulations and spatial organization in GPM can simplify generation and maintenance of 4D models.

2.5.2. Automated process planners

Automated process planners generate tasks required to reach a goal state, assign resources to tasks, sequence these tasks, and calculate their durations. Construction process planners automate this process for construction, preparing a construction plan and a schedule, and assigning required resources for the process of interest as a result (Zozaya-Gorostiza et al. 1989).

The purpose of GPM is modeling and simulation, rather than automated process planning; it assumes the crews and their sequences are given. However, existing research on automated planners is relevant in several ways, such as capturing planning methodology, managing the process level of detail, and spatial content and reasoning.

Process planners mainly use two strategies for planning: top-down or bottom-up. Top-down planners use *elaboration* (or task-decomposition) mechanisms to generate a detailed plan from a macro plan, making use of the physical organization of the project. The elaboration mechanism stops when the most detailed representation for the components is reached, in which case activities associated with the components are created. In some cases, they aggregate the activities to an appropriate detail. OARPlan (Darwiche et al. 1989) associates components and activities as pairs at the beginning of the planning process and keeps that association fixed during planning. In effect, this requires a joint hierarchy for both the activities and components and prevents independent generation of these hierarchies. This approach generates activities using the product structure. ZonePlanner (Winstanley and Hoshi 1993) is an extension to OARPlan, which tries to optimally aggregate detailed sets of activities to create subnetworks.

An example bottom-up planer is Planex (Zozaya-Gorostiza et al. 1989). Planex utilizes a coding scheme based on Masterformat to obtain a hierarchical organization for both components and activities by material, component type, and location. Its first planning step is decomposing the model of the finished facility into primitive *design elements*. Planex then determines the activities required to produce each design element, which are called *element activities.* Subsequently, it aggregates element activities into project activities. The location information describes a fixed and predefined (floor, sector, and project) spatial decomposition for the project which needs to be manually assigned to each component. This is limiting, because planners might have different preferences in physical organization of the process than the organization of to the finished facility.

GPM has similarities to both top-down and bottom-up approaches. The region hierarchy and other geometric techniques can decompose the components top-down using the planning parameters. Similar to the bottom-up approach, after simulation using detailed work locations, activity durations can be obtained at the desired level of detail.

Automated process planners commonly use physical support relations to determine the sequence of activities, e.g., Planex (Zozaya-Gorostiza et al. 1989), Ghost (Navinchandra et al. 1988), Builder (Cherneff et al. 1991), CMM (Fischer and Aalami 1996). The supporting component should be installed before the supported component can start. For example, footings must be installed before work on columns can start. Similarly, some activities cannot start unless its required work is ready. For example, scaffolding should be installed for the activity that requires scaffolding to start. Echeverry et al. (1991) describe general factors for sequencing of construction activities, including physical relationships among building components, trade interactions, path interference, and code regulations. GPM describes interactions between subsystems that is inspired by and that can support some of these relations (Section 3.4).

One significant limitation of existing research on construction process planners is their limited spatial analysis capability. Planex and OARPlan use axis-aligned prismatic shapes for component geometry. Component geometry is kept fixed throughout the planning process and there is limited consideration of local geometric properties. The activities generated depend on the most detailed component representation and the original organization of the project.

Some automated process planners utilize geometric models during the planning process. Morad and Beliveau (1994) presented an automated planner, KNOW-PLAN, which uses information extracted from 3D CAD models in its reasoning. KNOW-PLAN extracts the bounding box information for 3D CAD models and performs basic spatial analysis, such as calculating height differences and sorting components in a single axis for planning purposes. It then sequences the activities using a set of rules. Cherneff et al. (1991) developed Builder that has a CAD modeler and uses sequence, production rates, and resource availability to determine the plan. CMM (Aalami 1998) defines construction method model templates extending the OARPlan methodology so that planners can automatically develop schedules from CAD models. CMM supports general geometric models and performs simple spatial analysis but gives inadequate consideration of important geometric elements for the planning process. For example, it sequences work without an underlying directional workflow strategy.

2.6. Information content for the product

One basic construct for GPM is a model for the finished facility, composed of a set of physical components. Each component can have geometry, materials, and assembly information. This section describes relevant information modeling approaches for the representation and organization of physical components.

Much effort has been done on the electronic representation of the product and processes for information sharing and integration purposes (Froese and Paulson 1992; Yu et al. 1998). Large amounts of data are generated during a project. Architects and engineers provide information as design drawings and specifications, generally representing the final shape of a component. Product and building modeling is a general effort to develop an electronic representation of a building, in a form capable of supporting all major activities throughout the building lifecycle (Eastman 1999). Product models can contain a wealth of semantic information about the products that they represent other than the geometric representation. These models focus on defining a core schema sufficient to share and integrate information between different applications, participants and phases. Since project planning and control require information from different sources, a shared information representation is useful. However, GPM focuses on minimal semantic information for a physical component: its type information and a descriptor. Detailed product models are not needed for this research.

2.7. Formal approaches to modeling and simulation

The previous sections described the related work from the construction perspective. This section shifts the focus and introduces general approaches for formal modeling and simulation of a system of interest. A formal modeling and simulation technique for physical conversions in construction processes is an important goal of this research. Specifically, I consider the physical conversions in construction processes as a *discrete-event system* (Cassandras and Lafortune 1999; Zeigler et al. 2000).

2.7.1. Systems concepts

The approach followed in GPM has origins in general systems theory. Systems theory describes an input-output model. Mathematically, the behavior of a system is converting input variables into output variables. There is a clear partition of state variables in a system. Input variables are variables that can be controlled, and output variables are variables that can be observed. The internal structure of a system completely determines its behavior. Internal structure of a system includes *states* and *state transition mechanisms*. A *state* is a set of parameters and variables that allow for monitoring, recording and possibly control of an entity. Each state variable has a *state space*, usually denoted by X, which is the set of all possible values that the state may take.

A system also has associated temporal semantics. *State changes* or *state transitions* are a set of variations in descriptions and/or values observed in some or all of the states that emerge in time. A state is tagged with the moment of time. The state of a system at a time instant t should describe its behavior at that instant in some measurable way. *Events* cause state transitions. *State trajectory* or *sample path* is the solution function for how a state evolves over time. Mathematically, the temporal strings of state changes are called *processes*.

One way to characterize systems is by the governing state variable types: continuous, hybrid or discrete. For continuous variable systems as in the traditional systems theory, input-output functional relationships are differential equations. A discrete event system is a discrete-state, event-driven system, whose state evolution depends entirely on the occurrence of asynchronous discrete events over time. Therefore the state space is a discrete set and the state transition mechanism is event-driven. In discrete event systems, events occur instantaneously and cause transitions from one discrete state to another. Discrete event systems have many practical applications, such as communication networks, automated manufacturing systems, and traffic control systems.

There is a clear distinction between a system, model and simulator (Zeigler et. al. 2000). A *system* is something real (e.g., the physical conversions in the construction process in this research). A *system* contains all the relevant information of the real world structure it represents. A *model* is an abstraction of a system, which approximates its true behavior. A *simulator* is any computational system capable of executing a model to generate its behavior.

A model is “an artificial, symbolic or mental system, which is substantially simpler than a system of interest, yet gives an opportunity to reason about, or simulate the processes in the system of interest with accuracy sufficient for decision making” (Meystel and Albus 2002).

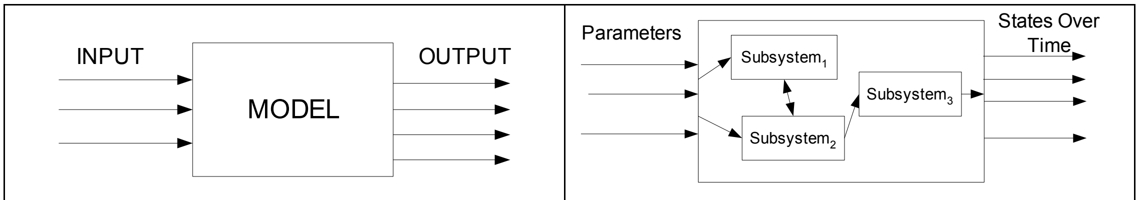


Figure 2-4. Application of discrete event systems theory: a) A general model description, b) A model decomposed into subsystems.

A system consists of interacting parts. Although both the terms of *component* and *subsystem* are used to describe parts of a system, GPM uses *subsystem* because of the use of the term *component* to reference physical elements in the construction literature. The subsystems can be coupled together to compose a system (Figure 2-4). Subsystems have fewer interactions with each other than within each subsystem. This property allows focusing only on individual subsystems and their boundaries to simplify the modeling process.

2.8. Summary

I described the related work for the GPM approach. This research combines and extends different aspects from previous work. The main points of departure are Birrell’s model, line-of-balance techniques, discrete-event-simulation, 4D models and general systems theory. I postpone the related work discussion for geometry techniques until the chapter on geometry techniques (section 5.2). The next chapters formally describe the process modeling and simulation approach.

CHAPTER 3

DESCRIPTION OF THE PROCESS MODEL

This chapter describes the process modeling approach formalized in this research in a bottom-up fashion. The goal of the approach is to represent the basic geometric parameters of the construction process. The modeling structure should easily support discrete event simulation and visualization while being compatible with common modeling techniques in practice, e.g. CPM networks and linear scheduling techniques. Furthermore, the modeling elements should be independent of the type of activities, components, or the geometric representation.

Overall, the input for GPM is a set of parameters describing planning decisions characterizing each crew and the interactions of the crews. After a simulation, the output is how the construction process is performed, stored as states over time on the crews and the locations. Therefore the output provides, at any time instant, the installation state at any work location and the location where each crew is working.

Construction processes involve complex interactions between equipment, crews and materials and are subject to multiple management, control and design objectives. Instead of analyzing the complete project at once, GPM models the process of interest as subsystems with boundaries and their interactions. It describes flexible ways to define subsystems and manage their states for simulation.

I first describe the basic process elements that support the goals of this research. The initial sections of the chapter are concerned with describing the behavior of the processing elements (crews), and the processed elements (work locations). I then explain the modeling of subsystems.

3.1. Definition of process modeling elements

The only process elements in this research are crews and work locations.

A *crew* is a work unit that has a specific resource composition and performs a specific type of work. *Trade* and *production unit* are synonymous terms in the context of this research. This crew definition is generally accepted in the construction industry. The next section gives a formal crew definition by describing its parameters.

A *work location* is a geometric unit of analysis for the construction process. The definition extends that of Birrell (1980) to permit the use of geometric models as process elements. To represent, simulate, and visualize construction processes on geometry, appropriate work location definitions are necessary. Examples of work locations are a footing, a column, a piece of concrete slab, or a triangle. Section 5.4.2 describes the geometric techniques to support work location definitions from geometric models.

The constraints associated with work locations should guarantee that they are simulated correctly. At any work location, there can be at most one crew working at any time instant, i.e., a work location must have a unique installation state variable. For any work location, there is a fixed ordering for the crew processing sequence. A work location should also be smaller than what a crew can perform in a time unit. Additionally, work location size should be bounded to limit the production rate variation for any crew to prevent inaccuracies in production rate calculations.

GPM uses discrete event simulation as the analysis technique. After simulation, different temporal and spatial views of the process can result. GPM provides formalizations for *activity* and *zone* to relate the results to existing process modeling techniques, such as CPM and LOB.

An *activity* is an aggregation of work that a crew performs in a physical space. An activity, therefore, has a processor (crew), has a scope of work (work locations), and a spatial boundary. This activity definition is compatible with CPM networks and linear scheduling techniques. However, in GPM, activities are not the units of analysis, but instead are the results of analysis. An activity in this dissertation can also refer to the traditional CPM network definition.

The spatial counterpart of an activity is a *zone*, i.e., zones are also results of analysis. A zone is an aggregation of work locations that a crew performs in a time period. The simplest descriptor for a zone is a spatial boundary.

3.2. Crew model

This section defines a simple model for construction crews with the goal of completely specifying their behavior of work location processing on geometry. This crew definition aims to better represent how construction crews perform work on site, supporting flexible directions of workflow and production rates affected by various factors.

The crew model focuses on the crew as the basic work unit, rather than the individual crew members and equipment. The process model formulation captures how each crew performs its scope of work with a *workflow strategy* definition and a *production rate function*. Workflow strategy supports various types of directional or workflow decisions. Similarly, the production rate function combines several production rate elements. Formally, the parameters describing each crew are:

$$Cr = (D, R, t_{mob})$$

where D is the workflow strategy, R is the production rate function and t_{mob} is the mobilization date.

The elements in this crew model are a generalization of activities (or flow-lines) in linear scheduling techniques (described in Section 2.2.3). Each activity in the linear scheduling method has a mobilization date, a fixed linear direction, and a fixed production rate. GPM extends the linear direction to general directions of flow and orderings of work locations using the workflow strategy. Instead of a constant production rate, GPM represents the rate of crew production as a function of multiple variables. The definitions of workflow strategy and the production rate function require further explanation.

3.2.1. Workflow strategy

There is lack of support for general crew workflow directions in construction practice as summarized in previous work on spatial characteristics of construction work in Section 2.3.3. This section provides a simple, general and computational specification of how a crew processes work locations. It allows easy specification for flows of crews and enables various methods to describe and capture the rationale for crews working on site. Combined with the definition of work locations, the workflow strategy can sort geometry to represent planning decisions. This research keeps this definition minimal, except one attribute that defines the smallest size of work due to crew constraints or for modeling purposes.

I define workflow strategy as a function that assigns an order, or a sequence, for each work location for a particular crew. This sequence reflects the preferred order in which a specific crew will process work locations within its scope. Whether this preferred sequence can be satisfied depends on the other elements of the project.

Formally, workflow strategy is a function D that creates a sequence $\{l_i\}$ for all work locations (denoted by l) within a crew's scope of work.

Although all workflow strategies are functions of similar nature, there are many possible ways to specify them, ranging from manual entry to procedural evaluation (Figure 3-1). The simplest way to specify a workflow strategy is explicitly defining a sequence by manual entry. While this is sufficient for a small number of work locations, it is cumbersome when the amount gets larger. Furthermore, manual entry does not capture the rationale for the sequence. At the other end of the spectrum, a procedural strategy can automatically evaluate the project state at any instant to determine a good sequence. An example is applying path planning using site accessibility information at a particular time.

This research focuses on strategy definition somewhere in between this spectrum, in which the user specifies the workflow strategy by defining workflow directions on geometry. It uses the geometric techniques described in Section 5.4.3 to represent the workflow direction as a vector field and uses that to capture various types of construction workflow directions. *Directional*, *radial* and *edges-first* are the formalized workflow direction types in this research. Directional workflow strategies assume that the strategy does not change over time for a crew within a particular scope.

Unit work area of the workflow strategy represents the smallest quantity of work location that is significant for modeling and simulation purposes. Unit work area affects the size or quantity of work locations that a crew can process at a time instant. Section 5.4.2 describes a rectangular tiling technique on geometry to consider unit work areas for crews during simulation.

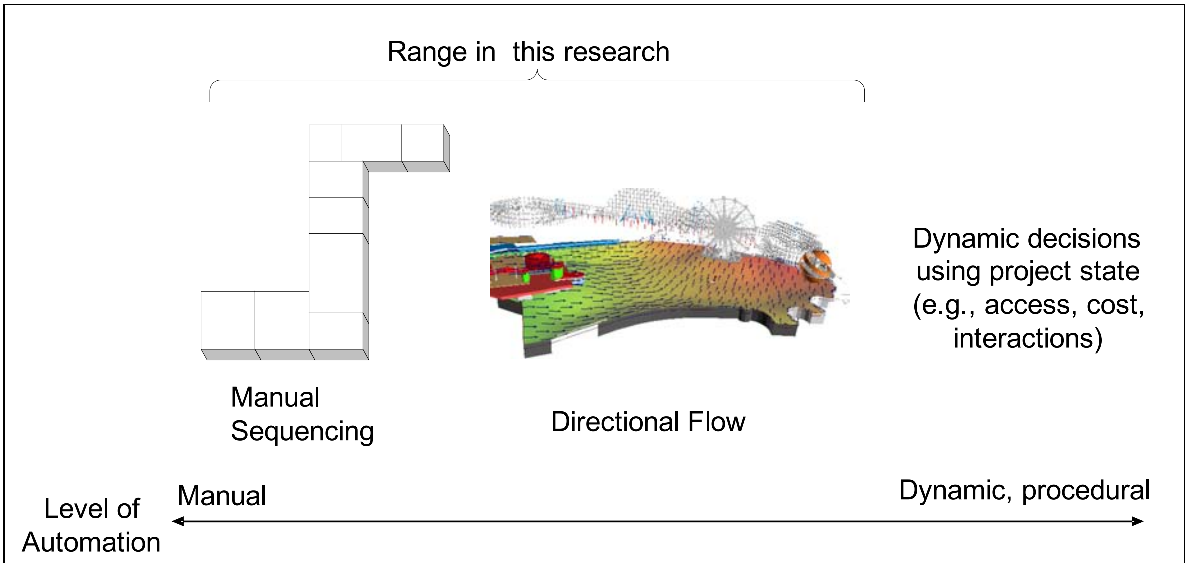


Figure 3-1. Range of possible approaches to specify workflow strategies.

3.2.2. Production rate function

I define a production rate function that specifies at what rate crews can perform work at a specific location at a specific time instant. The main purpose for the production rate function in GPM is to describe the performance of crews based on the geometry of the work locations during simulation considering different effects, such as shape attributes, nearby work, work progress and resource availability. The function elements take advantage of the GPM structure, i.e., the information about geometry and crews over time, to calculate the variations on the production rate. Previous work models the variations in production rate either as a constant factor or use random variables to consider the production rate in stochastic form (see Section 2.3.4).

The production rate is the main relation to calculate the serving time (duration) of a crew for a work location. It is the actual number of trade-specific *work units* per unit of time a crew is able to finish given constraints on their work (Tommelein et al. 1999). Work unit is the unit of measure that the crew uses, e.g., linear feet, each item. For any work location, the serving time is calculated with the basic equation:

$$t = r^{-1} * u \tag{3.1}$$

where t is the duration, r is the production rate and u is the quantity in work units. The production rate and the quantity should be using the same work units.

The production rate for any crew is a function of location, time and crew properties. A physical analogy for the production rate is velocity. When the production rate increases, more work is performed per unit of time. Instead of a constant or an explicitly specified production rate value at any location, the production rate model uses various factors. Each factor is expressed as a function and multiplicatively joining them evaluates the production rate for a crew for a work location. Factor coefficients vary from 0 to 1. A joint function value of 0 means that there is no work possible, effectively stopping the work of a crew at a location. A joint function value of 1 means that the production capacity can be reached.

Therefore, the production rate function in GPM is expressed as follows:

$$r(loc, t, crew) = \min(r_0 * k_{SF} * k_{WP}, r_{av}(t)) \tag{3.2}$$

where r_0 is the production capacity, k_{SF} is the shape factor effect, k_{WP} is the work progress effect, k_{NW} is the nearby work effect, and r_{av} is the resource availability, $k_{SF}, k_{NW}, k_{WP} \in [0,1]$. Figure 3-2 shows the elements of this production rate function.

Resource availability is a function of the global project time and allows the user to specify production rates for a crew at specific periods. In this research, production rates are deterministic. Description of the function elements are as follows.

Production capacity

Production capacity provides the number of trade specific work units per unit of time a crew is technically able to finish without constraints on their work. It is the constant element of the production rate function.

Shape factor effect

The GPM model introduces shape factor functions to represent the effect of a local geometric property on the production rate of a crew. Shape functions are functions of specific shape attributes at a particular work location. I have defined height, slope and distance to edge as the shape attributes supporting shape functions, that is $k_{SF} = f$(height, slope, distance to edge), where k_{SF} is the shape factor.

GSim derives the shape attributes from the geometric representation of the project (see Section 5.4.4). The shape functions are time-invariant (independent of time). This research does not make a comprehensive study of shape factor functions and assumes shape functions for different properties are independent of each other.

Work progress effect

Work progress effect is defined as a function of the percentage of work the crew has completed on a particular scope of work and accounts for the changes on production rate due to more work performed by a crew. This function is a simplistic way to represent learning curve functions expressing that the production rate increases after more of similar work is performed.

Nearby work effect

Nearby work effect is a function that accounts for the effect on the production rate of another crew working nearby. It reflects the effect of available work space of a crew on its production rate and is a function of the shortest distance from the active crew work area to other ongoing work. The nearby work effect is described in terms of the distance value at which the crew cannot perform work ($k_{NW} = 0$) and the distance value where there is no effect on the production rate ($k_{NW} = 1$). GSim uses the nearby work effect to calculate nearby work interactions between subsystems as described in Section 3.4.3.

Resource availability

Many factors that can affect a crew's production rate are not considered in this production rate model. One way to incorporate them is to provide a way to override other production rate elements using a function expressed as a time-series. Resource availability provides the upper bound for the production rate value for a crew at any time instant. The work to be performed is constrained by the availability of resources such as material, equipment, and labor. For example, a shared resource might cause unavailability, i.e., if the crew under consideration and another crew in another subsystem uses the same equipment, one of them needs to wait until one crew's work scope is complete. GPM uses piecewise constant functions to describe resource availability.

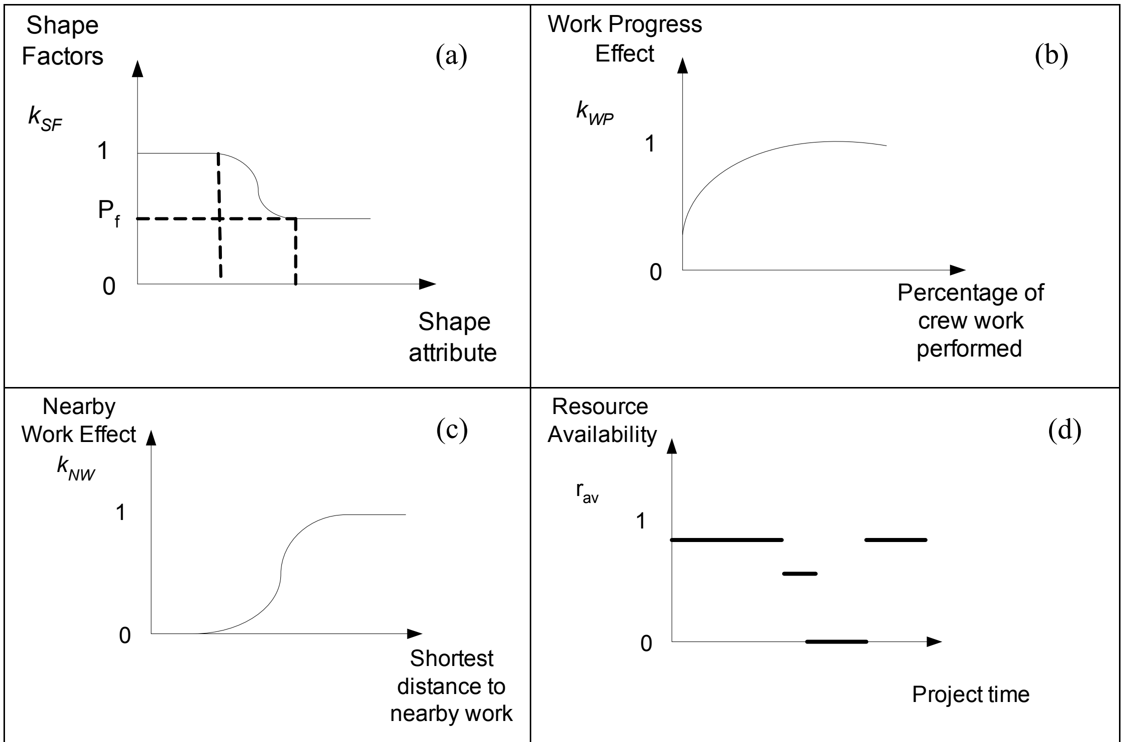


Figure 3-2. Example functions for the elements of the production rate function for GPM.

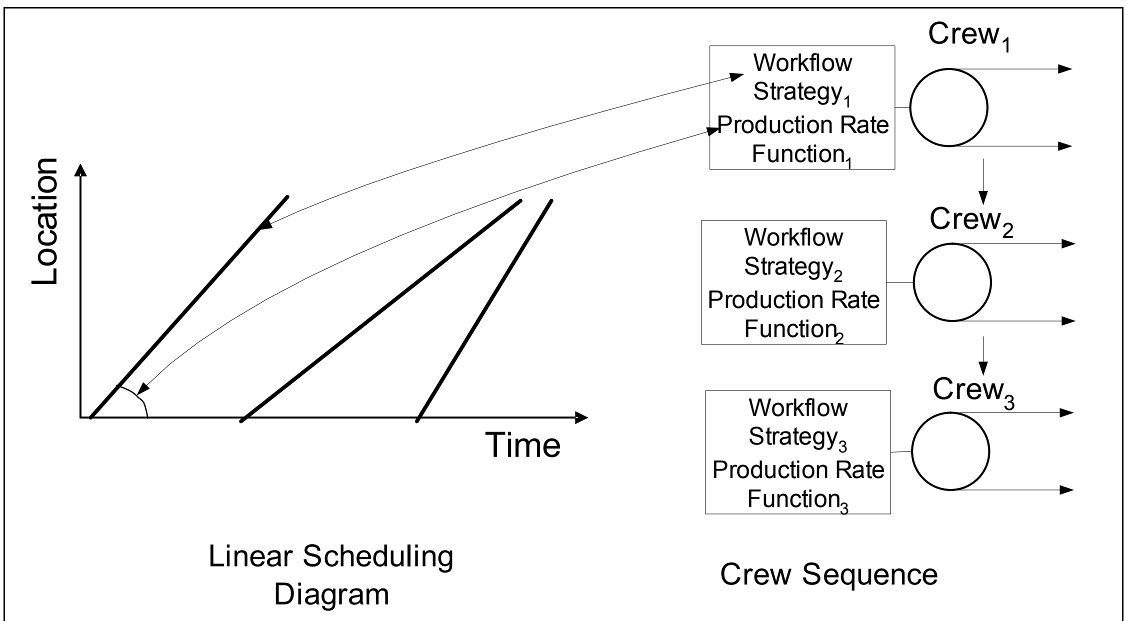


Figure 3-3. Input parameters for a subsystem are a generalization of the input for linear scheduling diagrams. A sequence of crews with parameters for workflow strategy and production rate function can support the mobilization date, the location ordering and the slope.

This production rate function, in current form, does not aim to capture general effects on production rates for all crew types. It captures a limited but relevant number of effects and demonstrates the evaluation of these effects on the production rate for the geometry-based process model.

3.3. Defining Subsystems

A subsystem is a part of a system that has well-defined functions, boundaries and interactions, as introduced among related system theoretic concepts in Section 2.7. The challenge is to compose a group of related construction work as subsystems in a well-defined, parametric way using the crew and work location models of the previous section. Additionally, subsystems should use formal state management techniques (such as finite automata) to define how states change and to correctly calculate state trajectories (states over time) during simulation.

In GPM, a subsystem consists of a physical scope of work described as work locations, a set of crews processing work locations and the internal structure that describes how this process works. Subsystems are able to consider the interactions of crews similar to linear scheduling techniques (Figure 3-3). There is a spatial boundary for every subsystem. The geometric techniques (Section 5.4.2) convert the geometric model for a subsystem into work locations using the input parameters.

Figure 3-4 demonstrates a conversion of a geometric model and input parameters into subsystems. In this specific example, each work location in the subsystem references the geometry in the 3D model, and the input parameters assign a sequence of four crews to process the work locations.

The subsystem definitions include state management, the state variables and the state space. Input parameters and the geometric model describe the static structure of subsystems. The internal structure includes the state management, description of the locations, and site conditions. There is not a unique partition of subsystems for a system, i.e., different combinations of the process modeling elements into subsystems is possible. Figure 3-5 shows a conceptual model for subsystems and interactions using the crew and work location definitions. Figure 3-6 shows a real world example of subsystems and interactions.

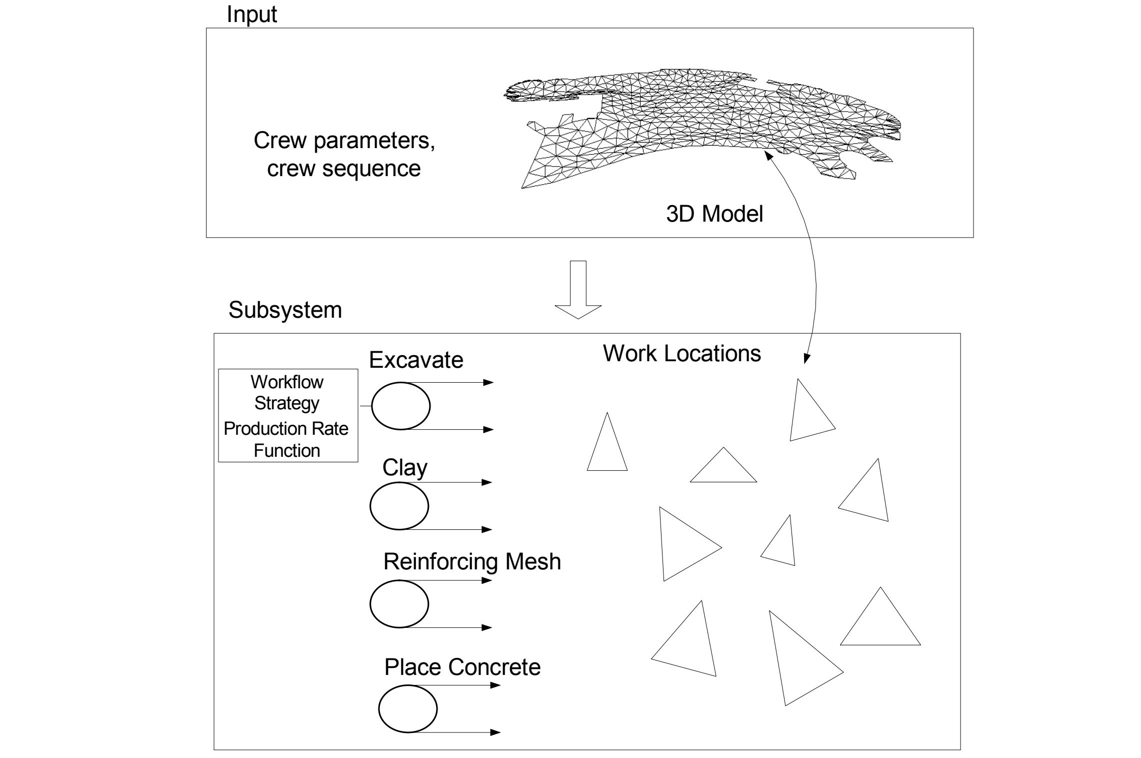


Figure 3-4. A conceptual model for a subsystem from an input 3D model and production parameters.

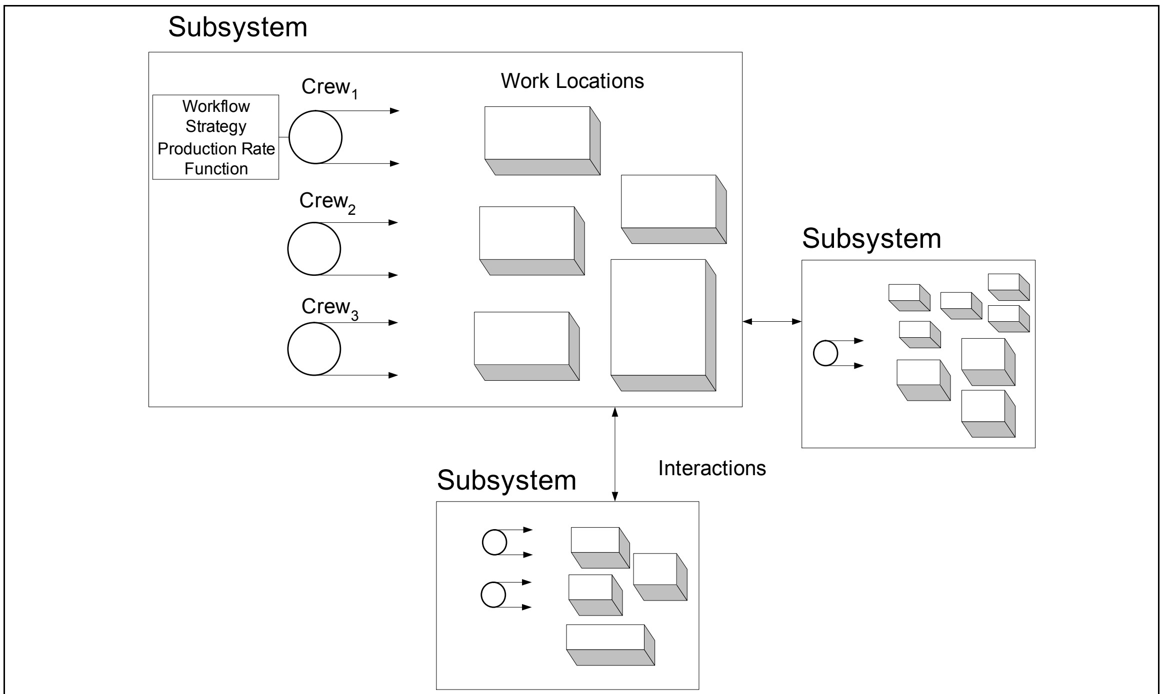


Figure 3-5. A conceptual model of work locations, crews, subsystems and their interactions.

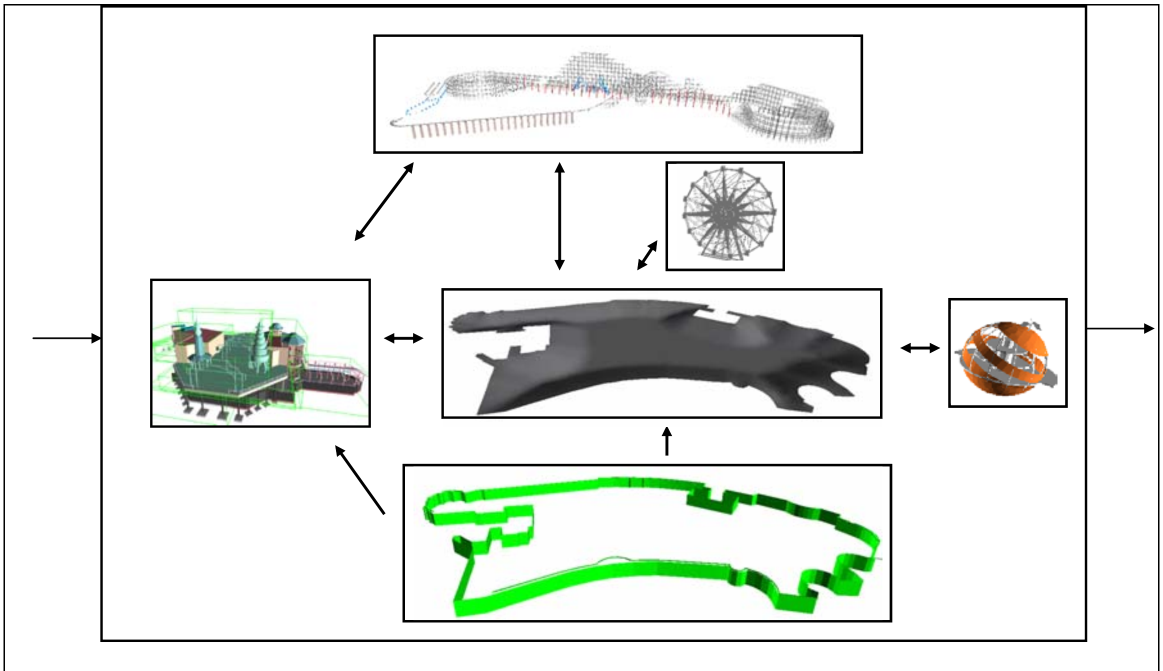


Figure 3-6. Subsystems and interactions in a real project. Each box represents a subsystem. Each arrow denotes an interaction. The subsystems for the building on the left are hierarchical.

3.3.1. Input parameters

The input parameters generate the static structure of subsystems. Once the static structure is available, state variables describe the dynamic changes in subsystems during simulation. Zeigler (1984) describes the difference between state variables and parameters as follows:

"In a parametric model, a set of variables called parameters span the class of models in the sense that specifying values for each of the parameters determines a unique model from the class. Parameters are like state variables in that they must be set to specify unique simulation run. However, unlike state variables, they cannot change during simulation, since this would amount to changing the model in midstream."

The input parameters for a subsystem define the static crew elements for the definition of the subsystem and their interactions with each other. In contrast, state variables, such as resource availability and work location availability, can dynamically change during simulation. State variables are described in the next section as part of the state management of subsystems.

The parameters in GPM are a crew sequence, parameters that describe interactions between sequential crews, the geometric scope of work for each crew, and parameters related to the production rate function and the workflow strategy for each crew.

The first input parameter for a subsystem is a sequence of crews, represented by $\{Cr_i\}$, where i ranges from 1 to the number of crews in the subsystem.

Between sequential crews, there are several parameters for describing the interactions between these crews. *Time buffer* describes a time lag that should exist between crews on the same work location, used to prevent crew conflicts. *Work performing type* specifies the strictness in the processing priorities for the following crew using the conventions of (Russell and Wong 1993). *Continuous activity* requires that work has to be executed without interruption in the specified sequence of work locations. *Ordered activity* follows the work location sequence, but can be interrupted relaxing the work continuity constraint. *Shadow activity* does not have to strictly follow the work location sequence. It can act on the first available work location.

For each crew, input parameters are the geometric scope of work, function parameters for the elements of the production rate function (Section 3.2.2), vectors for directional workflow (Section 5.4.3), and unit work area for workflow strategy (Section 3.2.1).

3.3.2. Internal structure and state management

The process model should describe its behavior during simulation, i.e., how crews process work locations. The internal structure for a subsystem describes this behavior. Since the subsystems for GPM are discrete event systems, the state variables change instantaneously at separated points in time.

Among the main components of a discrete event system are the states and the events. I provide separate state spaces for work locations and crews. The states on the work locations describe their installation status at any time during the process, stored as a timed sequence of installation events. The states on the crews describe how they perform work. A state transition function calculates the states using the events.

States for work locations

The work locations have three main state variables. The first one is the installation state, which represents the last crew that started work at that location. The state space for work locations depends on the crews in the subsystem. Initially, all work locations have the "not_started" state as their installation state. At the end of a simulation, all installation states are "done".

The second, ongoing state variable ($x_{ONGOING}$) describes whether there is ongoing work at a time instant, that is, the ongoing state is true when a crew is processing the work location. The third is the active state variable (x_{ACTIVE}), which describes whether work can be performed at the location. The main causes for a change in the x_{ACTIVE} state variable are the nearby work, crew spatial ordering and site conditions. Anything that affects the work of a crew outside that crew's control and nearby work is a site condition. Possible examples are soil, weather conditions and site access limitations.

Formally, the state space for each work location is:

$$X_{WL} = \{(x_{CR}, x_{ONGOING}, x_{ACTIVE}) : x_{CR} \in \{Cr_i, NS, D\}, x_{ONGOING}, x_{ACTIVE} \in \{T, F\}\}$$

where x_{CR} is the installation state, $x_{ONGOING}$ is the binary ongoing state, x_{ACTIVE} is the active state, *NS*: Not_Started, *D*: Done, *T*:True, *F*: False, and $\{Cr_i\}$ is the sequence of crews forming a subsystem.

States for crews

Crews also have states. In the simplest form, the state variables for crews represent which work location they are processing (processing location state - x_{LOC}), the active state (x_{ACTIVE}), and the reason for idleness (x_{IDLE}) if idle. The processing location state for a crew contains the id of the work location it is processing, or 0 if the crew is idle.

Formally, the state space on each crew is:

$$X_{CR} = \{(x_{LOC}, x_{IDLE}, x_{ACTIVE}) : x_{LOC} \geq 0, x_{IDLE} \in \{R, WL, S\}, x_{ACTIVE} \in \{T, F\}\}$$

where x_{LOC} represents states for ongoing locations and x_{IDLE} is the crew idleness state variable which describes the reason why the crew is idle, x_{ACTIVE} is the active state. *R*: No available resource, *WL*: No available work location, *S*: No available space (nearby work).

The events driving this system are the arrival and departure of the work locations to the queues and changes in any of the crew parameters. Examples of events are the entry of work locations to the system, start and finish of work location processing, enabling a server, production rate changes, and changes in availability of work locations.

3.4. Interaction of subsystems

Each subsystem describes individual modules that contribute to the overall system behavior with its individual transition and output functions. To completely specify a system, the subsystems should be coupled altogether with well-defined interactions.

For interactions of subsystems, GPM adopts the technique and terminology from (Zeigler et al. 2000). Accordingly, each subsystem can be influenced by other subsystems – its *influencers* – and may influence other subsystems – its *influencees.* GSim can simulate multiple subsystems together considering these sets of interactions.

Figure 3-7 shows the interaction types between subsystems in GPM. In activity network based methods (e.g. CPM), many sequencing relationships are necessary for detailed planning. These relationships need extensive maintenance when changes in a project occur. The number of interactions that must be described decreases significantly using the interactions in GPM. *Activity ordering* applies CPM style precedence relationships to subsystems. GPM also consider interactions not supported by CPM. *Spatial crew ordering* considers the spatial crew sequences on the geometric model using distance calculations. *Nearby work* considers the effects of crews working in close proximity over time using geometric analysis.

3.4.1. Activity ordering

This interaction specifies that an activity in another subsystem precedes an activity in the analyzed subsystem or vice versa. There can be various reasons for this constraint, e.g. physical, construction method or shared resource requirement, similar to the precedence relationships in CPM. Examples are excavation for the lagoon preceding exterior painting on the restaurant building (construction method) and interior wall installation in one floor preceding interior wall installation on the next floor (shared resource).

The specification of this interaction has a preceding activity and a succeeding activity.

3.4.2. Spatial crew ordering

For interactions based on a geometric model, CPM style precedence constraints are not sufficient. For example, as a physical constraint, work on a column can only start after the footing right beneath is complete. This is a common spatial constraint that can relate subsystems.

Spatial crew ordering specifies that a crew in the subsystem can start only after work on a nearby work location in a nearby subsystem with the specific component type is complete. The main difference from the previous interaction type is the spatial nature instead of activity completion for the interaction. In other words, this interaction states that the existence of a nearby predecessor is necessary for the successor to start. This interaction also includes a distance attribute that describes the maximum distance for which the spatial ordering is in effect. Section 5.4.4 describes a geometric technique to calculate this interaction.

Examples of spatial crew ordering are concrete slab placing preceding wall installation (physical constraint), scaffolding installation preceding exterior painting (construction method constraint).

3.4.3. Nearby work

This interaction results from space limitations in the construction process and is reflected through the nearby work effect in the production rate function of crews. Crews require sufficient space to perform their work. An ongoing activity in a nearby subsystem can cause spatial interference, which decreases the production rate or stops the work. When two crews are planned to work concurrently within a certain distance, one of the crews either has a decreased production rate or stops work. The specification of this interaction includes the effected component types and the distance for which the nearby work interaction is in effect.

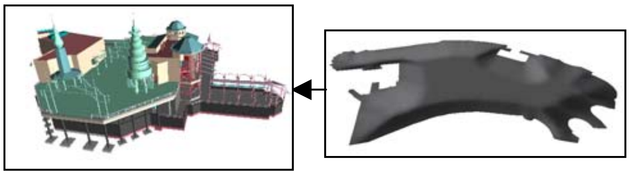
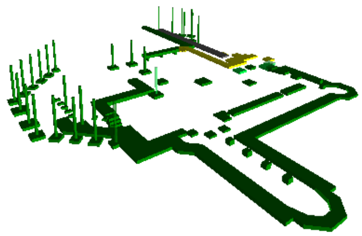
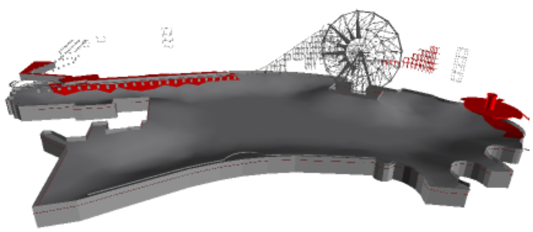
	**Activity ordering:** The *excavation* activity should finish before the *exterior painting* activity can start.
	**Spatial crew ordering:** The *install concrete columns* crew can only work in areas where the footing activities are complete.
	**Nearby work:** Two crews cannot work at the same location at the same time. There is a spatial conflict between work on the roller coaster and the lagoon.

Figure 3-7. Examples for types of interactions between subsystems.

3.5. Approach for process decomposition

The previous sections described the content and the behavior of subsystems. Construction professionals need to describe subsystems in different ways to account for different objectives and interactions during the project. To satisfy this need, GPM provides ways to flexibly define subsystems as decompositions of the overall system. The main elements for subsystem definition are the physical organization hierarchy and the region hierarchy.

3.5.1. Physical organization hierarchy

To decompose the process into subsystems, there is a need for flexible and hierarchical organization of the physical components in the finished facility. The elements in this organization should provide the components and their geometry for subsystems. Modifying this physical organization should give different decompositions of a system.

This research adopts approaches from previous work and calls this structure *physical organization hierarchy*. Some product modeling frameworks, such as IFC and Building Construction Core Model (BCCM) (Wix 1996), provide such organizations. Additionally, in a formal simulation approach, Zeigler (1984) uses a *decomposition tree* to represent a hierarchical decomposition of a large model into its components.

The physical organization hierarchy organizes every component in the project as a tree. This hierarchy is a finite, uniquely labeled tree structure. The root node references the overall system. Leaves of the tree have reference to physical components. Each non-leaf node is a reference to a region or a container for all components with a specific component type.

This organization also provides an interface to define subsystems and consider different levels of detail.

3.5.2. Region hierarchy

To manually define a physical organization hierarchy is a time consuming effort for large projects. Additionally, this hierarchy can change during the project. I define a region hierarchy to automatically generate the physical organization hierarchy and to serve as the spatial boundary for subsystems.

A region hierarchy is a user-defined, hierarchical spatial structure. There are discrete numbers of levels for a region hierarchy in GPM. The highest spatial level, level 0, encloses every component in the project. Every lower level region is contained by the higher level region. The geometric techniques to represent and use region hierarchy to automatically generate the physical organization hierarchy are described in Section 5.4.5.

3.5.3. Process decomposition alternatives

Physical organization hierarchy can represent the organization of physical components as a basis for subsystem definition, and the region hierarchy can automatically generate this organization. There are many different ways to use this flexibility to define subsystems for construction process planning. GPM considers three main categories for process decomposition: Spatial, flow-lines and organizational. These categories are not comprehensive and the subsystems defined are interrelated.

a) Spatial decomposition: This is a purely space-based decomposition of the process obtained by partitioning components into correct spatial regions using the region hierarchy.

b) Flow-lines decomposition: A flow-line is a set of crews following each other to construct a set of components of a particular type, as in the linear scheduling techniques. Each set of crew sequences can describe a specific decomposition. Describing such decomposition requires combination of the region hierarchy and component types.

c) Organizational decomposition: Another alternative for decomposition is using the scope of work for each subcontractor bounded by a space as a means to define the physical composition hierarchy. A subcontractor can be involved in several flow-lines in several regions. This category is important, because the interactions between subcontractors are generally critical and every subcontractor tries to optimize their own processes.

These decomposition types were satisfactory for the needs of the test cases. However, one can define additional categories for process decomposition within GPM.

3.6. Summary

This chapter described a process model on geometry that provides many benefits for design and analysis of construction processes. It abstracts the complexities of geometry, describes crew behavior with simple parameters, and allows modular decomposition of the construction process into subsystems and interactions. It also enables a simple reduction for simulation, as the next chapter will show.

GPM currently only considers conversion activities on the finished facility. Therefore, important elements of the construction process, such as equipment, temporary structures, and material flow are not part of the process model. Additionally, the process modeling elements are deterministic.

The next chapter describes the simulation of this model and the use of simulation output for important information, such as where a construction activity is ongoing at a particular time, work patterns and the performance for each crew over time, and the duration of activities given basic parameters for the process.

CHAPTER 4

PROCESS ANALYSIS AND SIMULATION

In the previous chapter, I explained how GPM represents the physical conversions in construction processes as construction crews processing geometry-based work locations and how it describes subsystems and their interactions based on this abstraction. In this chapter, the purpose is to simulate this process model using discrete event simulation to generate states for crews and work locations and describe ways to evaluate the simulation results. The research challenges to accomplish this are describing a common structure for simulation and describing methods that provide good evaluation of alternatives.

This chapter describes a reduction of the process model into a simpler abstraction, a queueing network. It also explains the basis for the simulation of a subsystem, simulation of a group of subsystems considering interactions and evaluation and visualization of the simulation results.

4.1. Basis for analysis

Discrete event simulation is the method of choice for analysis in GPM. The main goal for the simulation is to generate the state trajectories on crews and work locations accurately.

The simulation should satisfy several process constraints, described by the input parameters and internal structure of the subsystems. At any work location, there can be at most one type of work ongoing at a given time. The crews must follow a given sequence. Furthermore, the simulation should comply with the constraints due to the workflow strategy.

One way to include these constraints in discrete event systems is describing the constraints as a part of a state transition function using, for example, finite automata techniques (Hopcroft et al. 2001). These techniques are intuitive and easy to use, but require a different setup for every case and may lead to very large state spaces when modeling complex systems (Cassandras and Lafortune 1999). While such a modeling formalism is a necessity in the case of additional constraints, the GPM model can, by design, directly be converted into a simpler abstraction, a queueing network.

4.2. Queueing Network Abstraction

To simulate the subsystems while satisfying the process constraints and to provide a simple and common abstraction for GPM simulation, I *transform* or *reduce* the subsystems into a queueing network model. This reduction supposes that the crews are static and waiting to serve work locations, while work locations move to be served by crews. This structure guarantees that at most one crew is working at a work location at any time instant. It also guarantees that the sequence of crews and the sequences of work locations for each crew are exactly as specified. This abstraction also allows the use of results obtained in queueing theory for GPM. After introducing the relevant properties of a queueing network, I describe the reduction process.

4.2.1. Definitions for queueing networks

In queueing theory, the *customer* or the *container* is the thing that waits for service (Hall 1991). The *server* is the thing providing the service. The *queue* is the group of customers waiting to be served. The *capacity* of a queue is the maximum number of customers that can be accommodated. Customers stay in a server for a time period, known as *serving time*. The diagrammatic conventions in this document are: a circle represents a *server*, and an open box represents a *queue* preceding this server (Figure 4-1). *Queueing networks* contain multiple queues and servers are connected as a network. They can represent complex processes arising from interactions between servers and customers, where customers are abstracted as flowing through the servers. Production and communication systems among others commonly use queueing networks to model their processes. On queueing networks, simulation is generally the method of choice for design and analysis (Hall 1991).

GPM uses queueing networks in its simplest form, where queues and servers are organized in series and every customer passes through every server. Serially connected queueing networks are also known as *pipeline systems*. Additionally, the customers (work locations) enter and exit the network, which makes this queueing system an *open network*. The queue capacity is infinite, i.e., there is no limitation for the queue length. I add the *production rate control* to each server as in (Cassandras and Lafortune 1999) to represent production rate effects for each crew. Figure 4-1 shows the basic elements of the queueing network in GPM.

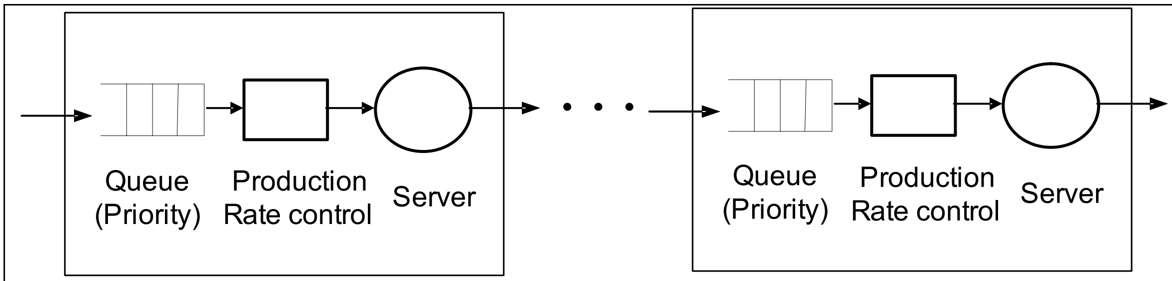


Figure 4-1. Basic elements of the queueing networks in this research.

4.2.2. The reduction process

The input parameters and the internal structure of a subsystem are sufficient to describe a queuing network. This section outlines the reduction process to describe the queueing network that is equivalent to the subsystem that it is reduced from. There are a range of possible cases for this reduction. The simplest case is when there is a single crew in a subsystem. The most complicated case of reduction is multiple crews in a subsystem, each having a separate set of work locations as the scope of work. GPM can also consider multiple subsystems and their interactions as a set of queueing networks.

Single crew case

For a subsystem with a single crew, the crew is converted into a server. All of the work locations, prioritized using the workflow strategy, become the customers for this server. The server can process the work locations by their sequence in the queue. The production rate function of the crew describes the production rate control for the server. The production rate control can calculate the production rate for the crew for a specific work location at any time instant.

The only constraints for reduction to a single server are the crew and the work location availability. The server becomes available (can start serving work locations) on its mobilization date. The work of a crew can start and stop depending on the active states of the servers (see Section 3.3.2). Additionally, the resource availability in the production rate function and nearby work interaction can stop work by changing this state. Similarly, the active states of work locations indicate whether they can be processed at a particular time.

Multiple crews case

The extension of this reduction to multiple crews is accomplished by connecting the servers serially using the crew sequence. As in the single crew case, each crew becomes a separate server, and the workflow strategy and production rate function determines the server properties. Figure 4-2 shows the automatic conversion of a subsystem into the queueing network structure. The work locations flow from the start to the end of the network.

If there are separate work locations for each crew in a subsystem, a base structure provides the link between work locations (see Section 5.3.3 for geometric representation for the base structure and work locations).

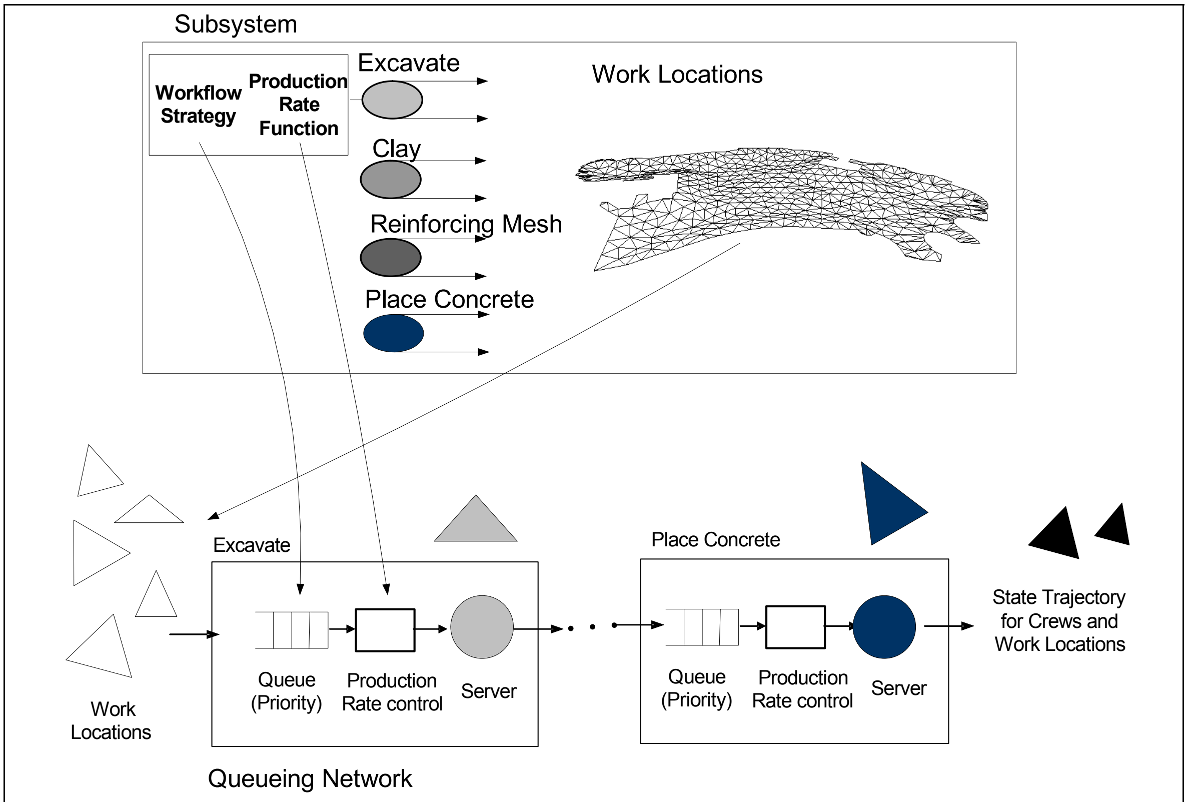


Figure 4-2. Automatic reduction of a subsystem into a queueing network. The sequence of servers is determined by the crew sequence. The work locations enter as customers to the network and are served by each crew. Each queue is prioritized by the workflow strategy. Each serving time calculation uses the production rate function of the crew.

4.3. Discrete Event Simulation

The previous section described the reduction of subsystems into queueing networks. This structure is easy to simulate using existing discrete-event simulation techniques. The next section describes the simulation conceptually, illustrating the differences from basic queueing network simulation. Then, it describes the scheduling of events, management of states and calculation of serving times during the simulation.

4.3.1. The simulation process

This section gives a conceptual description for the simulation. The simulation process follows from typical discrete event simulation techniques for serial queueing networks (Banks 2001; Law and Kelton 2000). The main difference is that every customer and server can be unique in GPM. The serving time for the customers (work locations) is dependent on the production rate of the server (crew) and the quantity of the customers. Additionally, the priorities of customers in the queues and conditions at which a server can serve customers can be different for each server.

The simulation starts from the first server. All the work locations enter the network and get placed in the queue for the first server. The work locations in the queue are automatically prioritized into a sequence using the workflow strategy of the first crew. By default, the servers become active at the mobilization date of the associated crew.

A server can process a work location when the server is active (the active state is "true"), not busy (not serving a work location) and an active work location is waiting in its queue. The serving time for a work location is equal to the evaluation of the production rate function multiplied by the quantity of the work location and takes a strictly positive amount of time. A server is busy while it serves a work location.

After serving of a work location is complete for a specific server:

(1) The work location is transferred to the queue for the next server. When there is a time buffer between crews, work locations need to wait for the duration of the buffer before this transfer. If the work location was served by the last server in the network, the processing of the work location is complete and it leaves the network.

(2) The server becomes ready to serve the next work location. It starts serving the next available work location in its queue, if the queue is not empty. Otherwise, it stays idle.

(3) The states of the servers and work locations are updated.

The simulation is complete when all of the work locations are processed.

4.3.2. Event and state management for simulation

In order to manage the simulation process described in the previous section, state and event management techniques are required. Existing discrete event simulation techniques are sufficient for this purpose. The only need is to define the simulation approach, and the event and state space.

The discrete-event simulation for GPM works on a queueing network, using the *event-scheduling* approach. The simulation schedules events and maintains the scheduled event list and the simulation clock. An event list is a sequence (e_k, t_k) ordered by the simulation time that shows the next event to occur. When an event is processed, the state transition function determines the next state and its time.

The state space for crews and work locations are already described in Section 3.3.2. Every work location has a "not_started" state at the beginning of the simulation. The simulation is initiated by "server_start" events scheduled at the crew mobilization dates. The events that can occur during the simulation describe the flow of the work locations in the network and changes in the crew variables. Example events are the start of a server, entry of work locations to the system, arrival of a work location to a particular queue, start of processing by a server, finish of processing by a server (departure), change in production rate, and change in the availability of servers and work locations.

The simulation provides state trajectories for crews and work locations. At any given time during simulation, the complete state of the project is known.

4.3.3. Model for simulation time

The simulation model needs to make a choice between discrete-time and discrete-event models. In the discrete event model, events can occur at any positive real number time t. When using a discrete-time model, time is discrete, linear and the process is a clocked system, i.e., it has a fixed predefined time unit increment. With each tick of the clock, every state in the model is updated. The discrete time model has a sequence of ordered points, $t_{k+1} - t_k = T$ for all k = 0, 1, 2, … , where T is the sampling interval and is constant.

GPM uses both models for different purposes. The discrete event simulation uses the discrete event model. The simulation model stores a sequence of events, maintaining the scheduled event list (e_k, t_k). Once the discrete event model is available, it is possible to convert it into a discrete time model by searching the events in each discrete time interval. The discrete-time model represents the overall model state at any given time for visualization and analysis.

4.3.4. Simulating interactions between subsystems

The previous sections described the simulation technique for a single subsystem. Using the interactions between subsystems (activity ordering, spatial crew ordering, nearby work), I extend the simulation to multiple subsystems.

The overall strategy for simulation of multiple subsystems is defining a separate simulator for each subsystem and using a coordinator to handle the interactions between simulators using the approach in (Zeigler et al. 2000). Each interaction has an *influencer* and an *influencee*. The influencers are automatically calculated for each subsystem. For activity ordering, the influencers and influencees are given before simulation, while for spatial crew ordering and nearby work, geometric techniques are necessary to dynamically update the possible interactions. Geometric methods to detect and analyze the interactions are described in Section 5.4.4.

GSim, the implementation of the GPM approach, handles each interaction during simulation as follows:

Activity ordering: To satisfy this interaction, the successor crew should be notified when the predecessor is complete. When all of the work locations for a crew are complete, GSim sends an event to the subsystem containing the successor activity.

Spatial crew ordering: Whenever any work location that is a potential influencer is "done", it sends its influencee a message. This message effectively enables the influencee for that particular work location requirement. This ordering requires preprocessing of possible geometric influencing cases to avoid computation complexity.

Nearby work: To handle this interaction, the simulator needs to know all the possible nearby work. During simulation, GSim determines all work locations in other subsystems that are candidates for performing nearby work. It then calculates the distance between nearby work candidates using geometry analysis techniques and evaluates the nearby work element of the production rate function to determine how the crew production rate is affected.

Consideration of these interactions demonstrates that the simulation technique is capable of considering multiple subsystems.

4.4. Simulation Results

One of the goals of this research was to combine visualization techniques with process modeling and simulation. Basing the process model on geometry provides a great advantage, since the temporal visualization of the process is a direct result of the simulation. Once the simulation is complete, there are various ways to use and explore the results (state trajectories). Important aspects of the results are the measurements of performance and visualization.

4.4.1. State trajectories and measurement of performance

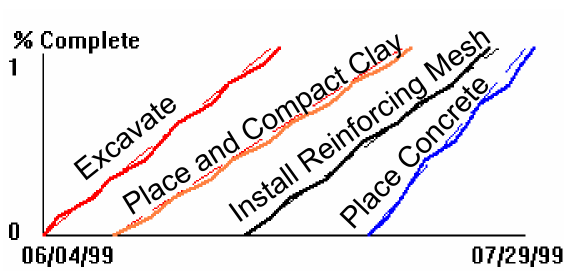
After the simulation, the state trajectories (or sample paths) for every crew and work location in the system are available. The state trajectory on the work locations describes their installation status at any time during the process. The crew state trajectory describes the crew work pattern over time. The challenge is to make effective use of this data to provide users the opportunity to make meaningful analysis.

Traditional methods to measure performance for construction processes are based on time, cost, safety or quality. At the same time, queueing systems have common measures of performance such as average waiting time and average serving time (Law and Kelton 2000). This research uses only basic temporal measures of performance, such as crew utilization (fraction of time a crew is busy), average production rate, and the reason a crew is idle.

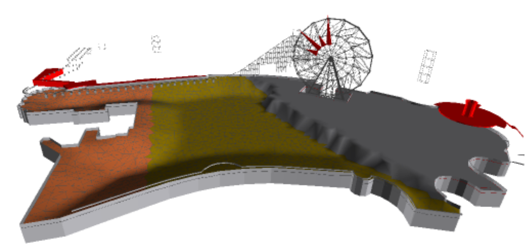
The state trajectory on a particular crew can provide information about the activity as a whole, such as the activity duration, the idle duration of the crew, etc.

For performance evaluation purposes, GPM defines state variables for each crew that are derived from the other states, such as *work progress* (percentage of work completed), *crew utilization* and *average production rate*. The work progress element of the production rate function uses the work progress state to determine its effect.

Converting the results of a simulation into a CPM network is one way of evaluation. Users can analyze the activities (their durations) and the precedence relationships as automatically generated from the simulation results. Section 7.3.1 explains this conversion and gives an example in GSim.



(a)



(b)

Figure 4-3. Two ways to visualize the simulation results: (a) Percent complete for crews, (b) 4D visualization.

4.4.2. Visualization of simulation results

The users should be able to easily evaluate process alternatives by means of the visualizations of the simulation results. Figure 4-3 shows two possible uses of the simulation results. Figure 4-3a shows an overlay of the percentage complete of crews over time on the planned performance of crews. Section 7.2.2 demonstrates different examples for this technique on a test case.

Existing discrete event simulation techniques provide performance parameters and charts for the simulated process. However, in most cases, the visualization of simulation results in 3D is not possible. Recent research requires that simulation results are fed and manually related to a 3D model for visualization (Kamat and Martinez 2001). 4D CAD provides visualization of the process on 3D models, but relies on the activities in CPM networks, thus it is more suitable for macro-level visualization.

In this research, 4D visualization is a direct result of the simulation. GSim uses the installation state trajectory on the work locations to describe the corresponding geometry states at each discrete time interval. Color coding is the method to differentiate different work states at different locations, a technique adopted from 4D CAD. To achieve this, GSim assigns different colors for each installation state.

Figure 4-3b shows an example 4D visualization using color coding. The work locations with "not_started" states are not visible. While a crew is processing a work location, the color of the work location changes to the color of the activity type of the particular crew. The "done" state is visualized as the original color of the component.

4.4.3. Possible viewpoints for simulation results

Once the complete state trajectory is generated, information such as crew input parameters, how they perform work, and the states at any work location are known. Constraining different degrees of freedom for this geometric process model provides different information about the simulated process. These viewpoints are complementary, representing different observers.

Section 3.1 introduced the activity and zone definitions for GPM.

One can concentrate on either the locations or the crews that perform work. For the work locations, at any time instant, the complete set of installation states for the entire model, namely the installation snapshot of the project, is known. This is similar to a photo of the actual construction site during construction. This viewpoint is necessary for visualization and spatial analysis, e.g., to determine spatial interference or access, or perform layout analysis.

The work location focus can be extended to a time interval, instead of a time instant. During an interval, the work locations in which a particular crew is working describes a work area zone. The work area zones enlarge when the time interval increases and shrink when the time interval decreases. At the limit, extending the time interval to the active period of a subsystem, the zone becomes the entire subsystem geometry. The time period for each crew in each subsystem describes activities.

Another viewpoint from this construction process model is focusing on the crews. This essentially makes it possible to trace the work paths of crews, i.e., the work locations at each time interval.

4.5. Conclusions

This chapter described a simple simulation strategy for the geometric process model using discrete event simulation. It explains how simulation can be performed on geometry, including state calculation, time management, and analysis of simulation results. It provides an intuitive reduction of the process model, which allows application of queueing theory results to simulation on geometry. The deterministic nature of the GPM model makes the simulation simpler to analyze, compared to stochastic networks.

Many extensions of this strategy are possible. For example, crews can have dynamic decisions over time considering the states of the project at time instants. The simulation can have more complex state management and external control using existing techniques.

The next chapter describes the geometric techniques that enable the modeling and simulation approach.

CHAPTER 5

GEOMETRIC REPRESENTATIONS AND ALGORITHMS

The previous chapters describe the process modeling and simulation approach, GPM, without detailed description of the enabling geometric techniques. Indeed, this research relies strongly on geometry. Describing appropriate geometric techniques to represent, manipulate, analyze and organize geometric models is a crucial part of this research.

The needs from geometric techniques are quite extensive. The input representation and organization of the geometric model of a project rarely matches the needs for process modeling and simulation. Techniques are needed to manipulate, generate and organize geometry for typical construction cases. To support directional workflow strategies for crews, there should be a way to capture this workflow on the geometry and calculate the strategy accordingly. Additionally, the information in the geometric model that relates to the construction process including shape properties, interactions and interferences should be extracted appropriately.

To satisfy these needs, there is no shortage of existing geometric representations and algorithms. However, geometric techniques specific to construction processes and the organization of these techniques are lacking. The approach in this chapter is to formulate and organize the categories of geometric techniques to support GPM and provide solutions for specific cases. The next section summarizes these categories in the overall research context. After reviewing the existing work, the rest of the chapter explains the geometric representations and algorithms used in this research in depth.

5.1. Introduction

5.1.1. Summary of geometric techniques within the overall research context

This research defines a construction process model based on geometry, defining the process of interest as crews acting on geometric work locations to change their installation states. This process modeling approach is called GPM (Geometry-based Process Model). Each crew has certain parameters, including a production rate function and a workflow strategy. The production rate function specifies at what rate crews can perform work at a specific location at a specific time instant. The workflow strategy specifies in what order crews plan to perform their scope of work. A set of crews acting on a geometric model in a bounded space defines a subsystem.

Coupling of a set of subsystems and considering their interactions defines the complete process model. For simulation purposes, each subsystem is reducible into queueing networks, and discrete event simulation determines the states of crews and locations over time.

At almost every stage of this process modeling and simulation effort, geometric techniques are necessary (Figure 5-1). I organize these techniques into four categories that relate naturally to geometric fields and describe solutions for various cases in each category. Each category describes the specific algorithms that GSim (the implementation prototype for this research, see Chapter 6) uses.

A set of geometry generation and manipulation techniques to define geometrically the process elements (work locations, base structures and their relationships) are under the *geometry tessellation* category. They involve triangulation, geometry splitting and aggregation techniques. One of the inputs for this process model is a geometric model, represented as triangle meshes. The first problem arises from converting this input geometric model into process units suitable for analysis in this process model, namely work locations. Work locations are the main abstractions relating the construction process to geometry. They are the basis for production rate calculations and installation states. Another abstraction GPM uses, the base structure, manages the consistency of work location processing, definition of workflow strategy on geometry and evaluation of the production rate function at every work location.

Geometry sorting specifies and determines the sequence for processing the work locations on the base structure. It lets users define the directional workflow strategy for crews on the geometric representation and uses this strategy to define a preferred sequence of work locations for process simulation.

The main purpose of *geometry analysis* is to evaluate the geometry to calculate the geometric factors affecting the production rate, including shape factors and effects of nearby work. The production rate function determines the serving time for each crew on a work location during simulation. Other elements of GPM that need geometric evaluation, such as spatial crew ordering and quantity of work locations are also under geometric analysis.

Hierarchical space decomposition deals with geometrically organizing the building components within subsystems. It hierarchically allocates building components into correct regions by checking their containment in specific, user-defined regions.

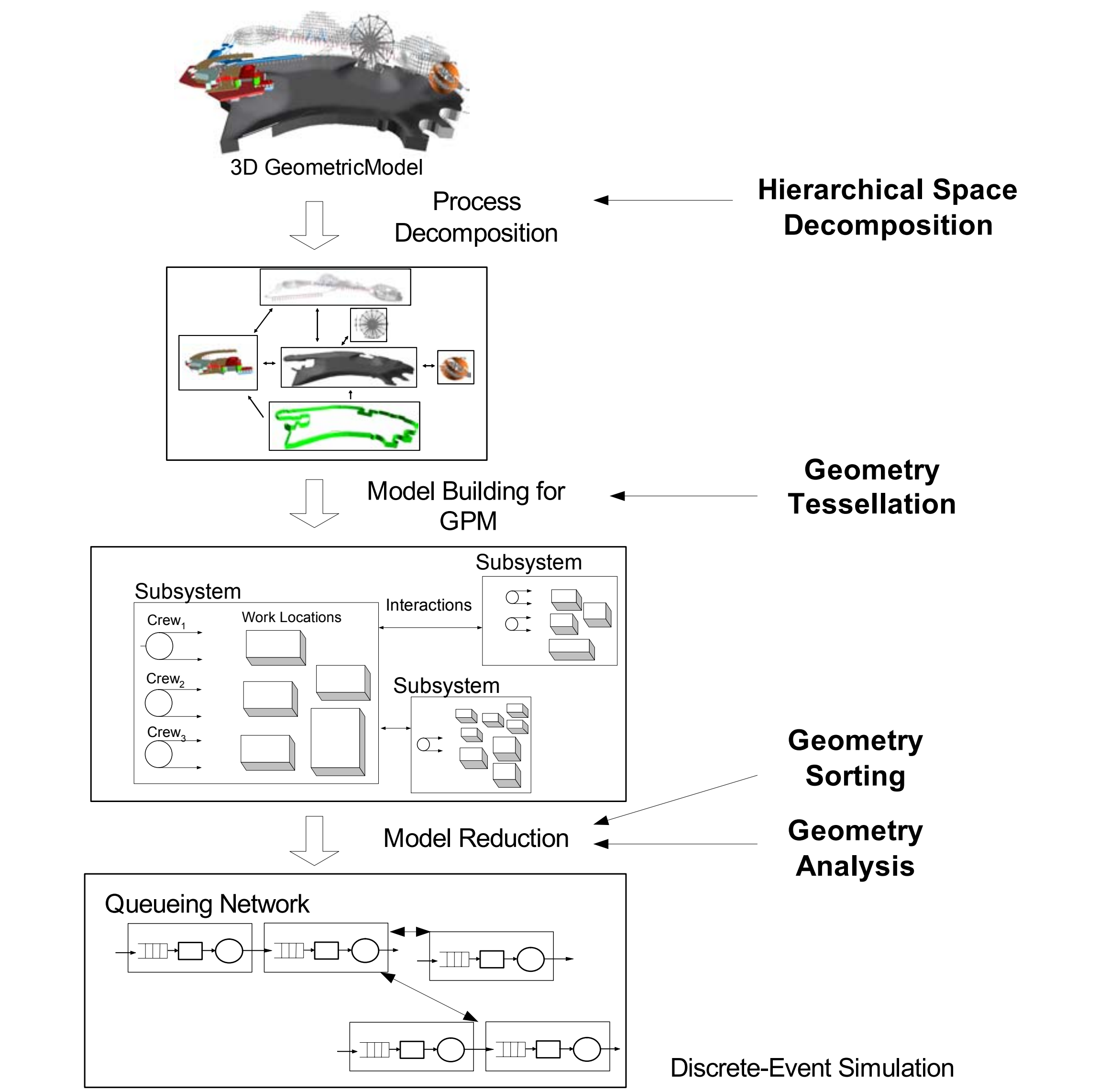


Figure 5-1. Categories of geometric techniques in the overall research context. Each category contains a group of algorithms that supports the process modeling and simulation approach.

5.1.2. Design criteria

The design criteria for the geometric techniques in this research are as follows:

- Generality: The representation and algorithms need to cover most of the possible shapes for construction components and the modeling and simulation needs of GPM. At the same time, the techniques should clearly connect to geometry related research fields.
- Extensibility: Each category should describe the general formulations for their requirements and solve them for all or specific important cases.

- Transparency: The process model and its simulation should not need to know anything about these geometric representation and algorithms.
- Efficiency: Although this is not a primary goal, the representations and algorithms should be able to handle large and complex cases. Real life construction projects are likely to have a large number of components, possibly with complex geometry.

In addition to these goals, it is also worth mentioning the aspects of geometric techniques that were not the goals of this research. Spatial precision of the algorithm results are not critical. The techniques do not guarantee optimality in terms of running time or storage cost.

5.2. Background and Related Research

This research makes use of various research areas that focus on geometry. After summarizing these research fields, I introduce the existing research and practice on the use of geometry in construction projects and specifically for construction planning and simulation.

5.2.1. Geometry related research fields

Several geometry related research fields exist with overlapping interests. *Computational geometry* and *geometric algorithms* define data structures and efficient algorithms for geometric problems (Berg et al. 2000). Many of the geometric techniques in this research are based on computational geometry. In three closely related fields, *geometric modeling* describes the spatial and topological elements of a project (Mortenson 1997), *solid modeling* describes a consistent set of principles for mathematical and computer modeling of three-dimensional solids (Mäntylä 1988) and *computer aided geometric design* (CAGD) describes computational and geometric aspects of free-form curves, surfaces and volumes (Hoschek et al. 2002). Geometric representations and geometry analysis are mainly based on these fields. *Mesh generation* is concerned with describing meshes on geometric objects for various purposes (Edelsbrunner 2001; Frey and George 2000). Geometry tessellation techniques in this research adapt algorithms from mesh generation. *Computer graphics* is about creating images of modeled scenes on a computer screen or other output device (Foley et al. 1995). Hierarchical space decomposition, vector field representation and the visualization of the results uses techniques from computer graphics.

5.2.2. Geometry use for civil engineering projects

Geometric techniques commonly used in other aspects of architecture/engineering/construction (AEC) projects find limited application in construction. For architectural design, geometric models can support large and complex geometric structures.

Geometric models for the finished facility are increasingly available as designing in 3D gradually becomes an integral part of the design process.

For structural and energy analysis, geometry is used in a similar way to the other engineering disciplines. Structural and energy analysis use finite element or finite difference methods approximating the geometric representation as a mesh or a grid. Other areas where geometric models are used are process plant design, steel design, crane operations planning, site layout planning and highway construction planning.

Vastly improved geometric techniques, inexpensive graphics hardware triggered by entertainment and scientific visualization industry needs and the relative ease of building 3D models for construction projects resulted in effective navigation and animation tools for construction projects. However, techniques to incorporate geometric information in process modeling and analysis are largely overlooked for construction projects. Consequently, modeling and analysis of the construction planning decisions for a specific project do not use detailed geometry effectively. The next section specifically looks at use of geometric techniques for construction planning and simulation.

5.2.3. Geometry use for construction planning and simulation models

Previous construction planning and simulation models did not emphasize the geometric aspect of the construction process analysis, although several of them identified the need for better geometric mechanisms (Thabet and Beliveau 1997; Winstanley and Hoshi 1993). While process visualization techniques are common, process analysis approaches use simplistic (mostly prismatic) 3D component geometry or make limited automatic use of geometric information. For example, Kamat and Martinez (2001) visualize the results of discrete event simulation for earthmoving operations as animations in 3D. However, they do not use the geometric information to drive the simulation. The geometric parameters driving the simulation are not captured. The directional workflow information, for example, is either not considered or only uniform axis-aligned directions are allowed.

The rare use of geometric models for construction process analysis is reflected by limited tessellation or mesh generation applications. Some research efforts change the level of detail of geometry for planning purposes, using aggregation (grouping) and decomposition (subdividing) based on space. AbouRizk and Mather (2000) apply a structured grid to decompose a component surface or aggregate components. ZonePlanner (Winstanley and Hoshi 1993) describes a way to perform activity aggregation, given a geometric model and activities with production rate and cost data. The purpose is to provide geometric support for a construction process planner.

Assuming one-to-one correspondence between activities and work locations, their system creates a structured grid, partitions the content of each grid element and performs an exhaustive search for an optimal zoning plan for the given cost and duration criteria. The geometric structure for components is prismatic. In GPM, geometry tessellation can support any triangle mesh and solutions include triangulation and rectangular tiling as well as subdividing and aggregating geometry using a structured grid.

For geometry sorting, existing crew workflow definitions are mostly conceptual or without a robust computational model based on geometry (Birrell 1980, Sanvido 1994). The sorting process is generally manual or it requires axis-aligned sequencing by a user. There is also some research on the analysis of geometry for automation of work location sorting. For example, Kunigahalli and Russell (1995) define a data structure and algorithm for nearly optimal sequencing of slabs for concrete placement. However, their analysis focus is on extracting information from 2D drawings.

For hierarchical space decomposition, Thabet and Belivaeu (1997) define a hierarchical work block structure to define spaces formed by cubes to analyze the effect of workspaces on productivity. Each work block must be the same at every floor. Once the geometric model is converted into spaces, the information about the enclosed building components is lost, preventing integration with other planning structures.

5.3. Geometric Representation

The GSim uses and extends existing geometric representations to support the process modeling approach. After the description of the input geometry, I discuss work locations and base structures from the geometry perspective.

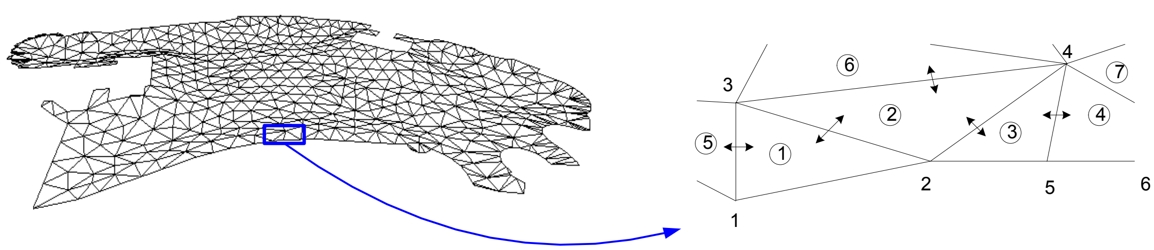
5.3.1. Geometric primitives

This research uses well studied geometric primitives: triangle mesh, structured grid and polygons. Triangle mesh describes the geometry of building components. Structured grid and polygons partition the space for the geometric model.

There are many geometric representation techniques including boundary representation (B-rep), Constructive Solid Geometry (CSG), and parametric and implicit surfaces (Hoschek et al. 2002). This research uses triangle meshes as its geometric representation because they are easy to obtain, manipulate and render. Triangle meshes are widely used for analysis and visualization. Additionally, algorithms are available to effectively manipulate, refine and store them.

Geometrically, a *triangle mesh* is a surface consisting of triangular faces pasted together along their edges. The mesh geometry can be denoted by a tuple $M = (K, V)$, where K specifies the connectivity of the mesh (the adjacency of the vertices, edges, and faces) and V is the set of vertex locations defining the shape of the mesh in R^3 (Euclidian space). Three ordered vertices define a triangle. Each vertex has a location. *Vertex data* consist of the coordinates of all the vertices and optional attribute information such as associated normal vectors and color information. *Connectivity* information captures the relationships between the triangles of the mesh and their bounding vertices. Figure 5-2 shows the triangle mesh representation for the lagoon base example.

Figure 5-3 shows other geometric representations used in this research. A *structured grid* is a grid composed of volumetric elements (or *cells*). Three identifying indices, *i*, *j*, *k* describe each grid element. Structured grids have regular topology, i.e., the connectivity information is determined solely by the identifying indices. Structured grids are widely used for numerical techniques to solve partial differential equations such as finite difference methods. This research describes a structured grid by a bounding box and the number of rectilinear grid elements on each axis. A *polygon* is an ordered list of three or more points lying in a plane. A polygon with four points is a *quad*. In this research, a *region* is a polygon with a height range. It serves as the boundary for the geometry of a subsystem.



Mesh Information

Triangle	Indices	Connectivity
1	1,2,3	-1,2,5
2	2,4,3	3,6,1
3	2,5,4	-1,4,2
4	5,6,4	-1,7,3
...	...	...

Figure 5-2. An example for triangle mesh representation.

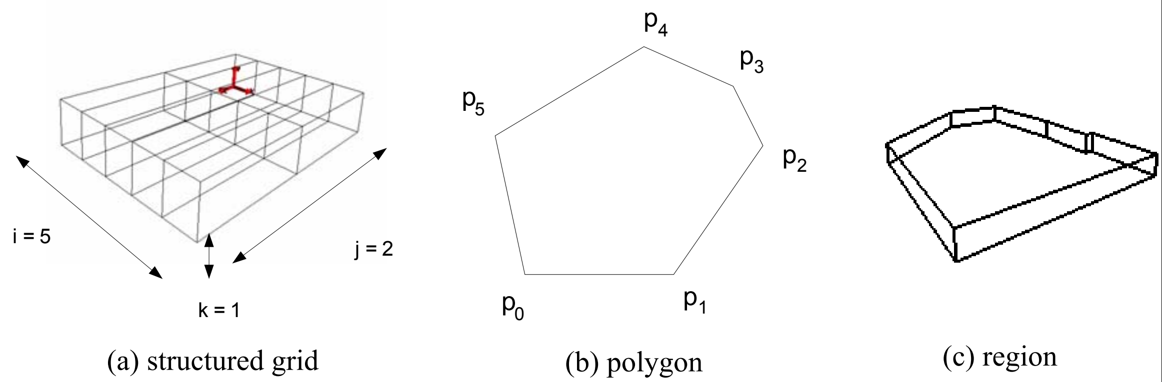


Figure 5-3. Other geometric representations in this research: (a) a structured grid, (b) a polygon, (c) a region.

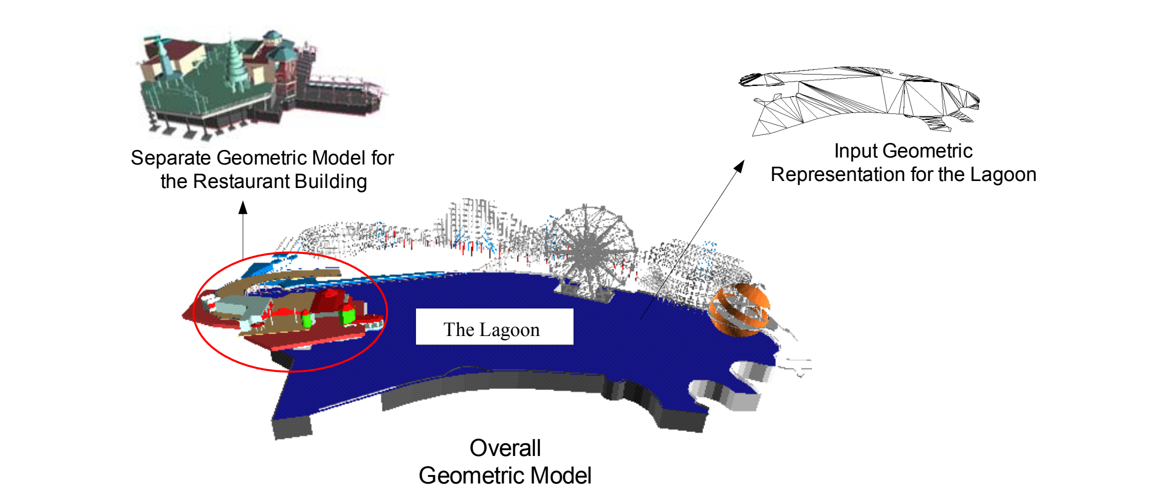


Figure 5-4. The input geometry for the DCA Project.

5.3.2. Input geometry

GSim does not model the geometry for the finished facility. Instead, geometric models can be imported from 3D CAD or geometric modeling applications for the set of components to be built or installed. The input geometry model for GSim is limited to triangle meshes with vertex locations and connectivity. The representation for a construction component also contains some semantic information, and the only semantic information relevant from the geometry perspective is the component type.

Figure 5-4 shows examples of input geometry for the lagoon and restaurant cases in the Disney's California Adventure (DCA) project. The geometric model for the lagoon is a single triangle mesh, not directly useful for process analysis. In contrast, the restaurant building is composed of many components with separate geometric representations.

5.3.3. Work locations and base structure

The input geometry described in the previous section is not always ready for process modeling and simulation. A common requirement for construction planning using geometric models is to modify the original geometry to visualize, simulate and analyze the construction process (Akbas and Fischer 2002; Fischer et al. 1998). Work locations and the base structure satisfy the transparency and extensibility goals by abstracting geometry into process elements for GPM.

A work location can be part of a component, the same as a component or composed of a group of components. The representation for work locations contains geometry and several additional attributes. The additional attributes are a current installation state, an installation state trajectory, installation sequence attributes, a bounding box and work quantity described in units of work. The work quantity is either derived from the geometric representation or is user-defined. A work location also has a reference to the set of related base structure elements.

Each crew can have different sets of work locations in a subsystem. A structure is necessary to relate these different work locations and maintain the workflow strategy for the subsystem and interactions between subsystems. For these purposes, I define the *base structure* concept. The base structure is the common geometric basis for all of the internal structure of a subsystem. The base structure guarantees accurate state calculations for work locations even when the work locations are different for each crew. There is a reference from base structure elements to the work locations for each crew. The same structure maintains the workflow strategy and interactions between subsystems.

Figure 5-5 shows examples of work locations and base structures. There are various possible types for work locations and base structures. The work location types that GPM considers are below.

- Work location is composed of triangles: This is the default type since the input geometric model is composed of triangles. Every triangle becomes a separate work location in the lagoon test case.
- Work location is composed of components: This type also uses triangle meshes and is different from the previous type because the geometric representation as a whole is the unit of analysis. In the restaurant test case, every triangle mesh associated with a building component (e.g., footings, columns) is a separate work location.
- Work location is composed of quadrilateral elements (quads): A quad work location is a result of rectangular tiling (see Section 5.4.2). Figure 5-5c shows the generated quads for the reinforcing mesh activity in the lagoon test case.

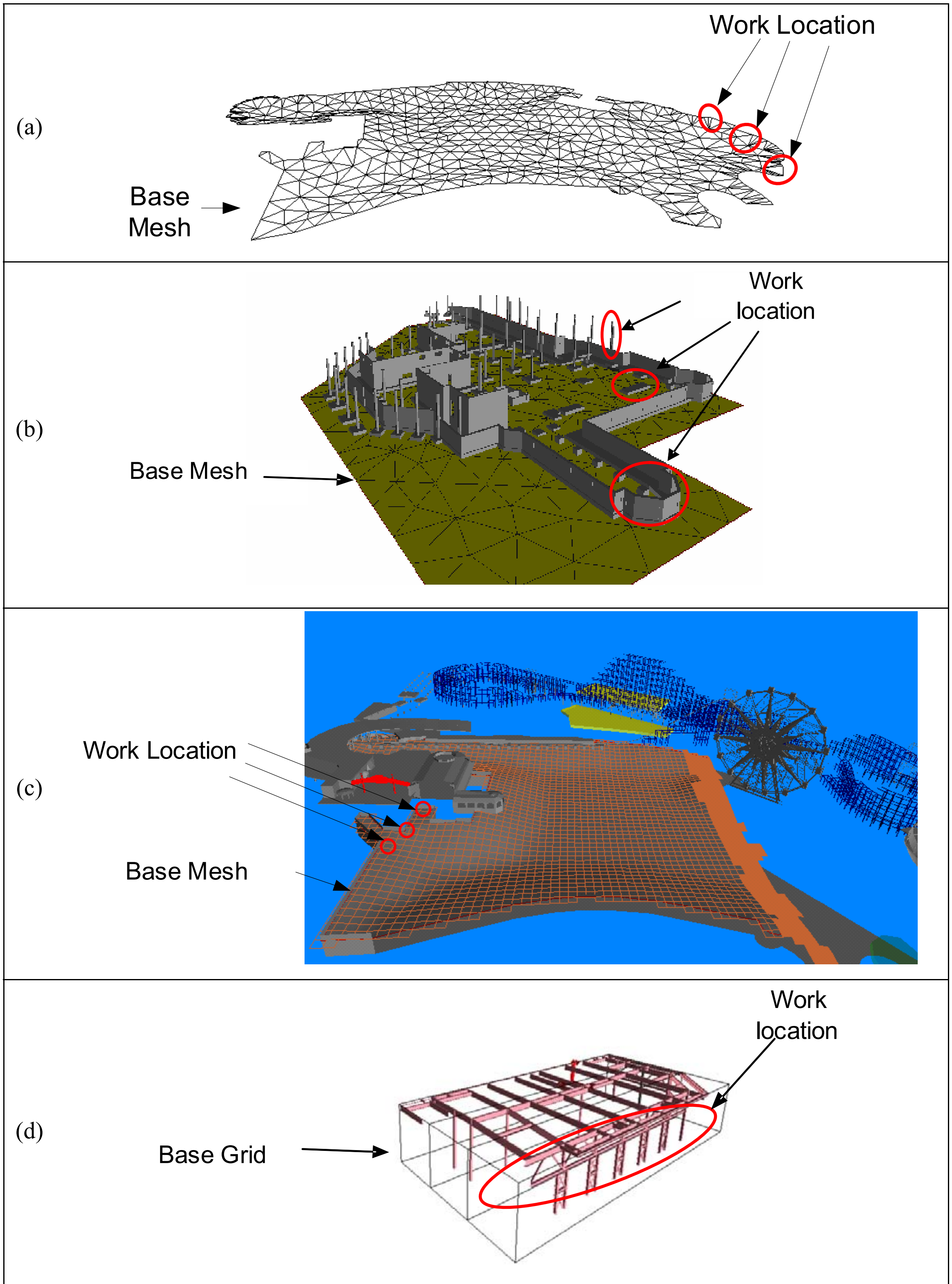


Figure 5-5. Examples for work locations and base structures.

The base structure geometry is composed of either a triangle mesh or a structured grid. This choice is user-defined. The triangle mesh base structure, or a *base mesh*, is able to capture bottom-up decisions such as workflow strategy. The structured grid base structure, or a *base grid*, is suitable mainly for top-down planning decisions and decomposes geometry into work locations of user-defined sizes.

Using the same abstraction, one can extend the work locations and base structure to other geometric primitives. 1D (linear) elements and volumetric elements such as cubes, tetrahedrons are possible future work location types.

In this section, I summarized the choices for the geometric primitives in this research and abstractions that relate these primitives to the process modeling approach including work locations and base structure. The next section uses these geometric representations for the geometric techniques.

5.4. Geometric Techniques

I formulate the geometric techniques as problems specific to GPM. The problem statements for these geometric techniques are such that the general solutions satisfy all the requirements of the process model. The descriptions of the solutions are for the specific cases of the problems. The section starts with the basic operations and methods that the geometric techniques use. The following sections describe the geometric techniques in detail. I adapt existing geometric techniques whenever possible.

5.4.1. Basic geometric operations and methods

A group of methods and operations provides the basis for the following geometric techniques. Split and aggregate operations subdivide or aggregate triangle meshes. The operation *split*(***M, P***) splits a mesh into two partitions using the plane ***P.*** It returns two meshes M_1 and M_2. This operation is the basis for the other split operations. *split*(***M***, *Gr*) splits the mesh ***M*** using a structured grid *Gr*. This operation uses *split*(***M, P***) and planar point location. *split*(***M***, ***Rgn***) splits the mesh ***M*** into two partitions: internal mesh enclosed by the boundary of ***Rgn****,* and the external mesh. *aggregate*() is the inverse of a *split* operation and combines geometric representations within a space.

The planar point location problem is: given a point *p* and a planar subdivision defined by a set of edges, find the face that encloses *p*. Efficient algorithms exist to solve this problem (Berg et al. 2000). GSim uses a point location algorithm to determine the triangle enclosing a point in a planar triangle mesh efficiently.

The *IsInside*() operation determines whether a point is inside the polygon, given a polygon and a point in a plane. The *dist*(l_1, l_2) operation calculates the minimum Euclidian distance between work locations l_1 and l_2.

5.4.2. Geometry tessellation

Geometry tessellation is the subdivision of an entity or surface into one or more non-overlapping primitives. In this research context, it is a group of geometry generation, manipulation and reorganization techniques to define work locations, base structures and their relationships. The techniques involve triangulation, tiling, and geometry splitting and aggregating.

These tessellation techniques are necessary because the input geometry does not automatically describe work locations and base structures that are accurate for construction process modeling and simulation (see Section 5.3.3). Every subsystem initially contains a set of components with a geometric representation that represents designer or geometric modeler preferences in terms of component size and geometry detail. GPM makes only basic assumptions on the input geometric model (that is, it is composed of triangles and it has no overlapping vertices). Given the user choices, work location geometry should automatically be converted into appropriate work locations to embody the requirements for the construction process. In addition, a base structure should be defined that encloses all the geometric representation for the components and relates the work locations for different crews.

In general terms then the geometry tessellation problem for GPM is: given an input geometric model and parameters describing a subsystem, determine:

i) an appropriate discrete set of work locations to be processed by each crew,

ii) a base structure for all the work locations in the subsystem.

The solutions to this problem vary depending on the type of the base structure and work locations. I consider three cases commonly encountered in practice. First, I consider the case where the base structure and the work locations are triangle meshes, followed by work location definition by rectangular tiling and base grids.

Case I: Generating work locations and base structure for triangle meshes

When all of the work locations are triangles, the problem of generating appropriate work locations from input geometry is a special case of triangle mesh generation (or *triangulation*) and triangle mesh refinement.

In this case, the input geometry is a set of triangles with no isolated or overlapping vertices. The boundary edges and maximum triangle areas are the constraints for the triangulation. When the region structure provides the boundary, the algorithm can automatically triangulate the polygon described by the region structure.

GSim uses an existing algorithm, constrained Delaunay triangulation (CDT) and refinement (Chew 1989; Ruppert 1993; Shewchuk 1996), to generate provably good planar triangle meshes with boundaries. The input for CDT is a planar geometry with possible holes, boundary constraint edges (also known as Planar Straight Line Graph or PSLG) and area constraints. CDT creates a triangulation using the interior and the boundary vertices using the Delaunay criterion. The Delaunay criterion describes how to connect existing points in space: No vertex may be contained in the circumcircle of any triangle within the mesh. This criterion also maximizes the minimum angle for each triangle.

Since the CDT algorithm is planar, some preprocessing is necessary to prepare the general triangle mesh input. As the first step, GSim builds the mesh connectivity while determining the boundaries and the creases in the mesh. An edge with a single neighboring triangle is called a *boundary edge*. A *crease edge* is an edge with normal discontinuity, i.e., one with the angle between the normals of adjacent triangles greater than a user specified value. To extract the boundary edges of a surface, it is sufficient to count the neighbors of each triangle.

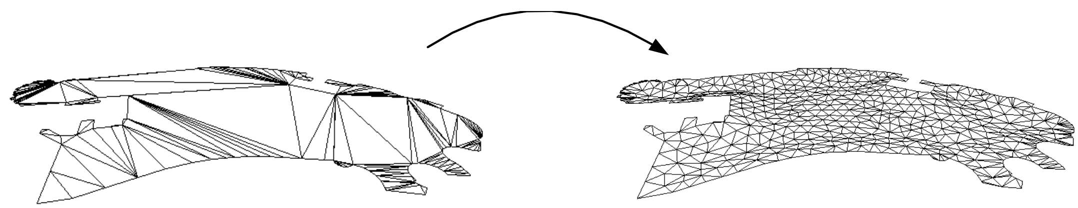
The preprocessing step also extracts the smooth areas out of the input surface using a technique adapted from (Möller and Haines 1999). In construction, work progress for most crews can be approximated as planar, usually one plane axis being horizontal or vertical. Starting from any triangle, this step grows the set of triangles by recursively traversing the neighboring triangles. When a set of triangles are enclosed by boundary or crease edges, that set becomes a *smoothing region*. Every smoothing region is a planar or near planar mesh, i.e., there is no significant change in curvature anywhere on the mesh. Smoothing regions that share crease edges are connected.

The triangulation using CDT starts from the boundary vertices. The CDT algorithm inserts the internal vertices incrementally, redefining the triangles at each insertion to maintain the Delaunay criterion. After inserting the internal vertices, the Delaunay refinement algorithm adds new vertices to refine the triangulation until it satisfies the given triangle area constraints and boundary parameters. The insertion of these new vertices are at triangle circumcircle centers as proposed by (Chew 1989; Ruppert 1993).

For implementation purposes, GSim adapts an existing software code for CDT by (Shewchuk 1996). Since this CDT algorithm is planar, GSim projects the original vertices of each near planar surface to a plane with the least length axis and stores the original heights as an attribute. This results in a planar mesh with a height attribute assigned to each vertex, also known as *height fields*. After obtaining the refined planar mesh with CDT, GSim updates the height information of each vertex in the generated mesh by interpolating the height values of the vertices in the original mesh using Barycentric coordinates.

Figure 5-6 shows examples of generated base structures for two separate examples. The first example shows the original geometry of the lagoon base and the tessellated version. After determining the boundary edges for the original triangles, the internal vertices are discarded and internal vertices that satisfy the area constraints are inserted and triangulated. In the second example, the region boundaries and the maximum triangle area are the constraints to generate the triangulation.

(a)



(b)

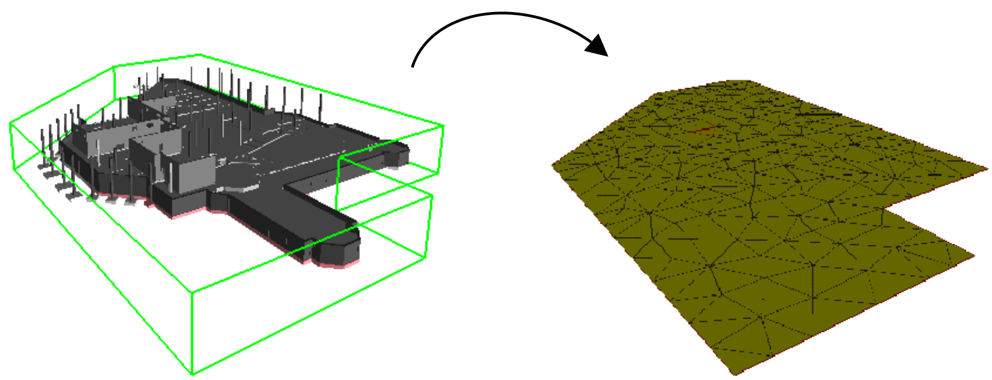


Figure 5-6. Geometry tessellation examples: a) an input triangle set describing a surface with boundary and b) work locations bounded by a region. Both examples use constrained Delaunay triangulation and refinement.

Case II: Generating rectangular work locations on a triangle mesh base structure

This case is a variation on the previous case, in which the work locations are rectangular instead of triangles on a base mesh. This case is necessary when a crew workflow strategy has a unit work area requirement. The challenge is to define an approximate rectangular tiling of user-specified dimensions on a given triangle mesh, with conforming boundaries.

I introduce a simple tiling algorithm that generates fixed size rectangles on the base mesh. Existing work provides various alternatives for such a tiling, some with guaranteed error bounds. The *paving* method is a mesh generation technique to generate all quadrilateral elements with varying element sizes at the boundary and the interior (Blacker 1991). It is related to the *advancing front technique* (Lo 1985; Thompson et al. 1999), which starts generating the mesh from the boundaries of a surface, advancing until the surface is completely meshed.

This simple tiling technique is adequate for the purposes of GSim, since spatial precision is not a design goal. I call the plane that the tiling technique works on the *base plane*. Each base mesh is either planar or near planar. In the planar case, the mesh is within the base plane. In the near planar case, the mesh can be approximated by a base plane with a height field on the vertices. When the base mesh contains multiple smoothing groups, the preprocessing step in the previous case can create multiple base meshes.

The basic steps for the tiling algorithm are as follows:

Step 1: Project the base mesh vertices to the base plane if the base mesh is not planar.

Step 2: Define a 2D rectilinear grid on the base plane. This grid is bounded by the bounding rectangle of the base mesh. The size of each grid element is defined using the unit work area requirement in the crew workflow strategy.

Step 3: Project the grid back to the original base mesh surface. Each grid element becomes a quad work location.

Step 4: Create a mapping from the triangles in the base mesh to the quads and from quads to the triangles in order to maintain the correspondence.

The algorithm uses planar point location to determine the triangles in the base mesh that correspond to each grid vertex. Then, it uses Barycentric coordinates to calculate the approximate height value at each tile vertex. Each crew can have a different set of tiles on the same base mesh. The rectangular tiling establishes an additional constraint on sizes of the triangles in the base mesh, namely the maximum triangle areas should be smaller than the tile areas.

Case III: Generating work locations using a structured grid base structure

This case supports top down planning decisions on geometry. The structured grid is a convenient structure for breaking up geometry to represent construction processes. It can arrange geometry regularly using the enclosure of each grid and easily sort the work locations using grids. Component geometry enclosed by each grid element forms a work location. Figure 5-5d shows an example for application of a structured grid to organize steel elements for construction sequencing purposes.

GSim can split and aggregate geometry using the grid structure. The *split* operations (section 5.4.1) use the grid planes to subdivide component geometry. In this case, each split mesh becomes a separate work location. A special case for split is using a single plane to subdivide any mesh into two. The *aggregate* operation joins the geometry for multiple components to obtain a single work location. GSim calculates the enclosing grid element for each component using the planar point location algorithm (section 5.4.1).

5.4.3. Geometry sorting

Section 3.2.1 illustrated the concept of workflow strategy as a preferred sequence of work locations for crews to process their scope of work. This section describes geometrically capturing the workflow strategy and sorting work locations by that strategy. The goal for geometry sorting in this context is to solve the following problem: Given the work locations, the base structure and the workflow strategy for a crew, determine the preferred sequence in which the work locations are processed.

The geometry sorting in GSim focuses only on the directional workflow strategies using triangle meshes. The technique has two main steps. The first is geometrically capturing the directional workflow strategy. Users define directional workflow strategy on base structures using a set of input vectors and directional type. Then the algorithm calculates the vector field representing the directional information for this strategy. The second step is using this workflow strategy described as a vector field to sort the work locations. Figure 5-7 shows examples of directional geometry sorting on three examples.

Vector fields

Vector fields or *vector functions* represent a field of vectors with one vector at each point in the field. A vector field is a continuous function $V{:}A \rightarrow R^3$, where A is the set of all points on a two- or three-dimensional space in a region, curve surface, or a volume. Vector fields are commonly used for modeling natural phenomena, such as force fields in electromagnetics or velocity fields for fluids. The value of the field at any point contains magnitude and direction.

Vector fields allow the consistent description of the directional workflow strategy on a surface. This research uses unit vectors at every vertex of the base mesh to approximate a vector field function representing the workflow. The magnitude of each vector in the vector field is given by the production rate for a crew at that particular location, but this magnitude is time-dependent and not necessary for geometry sorting.

I have defined a group of directional workflow types to support common construction workflow direction needs: basic, radial and edges-first. Figure 5-8 shows examples of these direction types. In *directional sorting*, the user input is a set of direction vectors and output is a vector field interpolating input vectors. In *radial sorting*, given the user input of a starting location and starting direction, the output is a radial vector field and ordering for every work location. This type is suitable for activities that move along a circumference, such as exterior walls. For *edges-first sorting*, the vector field points radially inward starting from the boundary edges. This direction type represents a directional workflow moving to the center starting from boundaries.

The main contributions for the geometry sorting are the directional work types, use of vector fields to describe crew workflow directions and generalization of the scalar *sweep distance* from (Turk 2001) to describe the ordering of work locations for directional workflow strategies.

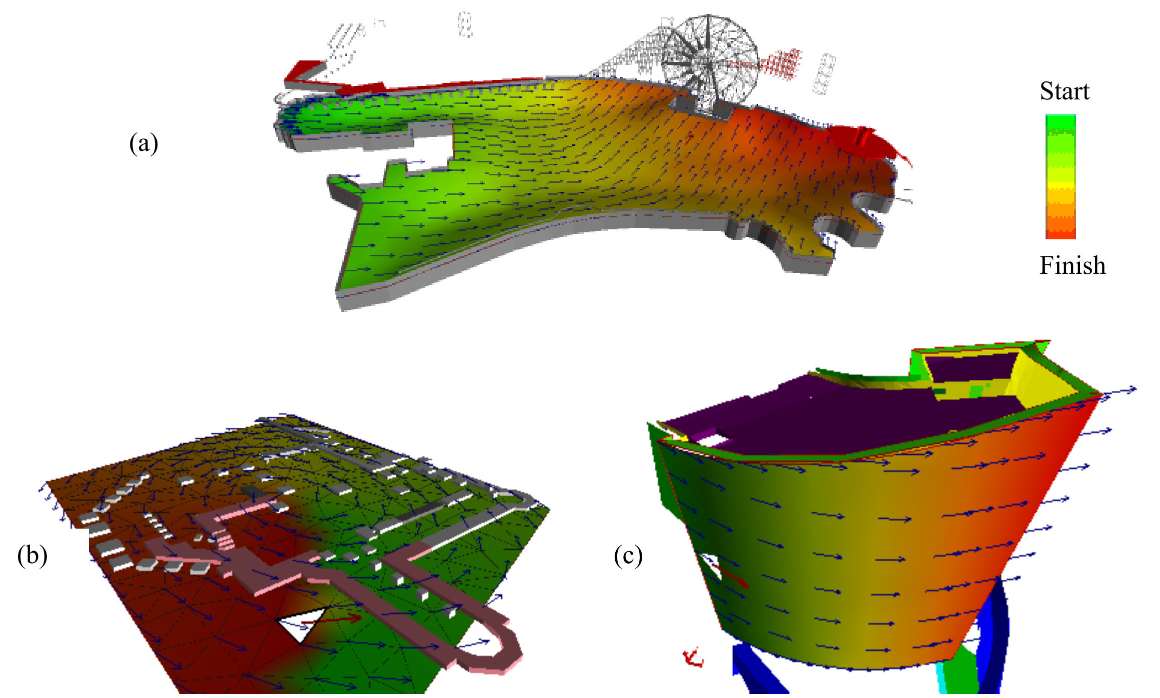


Figure 5-7. Directional geometry sorting using vector fields for three examples: (a) DCA lagoon, (b) DCA restaurant footings, and (c) Disney Concert Hall exterior enclosure. Arrows represent the vector field, and the color coding represents the workflow ordering of triangles.

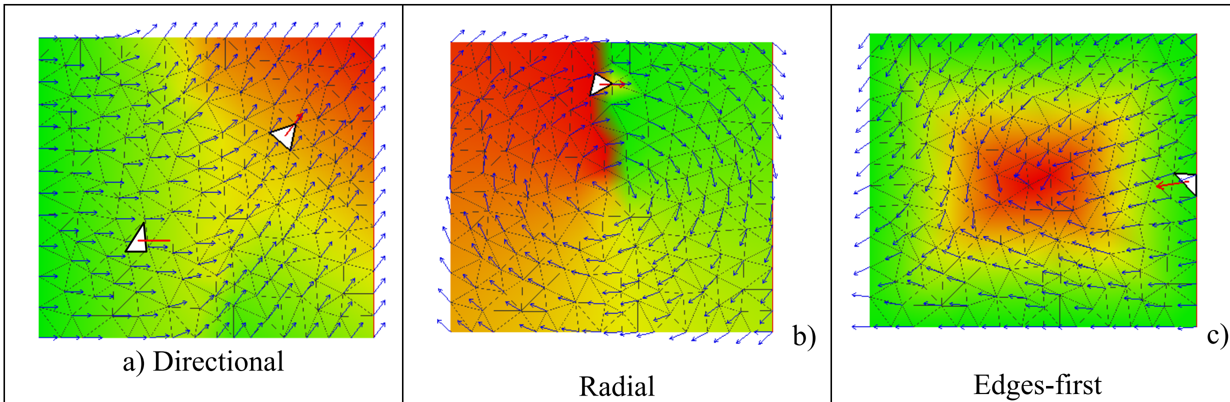


Figure 5-8. Workflow direction types used in this research. Arrows represent the vector field directions at vertices, and the color coding represents the sweeping distances.

Directional geometry sorting

This direction type sorts the triangles on a triangle mesh given a set of direction vectors. The algorithm that GSim uses follows the *surface sweeping* technique closely as described in (Turk 2001). The surface sweeping technique *diffuses* the input direction vectors over the entire surface to build the vector field. Then, the technique assigns a scalar value called *sweep distance* to every vertex. The goal in Turk's research is to define a multiple-level surface parametrization for triangle meshes for texturing purposes. This research adapts a single-level version of the surface sweeping technique. The ordering of triangles (work location ordering) in the mesh is obtained by sorting each triangle using this sweep distance.

Initially the algorithm assigns zero length vectors to all vertices in the mesh, except the vertices with user-defined direction vectors. Then, it diffuses the vector values iteratively over the surface keeping the user-defined direction vectors fixed. After each diffusion step, it projects vectors onto the tangent plane of the mesh surface at the vertex location. The diffusion process is complete when all the vertices on the mesh have non-zero vector field values. The calculation of the vector values at each vertex is using the equations:

$$V_{new}(v) = \alpha V_{old}(v) + \sum_{i=1}^{n} \beta_i V(v_i) \tag{5.1}$$

$$\alpha = 1 - k \sum_{i=1}^{n} w_i \tag{5.2}$$

$$\beta_i = k \cdot w_i \tag{5.3}$$

where $V_{new}(v)$ is the unit vector representing the vector field at vertex v, V_{old} is the previous unit vector at the same vertex, and α and β are the coefficients for the effect of the vector values to the original and neighboring vertices respectively. The value k must be fairly small (e.g. k = 0.1) to guarantee stable solution for the vector field. The values w_i in the above equation weigh the contribution of each vertex v_i, calculated using the inverse edge length (normalized by the sum of all the weights), i.e.,

$$w_i = \frac{\frac{1}{l_i}}{\sum_{i=1}^{n} w_i} \tag{5.4}$$

where l_i is the edge length at vertex *i.* After each vertex has a nonzero vector value, the algorithm assigns a sweep distance to all vertices by sweeping across the surface that follows the vector field. The starting location is assigned a sweep distance of 0. To propagate the sweep distance across the mesh, the algorithm repeatedly assigns vertices a sweep distance that shows how much further along the local orientation of the vector field they are compared to other vertices. The derivations and detailed explanations of these equations are given in (Turk 2001).

Once the sweep distances for all vertices are calculated, GSim assigns a sweep distance to all of the triangles by averaging the sweep distances of each vertex in the triangle. The triangle sweep value determines the sequence of triangles.

Radial sorting

In *radial sorting*, given the user input of a starting location and starting direction, the output is a radial vector field and an ordering for every work location. The algorithm first calculates the geometric center and the aspect ratio for the bounding box of the mesh that approximates the properties of the mesh. The vector field calculation uses the elliptical coordinates formed by the aspect ratio of the bounding box of the mesh. At every vertex location, the algorithm calculates the tangent vector on the ellipse using the calculated center and the aspect ratio and passing through the vertex (Figure 5-9). The sweep distance at every vertex is the angle θ from the starting location in the starting direction.

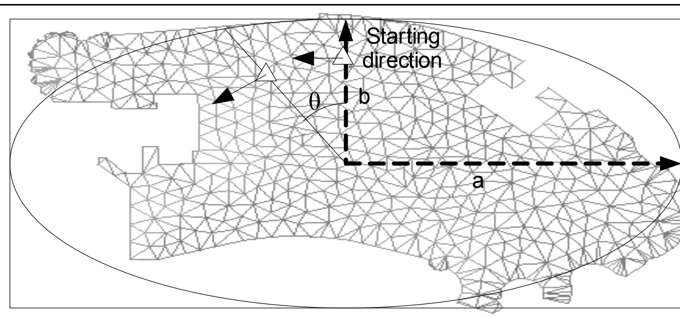


Figure 5-9. Radial sorting using elliptical coordinates.

Edges-first sorting

This direction type represents a directional workflow moving to the center starting from boundaries. It does not require input direction vectors. The algorithm calculates the closest boundary edge to each vertex using distance checks. It then assigns the vector field for every vertex using the center point of the closest boundary edge to the vertex as the direction vector. The sweep distance at any vertex is the Euclidian distance to the closest boundary edge.

These direction types are not comprehensive. I formalized these types because they are valuable in the test cases and they are capable to represent existing conceptual work (Riley and Sanvido 1995). It is possible to create new direction types using the same method. Section 7.2 gives an example for the combination of directional, radial and edges-first types for directional strategy.

5.4.4. Geometric analysis

Geometric analysis techniques in this research evaluate geometric properties (e.g., curvature, height, area, volume, distance) mainly for the purpose of production rate calculation at work locations. The general geometric analysis problem for the production rate function is: Given the functions for factors affecting the production rate of a crew, calculate the serving time for each work location (see section 3.2.2 for the description of the production rate function).

The main contribution in geometry analysis is relating the geometry to the crew production rate as various functions. Geometric evaluations use common computer graphics techniques (Foley et al. 1995). The geometry-related components of the production rate function in GPM are the shape factors and nearby work. Other geometric evaluations for GPM also fall under the geometric analysis category including spatial crew ordering and calculation of the quantity of a work location.

Shape factor calculation

I defined shape factors as the elements of the crew production rate function that incorporate various effects of shape on production rate. For simplicity, I describe and use linear and time-invariant shape functions: height, slope and distance to edge. The shape function parameters are user-defined. One reason for the choice of these shape functions is the capability to calculate them using pure geometric evaluations. Additionally, experience has shown that they are useful in construction practice and not limited to the test cases in this research.

GSim determines the values of shape factors by evaluating the shape functions at each vertex of the mesh. When there is more than one shape function at a given location, all the shape factor coefficients are multiplied to get the final shape factor.

Height factor: Describes the effect of height on the production rate. It requires a simple evaluation of the height factor function at every vertex and averaging the results.

$$k_{sf}^{h}\ (v_i)\ = f_s(h(v_i))$$

where h is a function $h{:}v \rightarrow \mathrm{R}$ that gives the vertical distance relative to the ground level at the vertex v_i and f_s is the height shape function. By default, the ground level is the bottom level of the region enclosing the subsystem. For triangle mesh work locations, the height is measured for the highest location of the bounding box.

Slope factor: Describes the effect of the slope on production rate at a given location.

$$k_{sf}^{c}\ (v_i)\ = f_s(n_i)$$

where f_s is the curvature shape function, n_i is the angle of the normal from the horizontal plane at vertex i.

Distance to edge factor: Describes the effect on the production rate of how far a work location is away from the closest boundary edge.

$$k_{sf}^{e}(v_i) \ = f(\min_{e \in B} g(v_i, e))$$

where B is the set of boundary edges and g is a function that calculates the *geodesic distance* (distance along paths within the domain) from a vertex to the boundary edges. At every vertex, the edge shape function is evaluated using the geodesic distance from the closest boundary edge. Figure 5-10 shows the calculation for the distance to edge factor on a test case.

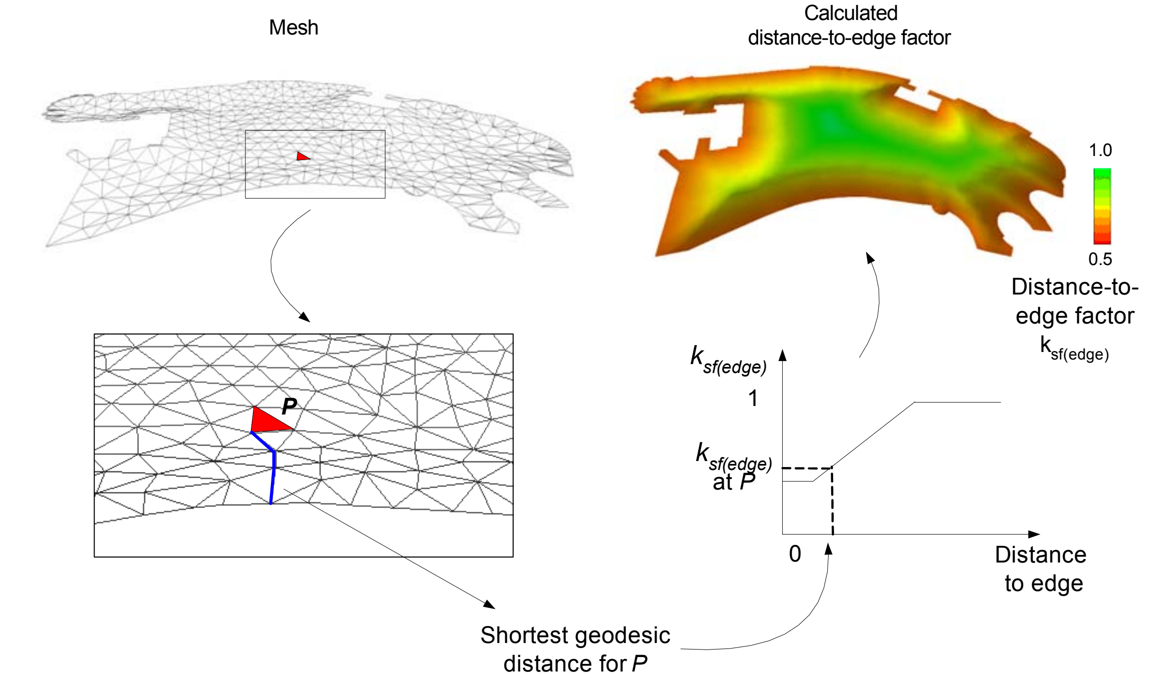


Figure 5-10. Calculation of distance to edge shape factor. For every triangle P, the shortest distance to a boundary edge is calculated. Evaluation of the shape function provides the edge factor.

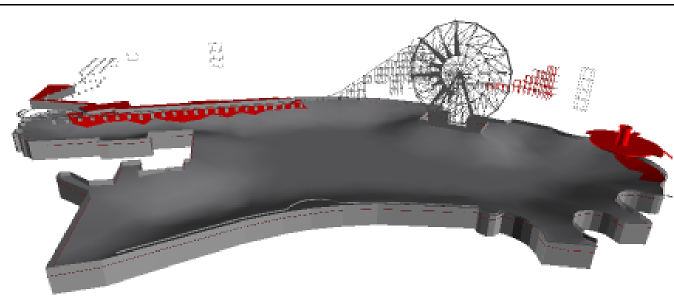


Figure 5-11. An example for a detection of the nearby work effect. The color coding shows a spatial conflict.

Nearby work effect calculation

I defined the nearby work effect as the effect of available work area of a crew on its production rate and as a function of the shortest distance from the active crew work area to other ongoing work (see section 3.4.3). It reflects spatial conflicts between crews at construction sites. The evaluation for nearby work effect uses Euclidian distance calculations between work locations. The challenge is avoiding exponential complexity for these distance checks considering large and complex models and many ongoing crews over time.

GSim performs distance checks only for work locations where concurrent work is possible. Using the global list of ongoing activities, GSim determines the possible set of interfering work locations. Since every subsystem is bounded by regions, only work locations in the intersecting or neighboring subsystems are possible candidates for this interaction. To further simplify the calculations, the distance checks are performed on a discrete-time basis. In other words, the algorithm checks distances only when the project day or hour changes (depending on the project time scale), and not after any discrete event during simulation.

The steps for the algorithm for nearby work evaluation are as follows:

Step 1: For all possible interfering work locations, perform a pair-wise distance check using the *dist*() operation. GSim uses an existing minimum Euclidian distance calculation library, PQP (Larsen et al. 1999), for implementation of the primitive operation $dist(l_1, l_2)$.

Step 2: Get the work location pair with the shortest distance among all candidates.

Step 3: Evaluate the nearby work component of the production rate function directly to determine its effect on the production rate. Depending on the shortest distance, the nearby work effect can cause work stoppage, slow-down or can have no effect.

Other geometric analysis

Spatial crew ordering is an interaction type that also relies on distance checks for geometric evaluation (see section 3.4.2). GSim determines the possible locations that a crew can perform using the sequencing relationship between activity types. The geometric goal is to find the work locations of a specific type within the specified distance that are completed, i.e., ready for the next crew. If there are such work locations, the crew can perform its work.

The quantity of a work location is either derived using the geometry or is an attribute of the work location. GSim derives the area of a triangle, a quad, or a triangle mesh work location and volumes for closed triangle mesh work locations to calculate the quantity of work. These calculations are common geometric evaluations.

5.4.5. Hierarchical space decomposition

This technique defines a general, user-defined geometric structure to automatically decompose the project geometry into hierarchical subsystems. Section 3.5.2 describes how this hierarchy works for process modeling purposes.

Spatial decomposition is a general problem from architectural modeling and general geometric perspectives. The idea of using hierarchical spaces for architectural design and construction can be traced back to the OXSYS CAD system in the 1970s (Hoskins 1973), as described in (Eastman 1999). The GLIDE-II project hierarchically decomposed parametric solid models (Eastman 1980). It automatically generated spaces using volumes bounded by a closed loop of wall surfaces, floor and ceiling information. However, these techniques focused on the requirements for the design phase of a project.

Existing geometric techniques for hierarchical space decomposition such a binary space partition (BSP) trees, octrees, and bounding box hierarchies focus on efficiency. In contrast, simplicity and flexibility of the structure and being able to define regions using enclosing elements is more important for GPM.

GPM formalizes a flexible hierarchical spatial structure using regions (planar polygonal structures with a height range). At each level of the hierarchy, there are a set of connected regions. The region structure at the next detailed level is the subdivision of the parent polygon and its height range, i.e., every region is contained by its parent. At the most detailed level, the region structure is a polygonal subdivision of the project. Any region at a higher level is the union of the regions at its lower level.

This structure can automatically organize component geometry using their containment and component type (Figure 5-12). *IsInside*() is the basic operation to check the containment of a shape within a region. GSim projects the bounding box of a work location to the region plane and checks if it is enclosed by the region. *IsInside*() returns either inside, intersecting or outside. Intersection between a region and a component geometry results in a split when a component is splitable. The algorithm uses the *split*() operation to automatically create two separate work locations and assign appropriate geometry to each. Figure 7-2 and Figure 7-12 show other examples of the spatial decomposition.

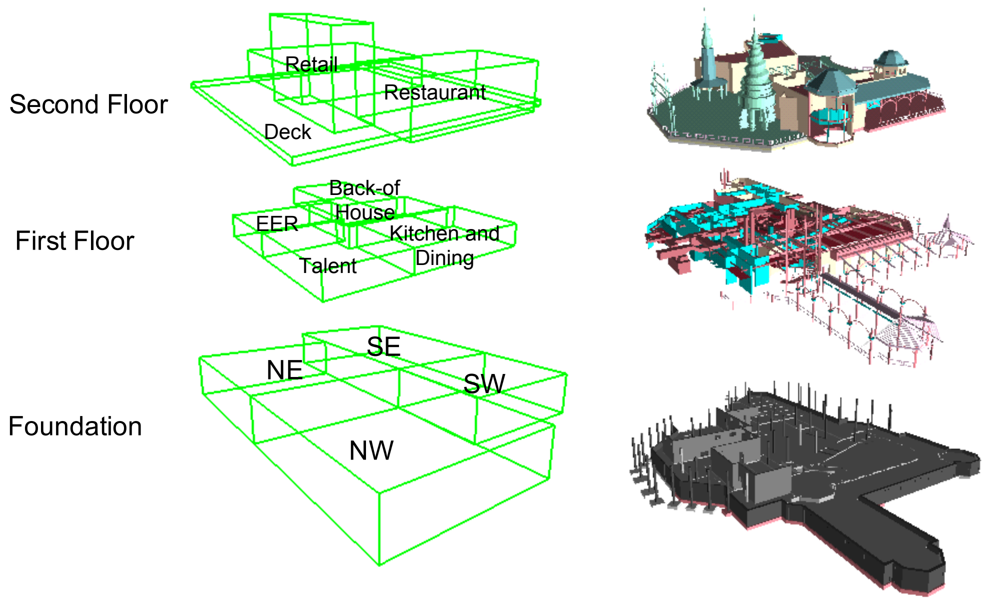


Figure 5-12. A hierarchical region structure for the restaurant case.

5.5. Validation of the geometric techniques

The main requirement for the geometric representation and algorithms is to support the process model and its simulation. Therefore, I show that for various types of input geometry and system parameters, modeling and simulation is performed correctly. I also validate the generality and efficiency goals for geometry. The validation of the extensibility and transparency goals of the geometric techniques within the overall research context is described in Chapter 7.

To validate the generality, I show the use of geometric techniques on various product shapes, ranging from simple rectangular components to complex shapes such as exterior enclosures designed by Frank O. Gehry.

For validation of efficiency, I record the running times for the algorithms for each geometric technique. I also demonstrate the algorithms on large geometric models. I do not optimize for efficiency, therefore a reasonable (polynomial) running time is acceptable for this goal. All of the timing studies use a Pentium IV 2.0 MHz notebook PC.

Table 5-1 shows the running time to generate a new mesh for the lagoon case for different numbers of vertices and numbers of faces resulting from different area constraints for Delaunay triangulation. The table also shows the duration for different geometry sorting types: directional, edge-based and radial. Figure 5-13 shows a chart for the same timing studies with interpolating functions for each time set. This shows that the tessellation and sorting techniques have polynomial time. Additionally, the running times are fast enough for interactive use. For example, triangulation of 32,318 faces takes less than a second.

Table 5-2 compares the running times for hierarchical spatial decomposition to create subsystems for different test cases. Although the implementation has not been optimized for efficiency, the results show that the hierarchical space decomposition works reasonably fast for interactive use.

Table 5-1. Comparison of times for triangulation and geometry sorting for varying mesh detail in the lagoon base example. Times are in 10^{-3} seconds.

Area constraint	Mesh Properties		Time for Delaunay triangulation (327 boundary edges)	Directional Workflow		Time for edge-based workflow	Time for radial workflow
	Number of vertices	Number of faces		Time for diffuse step	Time for sweep distance step		
1,000	760	464	80.06	31.97	69.94		
400	997	920	118.16	75.28	126.47	111.02	3.61
200	1,409	1,702	146.58	111.32	239.49	218.69	5.77
100	2,226	3,291	217.6	183.75	332.41	905.09	7.54
50	3,879	6,503	247.05	415.05	1,396.20	3567.7	15.74
25	7,107	12,836	343.24	833.34	2,432.34	12,848.87	18.36

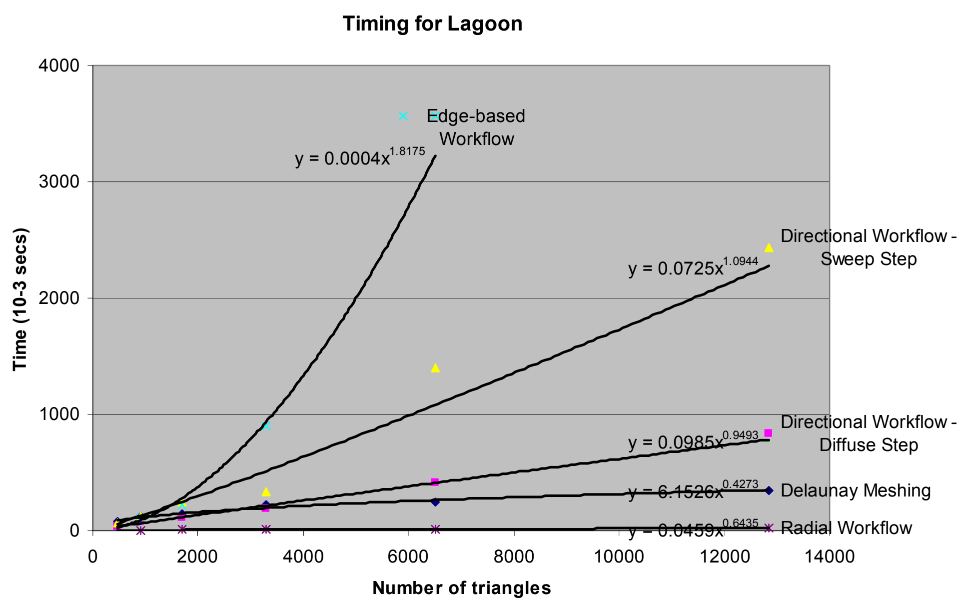


Figure 5-13. Timing for tessellation and geometry sorting for the lagoon test case.

Table 5-2. Comparison of times for hierarchical space decomposition in different test cases.

Test Case		Number of Components	Number of Triangles	Number of Subsystems	Decomposition Time (10^{-3} sec)
Restaurant	Three Spatial Levels	2,103	188,359	83	318.67
	Two Spatial Levels	2,103	188,359	27	259.42
Bay Street		13,097	278,601	64	14,082.00
Lagoon	6 zones	1	3,921	6	870.85
	3 zones	1	3,921	3	801.64

5.6. Summary and Future Work

This chapter described the geometric representations and algorithms to enable the construction process modeling and simulation approach in this research. Geometry tessellation, geometry sorting, geometry analysis and hierarchical space decomposition are the main categories. I defined each category in general terms to satisfy the extensibility goal and solved specific problems within each category.

These geometric techniques are a step towards a general approach for the use of geometric models as an integral part of construction process modeling. As such, this chapter serves several purposes. It makes the geometry-related fields more accessible to construction research, describing specific bindings between the two. It also describes specific geometry-related implementations that the construction practitioners and researchers can now assume as given. They can then focus on the process modeling and simulation aspects by treating these algorithms as a black box, without the need to understand in detail how they work.

5.6.1. Limitations

Geometry tessellation techniques in this research can only generate base structures with planar and near planar surfaces. Although this is a reasonable approximation for most construction components, there are many exceptions such as volumetric concrete placement in dams and construction of components with spherical nature. Additionally, the rectangular tiling technique only supports axis-oriented rectangular tiles.

The hierarchical space decomposition technique in this research does not support curved, variable height regions. In addition, the geometric algorithms are not optimized for efficiency.

5.6.2. Suggestions for future work in geometric techniques

There are many possible improvements from the geometric representation and algorithms perspective. One area of interest is the use of other geometric representations, such as solid models, NURBS surfaces and parametric models.

For geometry tessellation, work locations are limited to triangles and triangle meshes. Support for volumetric work locations and base structures can extend the value of the geometric techniques to wider construction work.

Finding the optimal workflow strategy in geometry sorting is not within the scope of this research. Instead, this research reflects the planners' decisions on the geometry. To find the best plan, one needs to use a search or optimization algorithm with a well-defined scoring function, such as shortest duration, minimum cost, resource utilization. Finding the minimum duration plan for a subsystem construction requires optimization of the crew traversal paths using the connectivity between work locations as a graph. For the base mesh, the topological information of the mesh describes the edges and the triangles describe the vertices of the graph. A weight can be associated to each edge using the connectivity information and a cost metric. One way to find the shortest path in a graph is using the Minimum Spanning Trees (MST) (Cormen et al. 1990) algorithm for traversing the mesh. A simple cost metric choice might be Euclidean distances from the root triangle. A* is a possible search algorithm for minimizing the path duration (Russell and Norvig 2003).

Shortest path workflow strategy for an individual crew in a subsystem does not necessarily provide an optimal solution for the project. The interactions between crews should also be under consideration.

Direction of workflow for one subsystem level of detail is useful at different levels. An interesting problem is to propagate the directional workflow strategy up and down. For example, workflow directions defined at a macro region automatically can provide direction information for its lower level regions, since the parent regions contain their children and regions have connectivity information. Conversely, a higher level directional structure can be inferred from detailed regions.

The next chapter explains the implementation of GSim.

CHAPTER 6

IMPLEMENTATION

This chapter describes the design goals, user interaction and implementation structure for GSim, the prototype implementation for this research. GSim supports interactive definition and management of the geometry-based process model, simulates the process model and visualizes the results.

6.1. Introduction

6.1.1. The design goals and challenges for GSim

- Generality: The implementation should support the representation and analysis requirements for GPM for various geometric models, activities, and physical organization structures. The implementation should also reflect the typical workflow of construction process design and analysis.
- Ease of use: The implementation should have simple and intuitive user interfaces.
- Extensibility: The implementation should easily support possible extensions, such as improvements on the process model and additions of other geometric techniques.

Given these design goals, there are various implementation challenges from different perspectives. From the modeling perspective, users should be able to enter the GPM process elements and subsystems easily, describing the crew parameters (workflow strategy and production rate function) and crew sequence.

From a simulation perspective, the implementation must correctly perform the simulation using the process model description and visualize the results of the simulation. From the geometry perspective, GSim should support the modeling and simulation approach as described in Chapter 5.

6.1.2. Basics of GSim implementation

The main functionality of GSim is as follows.

(1) Support organization of the project geometry using a hierarchical spatial structure. Use that structure and component types to decompose the construction process into subsystems.

(2) Support the assignment of crews to subsystems and definition of production rate and workflow strategy parameters for crews interactively.

(3) Simulate the construction process automatically using the input parameters.

(4) Implement the geometric representation and algorithms to support modeling and simulation.

(5) Depict the results of the simulation as 4D visualization and crew progress over time.

(6) Import 3D geometry and crew parameters for projects.

(7) Support work balancing in 3D and zone generation.

6.1.3. Implementation basis for 4D support

GSim code is partially based on Invizn, a 4D CAD prototype software developed at Walt Disney Imagineering Research and Development. Invizn provides 4D visualization by associating component geometry and CPM activities. It permits users to navigate spatially and temporally within the 4D model. It implements user interfaces for managing the physical organization hierarchy, physical components and schedule activities. Additionally, it imports CPM schedule activities and 3D geometry for the finished facility.

GSim uses the Invizn code base in several ways. GSim converts the input geometry of Invizn into a triangle mesh to satisfy the needs of the geometric techniques. It uses the physical organization hierarchy to define the scope of work (components) and the crews for subsystems. GSim can use the CPM activities to describe some of the crew parameters, e.g., the activity period provides average production rate and mobilization date information. After the simulation, GSim overrides the implementation of the original 4D visualization to visualize installation states for work locations.

6.2. Functionality of GSim

GSim supports all elements of the GPM approach, with a graphical user interface (Figure 6-1**).** Many figures in the other chapters use screenshots from GSim. GSim imports 3D geometric model as triangles for each physical component with component types to build the geometric model. Crew input is the activity description with activity types and parameters related to the production rate function and the workflow strategy. Other inputs are a sequence of crews for each subsystem and interactions between subsystems. The input is via a user interface or a text file input format.

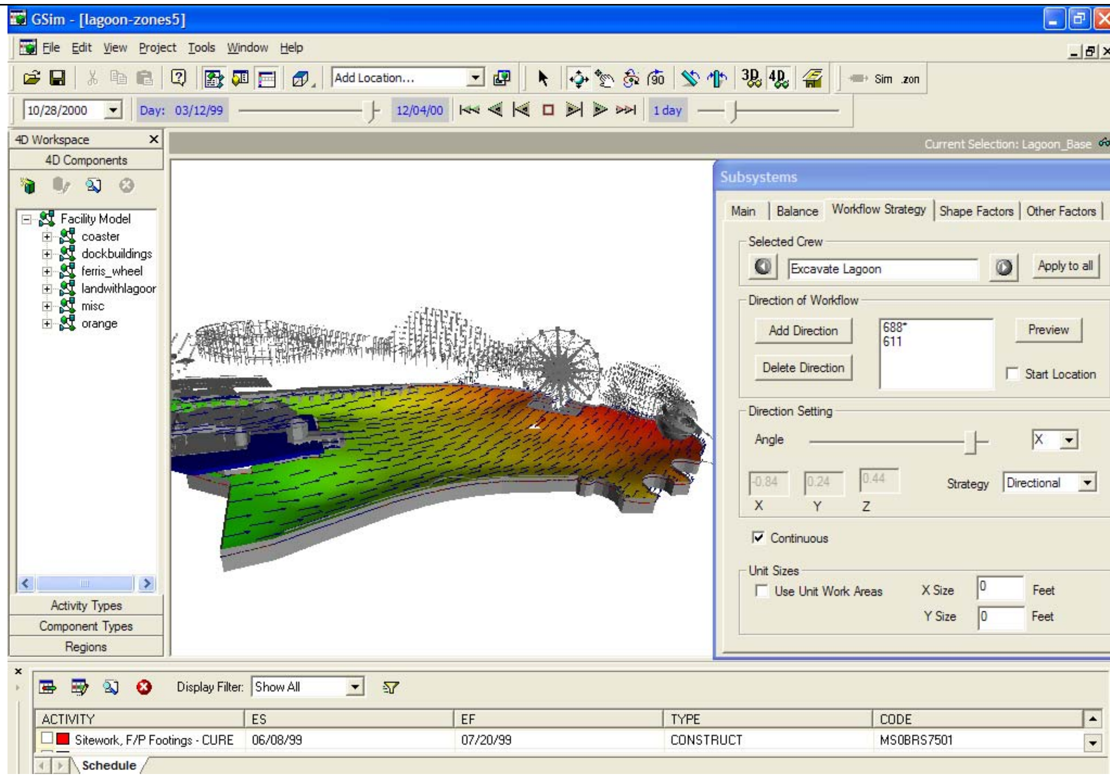


Figure 6-1. A screenshot for GSim.

The user first describes the subsystems by decomposing the 3D model and the process elements. Region hierarchy and component types provide support for this decomposition. Using a hierarchical spatial structure, GSim automatically builds the physical organization hierarchy by allocating every building element into a spatial region (e.g., Figure 7-5). The user associates each subsystem with one or more crews interactively.

The next step is the parameter definition for each crew: production rate function and workflow strategy. GSim supports interactive definition and update of the GPM crew parameters through a graphical user interface. Figure 6-2 shows the user interface for various parameters. An LOB diagram style interface aids the definition of crew sequences, their mobilization date and the production capacity (Figure 6-2a). The changes in the mobilization date and the production capacity for a selected crew are automatically reflected in the diagram.

The user can define directional workflow strategies interactively by picking locations on the 3D model and assigning vectors to reflect the direction of workflow at that location (Figure

6-2b). GSim builds the vector field, calculates the sequence of work locations for that crew and visualizes it as a vector field and color coding representing the workflow (e.g., Figure 5-7).

The user can also define parameters for the production rate function for each crew. Figure 6-2c shows the interface for shape factor functions (height, curvature, and distance to edge). Sliders are used to change function parameters. The effect of shape factor changes is directly visualized on the geometry. Figure 5-10 shows an example visualization for the distance-to-edge shape function. Other user-defined parameters in the production rate function are for nearby work effect and resource availability (Figure 6-2d).

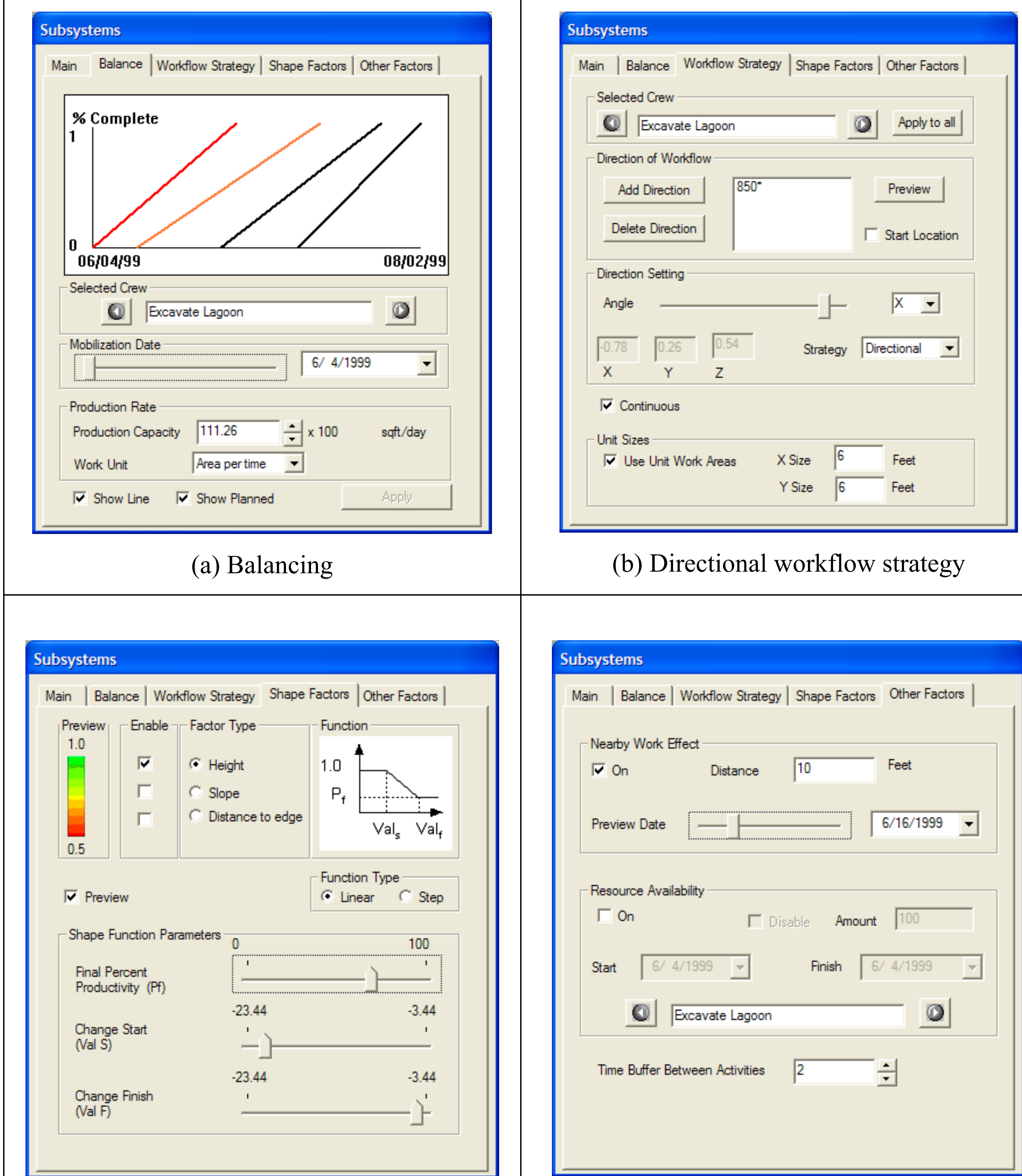
The user can evaluate the candidates of nearby work interaction from other subsystems over time by changing the preview date and visualizing the results (e.g., Figure 5-11). The other interaction types, the activity ordering and spatial crew ordering are currently input to the system via a text file.

After GSim automatically simulates an equivalent queueing network for each subsystem, it generates the states on the crews and work locations. The user can visualize these results in various ways. The 4D view allows temporal and spatial navigation to view work location states (e.g., Figure 7-9). A LOB diagram shows the predicted crew production curves (e.g., Figure 7-10). A direct export to a scheduling software permits evaluation of the simulation results and updating master schedules in CPM format (e.g., Figure 7-14). The user can change the planning parameters and re-simulate the GPM automatically to evaluate alternatives.

6.3. Implementation structure

GSim is developed in Visual C++. It uses an object-oriented architecture and simple data structures for generality and extensibility purposes. I use a component-based software architecture and make use of *design patterns* for a clearer design and extensibility (Gamma 1995) wherever possible. This section briefly describes the important classes for the implementation steps.

GSim has around 50 classes and 20,000 lines of code (excluding comments and spaces) for implementation of the GPM approach. The total size of GSim, including the baseline Invizn code, is around 70,000 lines. The following sections summarize the important classes and their functionality in GSim.



(a) Balancing

(b) Directional workflow strategy

(c) Shape factors on crew production rates

(d) Other factors on crew production rates

Figure 6-2. User interfaces for parameter entry in GSim.

6.3.1. Process modeling

There are several important classes that GSim inherits from Invizn. The C4dComponent class encapsulates component attributes and relates components to geometry. The CShape class represents geometry as triangle sets. The CScheduleActivity class represents CPM activities. Additionally the CTimeShow class performs 4D visualization by changing the colors of component geometry depending on the date visualized.

GSim defines the CZoneManager class to create, store and manage the subsystem input parameters. CZoneLoader imports the parameters using a text file format. The CWorkLocation class manages work locations and relates them to geometry. Additionally, there are a set of dictionary classes to store individual elements of the process model.

6.3.2. Simulation and visualization

The CActivityStateManager class generates the queueing network using the input parameters (see Section 4.2.2). It also calculates the states for simulation using finite state automata techniques and can support more complex state machines.

The CQNetwork class simulates the queueing network, stores the states and performance variables for the servers and the queues. The CQNetServer class represents individual servers in the queue and describes crew behavior during simulation.

After the simulation, each work location has an installation state at any project time which can be used for visualization. The CZoneShowManager class is responsible for visualizing the installation states over time using color coding. GSim uses OpenGL API for interactive 3D graphics, spatial and temporal navigation.

6.3.3. Geometric techniques

This section summarizes the approach in GSim for implementation of the geometric techniques described in Section 0 focusing on the important classes and their functionality.

Geometric representation:

The most important geometric data structure in GSim is the representation for a triangle mesh with its connectivity and attributes. Since the triangles are the units of analysis, GSim represents triangle meshes using a triangle-based representation, as opposed to edge-based representations, e.g., quad-edge (Guibas and Stolfi 1983). The geometric techniques need to obtain all triangles that contain a specific vertex, i.e., the *star* of a vertex, and the neighboring triangles for any triangle.

The CConnectedMesh class represents triangle meshes. There are three main elements for the triangle mesh representation: an array of faces, an array of vertices and an array of vertex data. There is a separate class for triangle faces (CMeshTriangle). Each triangle has attributes including an id and a mark, center point, area, normal for geometric techniques. Triangle attributes such as center, area, normal are updated whenever there is a change in the mesh. The connectivity information for a triangle consists of an index of its vertex locations, references to neighboring faces, the order of the neighboring edge in the neighboring face, and a boolean variable that shows if there is a crease in the neighboring edge. Vertices also have attributes, such as a vector to represent the vector field at that vertex and a sweep value.

Geometry Tessellation:

Section 5.4.2 describes the geometry tessellation techniques to define work locations and geometric base structures. The CPolyMesh class defines work locations from triangle mesh geometry and converts input geometry from polygon soup into triangle meshes.

I updated and used existing software code to triangulate base structure surfaces using constrained Delaunay triangulation. **Triangle** (Shewchuk 1996) is a two-dimensional quality mesh generator and Delaunay triangulator. GSim converts the internal mesh representation into **Triangle** data structure. The boundary edges of the original mesh become the constrained edges. **Triangle** generates a new set of triangles satisfying the constrained edges and area constraints. GSim then converts the generated triangles back to the internal mesh data structure.

The CSubdivisionGrid and CAggregationGrid classes generate a structured grid and use it to split or aggregate geometry.

Geometry sorting:

Section 5.4.3 describes the geometry sorting techniques for GPM. The CPolygonTraverser class is a parent class for classes that sort geometry in different ways. One of its subclasses, CPolyTraverserVField defines vector fields by implementing surface sweeping techniques and sorts the triangles in a mesh given that vector field.

Geometry Analysis:

These techniques are described in section 5.4.4. The CDistance3D class manages distance related to geometric functionality. GSim uses the PQP software library (Larsen et al. 1999) for 3D distance calculations. This library can calculate the minimum distance between any set of triangle meshes, and the minimum distance between a point and a bounding box.

The CShapeFactorSet class contains the shape functions and evaluates them on any geometric location, including height, slope and distance to edge function types. There is a separate class for each shape function type.

Hierarchical space decomposition:

Space decomposition techniques are introduced in Section 5.4.5. The CRegionDict class creates and stores the flexible region hierarchy that automatically organizes the components. The CRegion class represents and visualizes each region and determines the geometry enclosed by it.

6.4. Applications of GSim

6.4.1. Work balancing in 3D

The requirements for work balancing in 3D are to (i) interactively change production rates using a LOB style diagram, (ii) to interactively manage directional workflow strategies for crews, (iii) to detect interferences between crews, and (iv) to support work continuity. GSim allows users to perform this functionality (see Figure 7-10).

Each crew in a GPM subsystem forms a separate production line as in linear scheduling techniques (see Section 2.2.3). By manipulating GPM crew parameters, users can modify the production rate and workflow strategy parameters, until the planned flow satisfies continuous resource utilization and there are no interferences in a project subsystem. GSim can visualize conflicts caused by unbalanced flow, and modify mobilization dates, production rates or direction of workflow as necessary.

Future implementations should enable users to start work balancing ideally should start from the highest possible level (building, floors). If there is a possible conflict at a high level in the process model, balancing is necessary until all conflicts are resolved at lower levels. This process would continue to the lowest level of work locations.

6.4.2. Zone generation

Space allocation for crews is an important practical need for construction management. *Work area zones* are spaces allocated to crews for a particular time interval. Construction zone generation assists this process using geometric models. This application could replace the current manual technique of coloring 2D construction drawings to define work areas.

Previous research defines construction zones mostly for automated planning purposes. Examples are for planning high-rise buildings (Shaked and Warszawski 1995), to simplify the planning process by creating sub-networks of activities and constraints within zones (Thabet and Beliveau 1994), and to search for an optimal zoning plan on 3D geometric models for cost and duration criteria (Winstanley and Hoshi 1993). However these techniques do not use planning decisions to create zones, instead require users to specify volumes in a top-down fashion.

Zones can be defined as a result of a simulation or as a top-down planning decision. GSim can generate both types of zones. For the first type, once the installation states for work locations are generated after discrete-event simulation, the sets of work locations with the same installation state during a time interval define the work area zones. For the second type, zones may be a functional volume defined during design (e.g., a room) or partitioned specifically for construction planning to balance activity duration and resources in each zone. Regions, grid structure or geometric analysis techniques (Section 5.4.4) such as providing ranges on the shape functions or using the distance effects can describe this type of zones.

A zone can also specify the effective work area for crews with multiple construction methods for its scope of work because of different geometric features or spatial constraints. For example, in the Disney's California Adventure lagoon, the flat and inclined areas were different zones for the reinforcing mesh crew. Additionally, in 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 installation (Akbas and Fischer 1999).

Currently, GSim generates work area zones but there is no user interface and interactive visualization for this purpose. Additionally, GSim does not generate optimal functional volumes, but relies on the user to define them.

6.5. Summary and Conclusions

This chapter summarized the features of GSim which supports and demonstrates the concepts in GPM formalized in this research can be implemented in a software tool and applied to data and problems from real projects. Although it is a prototype, many of its functionality are robust enough to be tested on real projects. It is general, easy to use and extensible for future research. The next chapter describes the validation for this research.

CHAPTER 7

VALIDATION

This chapter describes the validation procedure composed of theoretical and empirical parts. Theoretical validation gives arguments for legitimacy of the GPM approach. It shows that the physical conversions in the construction process can be modeled and simulated as a discrete event system. It confirms the abstraction of GPM to represent construction operations as conceptualized in prior work. Additionally, the implementation prototype, GSim, provides evidence that the GPM approach is internally consistent. The validation for the geometric techniques is explained in Section 5.5.

For empirical validation, I use retrospective test cases to show that planners can define, simulate and evaluate what-if scenarios for construction processes. The main criteria for the validation of GPM are generality, flexibility, model simplicity and scalability as described in Section 1.3. Empirical validation section also demonstrates the use of the GPM approach and GSim on real projects. Lastly, I demonstrate conversions from GPM to some existing planning models (CPM and LOB).

7.1. Theoretical Validation

7.1.1. GPM process model

I argue for the legitimacy of the GPM approach from the bottom-up, starting from the crew parameters to the subsystems and the whole process model. I show that the existing conceptualizations in prior work, for specifically the physical conversions or transformations, can be supported by GPM.

Workflow strategy

I defined the workflow strategy as a function assigning an order to the set of work locations within the work scope of a crew in Section 3.2.1. This definition can represent any crew workflow strategy. However, GPM focuses on the directional workflow strategies described on surfaces. The geometry sorting techniques (see Section 5.4.3) support any directional workflow strategy on triangle meshes to sort work locations.

Production rate function

The production rate function in GPM is only a starting point for accurate crew production models on geometry. However, the function elements can support constant production rates, time-series based production rates (using resource availability), effects of shape complexity, and effects of nearby work. The resource availability can represent upper bounds for the production rate and work stoppage. The nearby work effect can capture work slowing or stoppage effects of a nearby ongoing activity. The *production capacity* element in the production rate function makes the same assumption as the linear scheduling techniques and CPM networks. Similarly, a constant shape factor function is the same as the assumption in the factor based productivity model (Thomas et al. 1990).

I did not validate or collect enough data on whether the types of functions, accuracy of the parameters and interactions between factors, i.e., multiplicative combination of factors, of this production rate model are realistic.

Subsystems

The subsystems are defined by a crew sequence with their parameters. A subsystem therefore can represent a work package in work breakdown structures. However, GPM subsystems contain parametric information on the process as well.

Interactions

GPM considers three types of interactions between subsystems: Activity ordering, spatial crew ordering, and nearby work. Activity ordering is the same as precedence relationships in CPM networks. The other interactions have geometric components. Spatial crew ordering can encapsulate many spatial precedence relationships between components. Consideration of nearby work effect using solely the distances between work requires validation.

7.1.2. Simulation

I discuss how the elements of the GPM approach come together for simulation. Additionally, GSim demonstrates that the GPM approach is internally consistent by implementing its contents.

GPM subsystems can be reduced to serial queueing networks. This reduction shows that the subsystems are discrete event systems as are serial queueing networks (Cassandras 1999) and that the subsystems can be simulated.

Geometric techniques, i.e., geometry tessellation, geometry sorting, and geometry analysis, support this reduction. Geometry tessellation defines work locations from the input geometry. Given the directional workflow strategy, geometry sorting generates the priority for work locations in their respective queues. Geometry analysis calculates the serving time using the production rate function and the quantity of work in the work locations.

For simulation, subsystems can be coupled together (Zeigler et al. 2000) using activity ordering, spatial crew ordering and nearby work interactions. Geometry analysis can detect spatial crew ordering and nearby work for any subsystem.

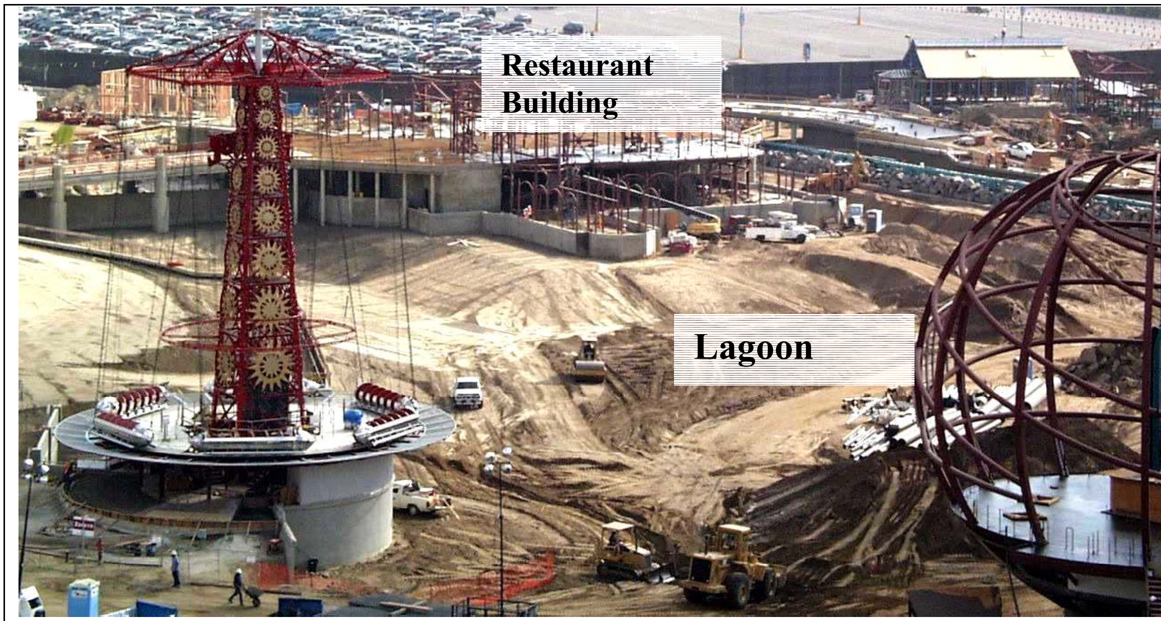


Figure 7-1. A photo of the construction of the lagoon and restaurant building in Disney's California Adventure project.

7.2. Empirical Validation Using Test Cases

This part of the validation uses retrospective test cases (Thomsen et al. 1998) to show that the GPM approach is general, flexible and scalable. I observed four separate real world cases at three construction sites. For these cases, I modeled the construction process for a variety of activities for building construction including sitework (excavation, grading, piling, retaining walls), structural concrete, roofing, mechanical components (HVAC), interior walls and exterior enclosures.

These cases demonstrate and validate the generality of the GPM approach with respect to different types of building components and geometric models. To test the flexibility, I show the evaluation of planning alternatives with respect to different parameters.

I also show the power of the approach by model simplicity and scalability. For simplicity, I compare the activities and relationships needed to represent the same construction operations using CPM with GPM. To test the scalability of the approach and the implementation, I simulate large models.

7.2.1. Process modeling and simulation using GPM

This section shows the validation of the contributions related to process modeling and simulation using the lagoon and the restaurant building construction cases in Disney's California Adventure (DCA). Figure 7-1 shows a photo of these areas during construction. The first part of the test case (the lagoon) demonstrates the workflow strategy, the production rate function, and the interaction of subsystems for earthworks operations. The second part (the restaurant building) demonstrates the use of the same contributions on a two floor building, focusing on the structural components of the restaurant foundation. These two cases also differ in their nature of geometric models. The lagoon case demonstrates the simulation on triangle work locations, while the restaurant case demonstrates simulation on discrete components.

The steps for this empirical validation are:

(1) Extraction of the basic planning parameters in test cases using the planned and actual construction information.

(2) Definition of the process model in GPM using these parameters. This includes using the region hierarchy, describing the crew parameters, and describing subsystem and their interactions.

(3) Simulation of the process model with the parameters in (2).

(4) Comparison of the results of (3) with the actual construction.

(5) Evaluation of planning alternatives by changing GPM parameters.

The available information for the actual construction process is a detailed geometric model and a construction schedule with the scheduled and actual dates. Additionally, the owner's construction manager provided feedback on the essential planning decisions during and after construction and validated the relevance and importance of the analyses and visualizations provided by GPM in support of planning decisions.

There are two geometric models for the DCA project. The first model, used by the lagoon test case, contains the overall project organized by areas. Some example areas are the lagoon, the restaurant building, roller coaster, and a ferris wheel. The lagoon geometry in this model is a single geometric entity. The detailed geometric model, used for the restaurant case, contains only the restaurant building. It is more detailed than the overall model and it contains 1,868 building components.

The master schedule for the project is a single CPM network composed of around 6,000 activities. The lagoon construction has 24 activities and the restaurant construction is represented by 900 activities, mostly for physical conversions. Every area has start and finish milestones. The following explanations are simplified and modified versions of the actual construction operations in these cases to better demonstrate the GPM approach.

The lagoon case

This case validates and demonstrates spatial decomposition, directional and radial workflow strategies, the elements of the production rate function including shape effects, and interactions including nearby work and activity ordering for triangle mesh surfaces.

The planners defined different zoning configurations as the construction plan evolved. The initial configuration had 6 zones, whereas the updated has 3 zones (Figure 7-2).

The lagoon construction has four main activities. The *excavate* activity starts from the front of the restaurant building, progressing towards the East. The main rationale for this is the eastward access location for the excavation equipment. The *place and compact clay* activity has also an eastward direction of workflow. However, it starts after the steel erection at the restaurant building, since the lagoon is used as the steel storage area. Activities for the roller coaster construction are performed before *place and compact clay*. The *install reinforcing mesh* activity starts from the edges of the lagoon and installs mesh on the inclined areas first. Next, reinforcement mesh is installed in the flat bottom at the center. The mesh cages come to the site prefabricated to a unit size. The production rate for the mesh activity is slower when mesh is installed on a sloped area. *Place concrete* follows the installation of reinforcing mesh. After a certain area is covered with reinforcing mesh, concrete can be placed there. The CPM schedule contains these four activities for the lagoon construction in each zone.

Using this process information, I describe the corresponding process model in GPM. Figure 7-2 shows the support of the region hierarchy to spatially decompose the geometric model for both of these configurations. After the decomposition, the subsystems are defined as the lagoon, the restaurant, roller coaster, and the other areas.

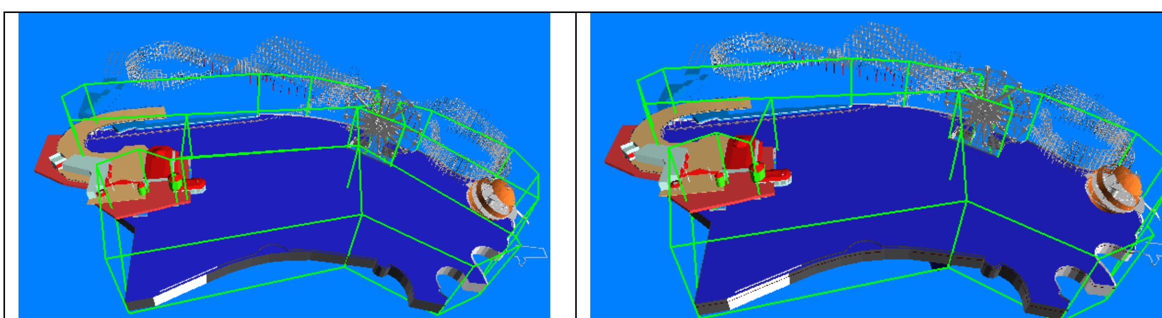


Figure 7-2. Two spatial decompositions for the lagoon case.

Table 7-1. Workflow strategy and the other parameters for DCA lagoon test case.

ACTIVITY	WORKFLOW STRATEGY	OTHER PARAMETERS
Excavate	Use directional strategy with two direction vectors.	Must start after steel erection at the restaurant building (activity ordering interaction)
Place and compact clay	Use directional strategy similar to excavation.	
Reinforcing mesh	Use radial workflow strategy. Install inclined areas first. Use unit work area.	Lower production rate near edges (shape factor effect).
Place concrete	Follow installation of reinforcing mesh.	Daily limit (resource availability).

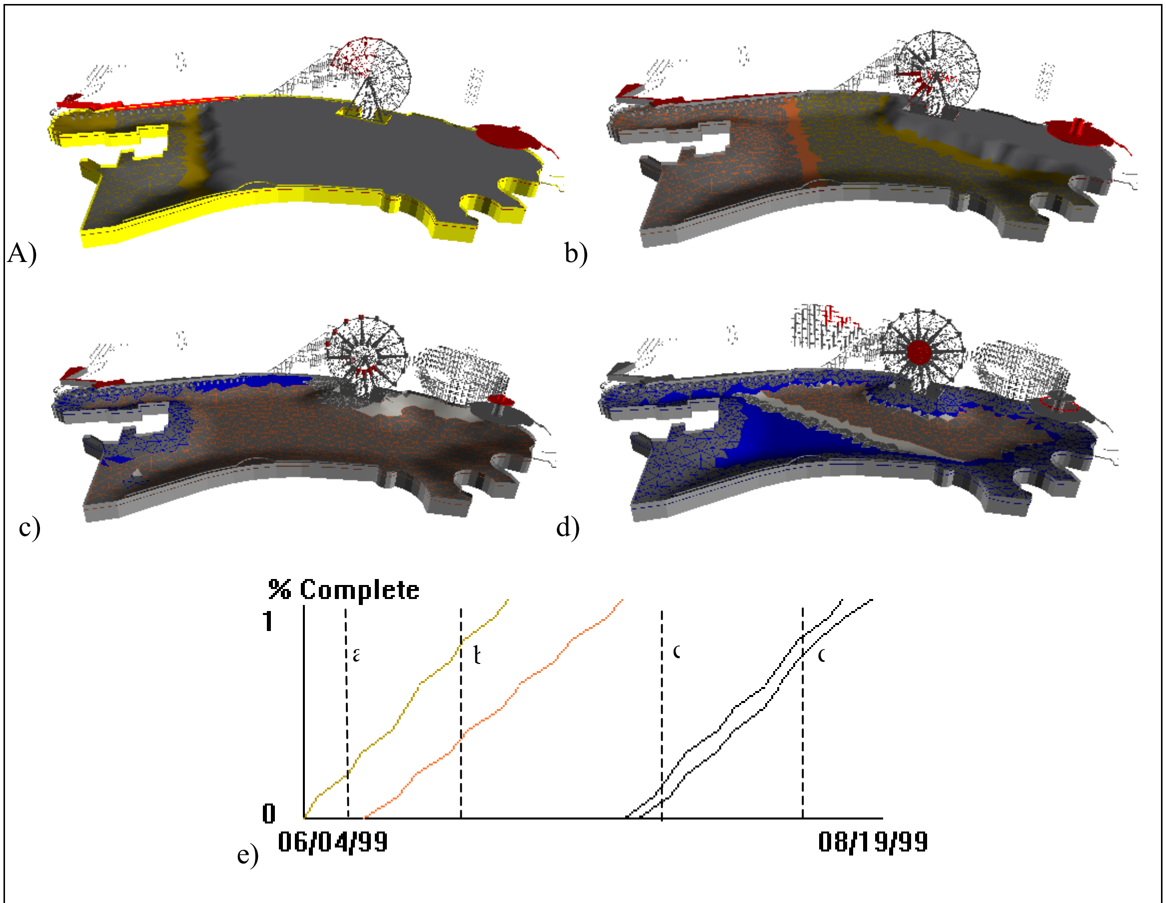


Figure 7-3. A simulation result for the lagoon case; a-d) show snapshots of the 4D visualization of the predicted states for different dates, e) shows the percent complete diagram for each crew; vertical lines show the dates of snapshots in a-d.

To build a model for this actual construction process requires numerous different production parameters. Table 7-1 summarizes the workflow strategy and the other parameters for these crews. The lagoon subsystem contains four crews, one for each activity. Crews have different workflow strategies: directional and radial. The *reinforcing mesh* activity is assigned a shape factor effect. The nearby work interaction detects and prevents crews in different subsystems from performing work close to each other. In addition, there are activity ordering interactions between the steel erection for the restaurant building and the *place and compact clay* activity.

The depth of the lagoon base changes over time during the excavation activity. In that respect, excavation is a special activity type: crew progress means a change in the surface height. Using an additional state variable (current excavation depth) and the height shape function, GSim provides a procedural way to describe surface height at any location during excavation.

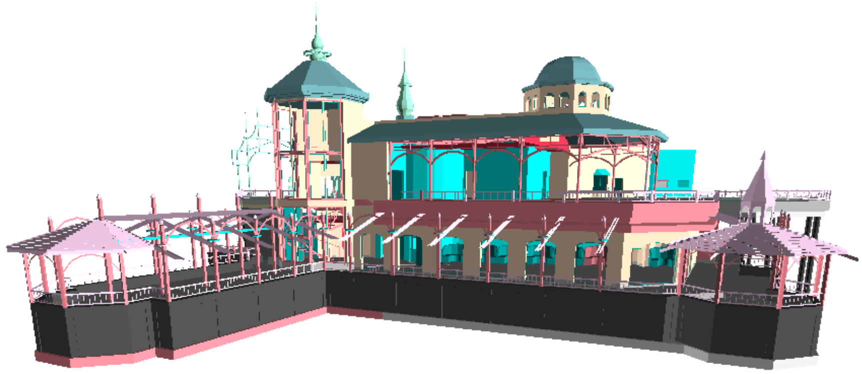
The results of the simulation for this process model are shown in Figure 7-3. Figure 7-3 a-d show the states on work locations as a 4D visualization. Figure 7-3e shows the simulation results as a LOB style percent complete diagram. It also shows the corresponding dates for a-d. Note that in Figure 7-3a, the surface height change during the excavation activity is visible. These results are reasonable approximations for the simplified actual process according to the owner's construction manager. They demonstrate that GPM can capture important planning parameters.

The restaurant case

The validation on this test case focuses on the structural components of the foundation, constituting of footings, retaining walls, concrete columns and slab on grade. Again, I extract the parameters from the planned and actual dates from construction information obtained from the site and simulate the process model. This case shows the hierarchical spatial decomposition, definition of subsystems and crew sequences, directional workflow strategies, and spatial crew ordering interaction.

The spatial decomposition of the restaurant is hierarchical into three levels as shown in Figure 7-5. The first decomposition level contains three main areas: foundation, first floor and second floor. At the second decomposition level, each region is a room or a quadrant. The original master schedule describes activities at the second decomposition level.

(a)



(b)

Figure 7-4. The restaurant building in DCA. (a) A rendering of the 3D model and (b) a photo of the actual construction.

The main activities for the footings and the retaining walls are *form*, *rebar* and *place concrete*. The construction of the concrete columns requires *rebar* and *place concrete* activities, while the slab-on-grade needs *form*, *rebar*, *place concrete* and *sand* activities.

Figure 7-6 shows the actual directional workflow for each foundation activity, which I obtained using the actual construction dates. The crews for the footing and slab-on-grade construction have radial flow, whereas columns are installed edges first, moving towards the inside from there, and foundation walls have a fixed directional flow. I obtained an average production rate for each crew using the actual duration for each activity and the quantity of each work location.

The physical constraints between the structural elements are: The work on concrete columns and foundation walls can only start after the footings are complete. Similarly, the work on the slab-on-grade should follow the columns.

The parameters observed on site form the basis for defining the corresponding process model. By choice, I model each type of the structural elements that make up the foundation as a separate subsystem. Every component is a work location. The directional workflow strategy for crews in each subsystem is shown in Figure 7-7. I assume that every crew in a subsystem has the same directional workflow strategy. Figure 7-8 shows each subsystem and the production capacities for each crew in the subsystems as a LOB diagram.

I represent the physical constraints between component types as spatial crew ordering interactions in the process model. For example, the *form* activity for a specific column cannot start until the *place concrete* activity for a footing is complete.

Figure 7-9 shows snapshots of the 4D visualization from the simulation, given the modeling parameters just described. Again, these results reflect the actual observations on site.

These cases show that GPM can approximate the actual construction process for many types of construction components using simple parameters. The next section confirms that the process model parameters are flexible by allowing evaluation of alternatives.

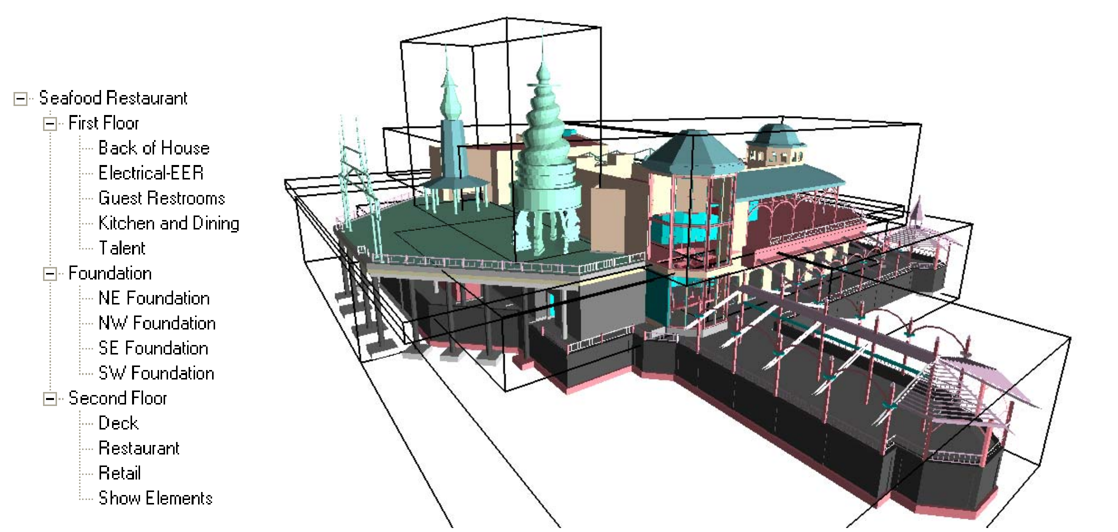


Figure 7-5. Spatial decomposition of the restaurant building using region hierarchy.

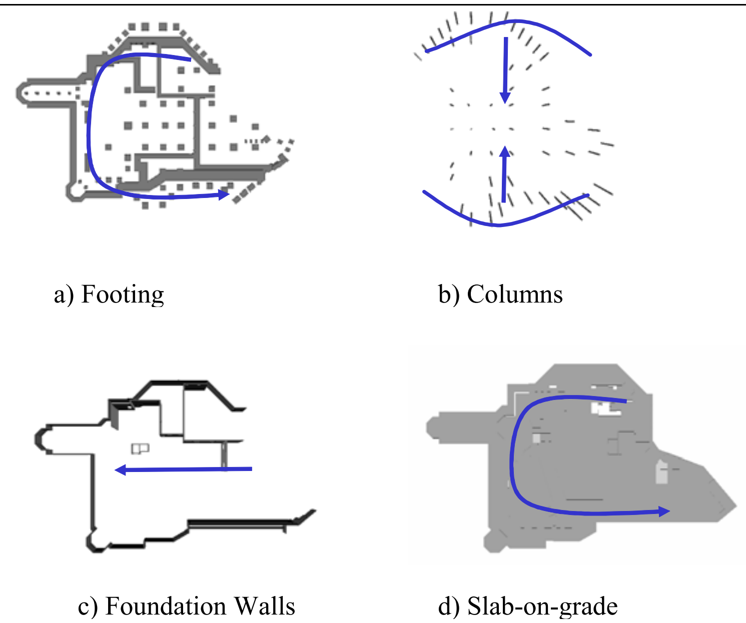


Figure 7-6. Actual directional workflow strategies for the construction of the restaurant case foundation components.

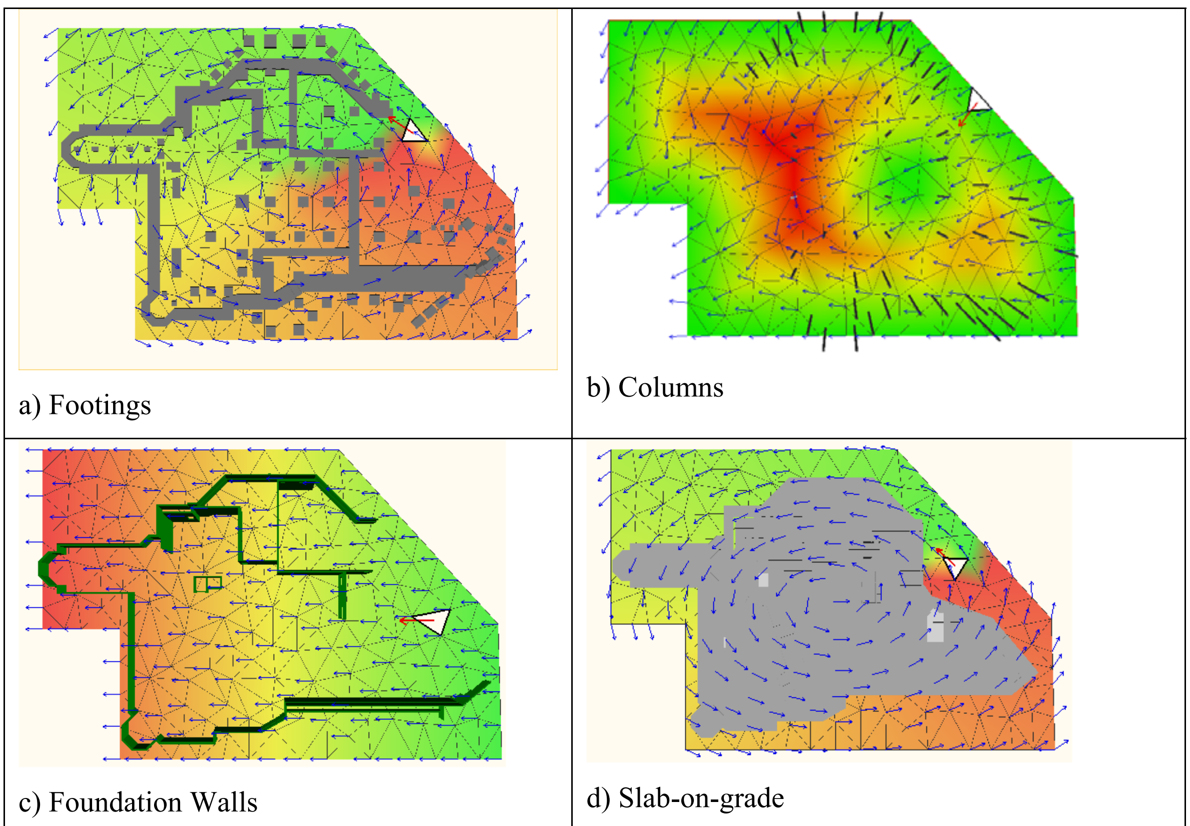
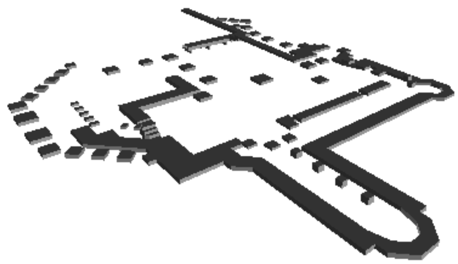
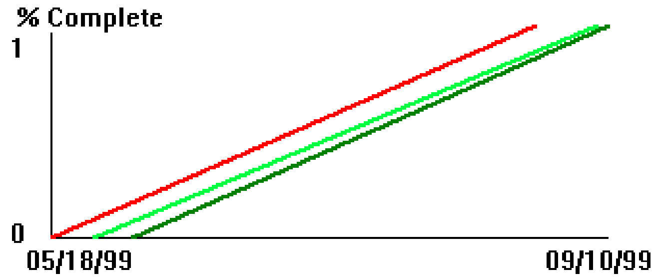


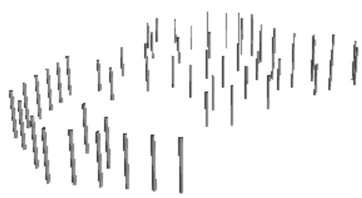
Figure 7-7. Representation of the workflow strategies for the restaurant foundation subsystems.



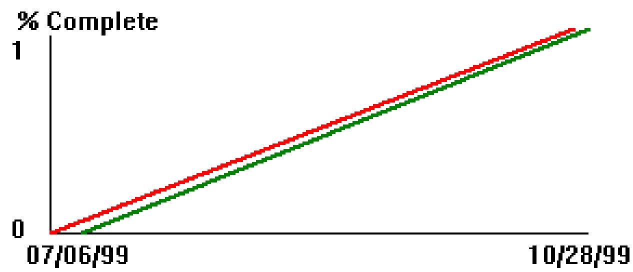
(a) Footings



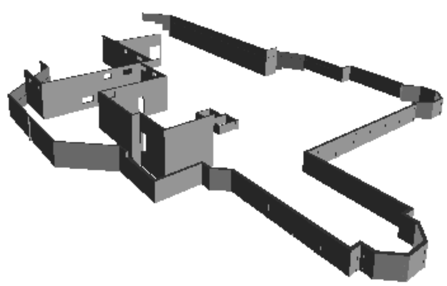
Crews: Form, rebar, place concrete



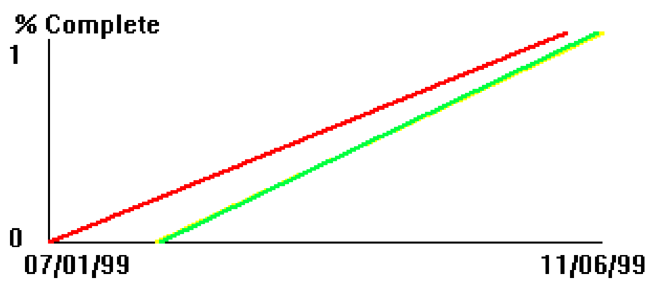
(b) Concrete columns



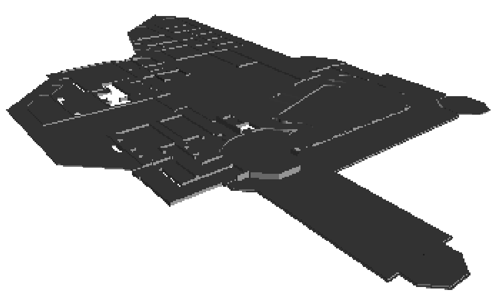
Crews: Rebar, place concrete



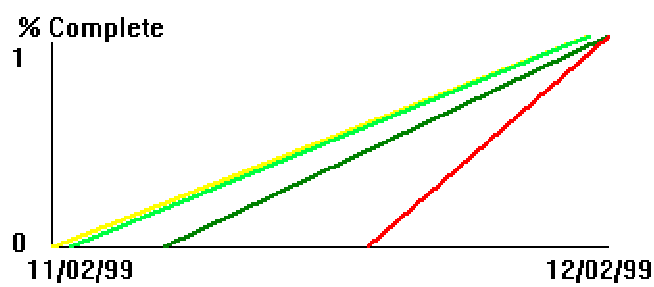
(c) Foundation walls



Crews: Rebar, place concrete



(d) Slab-on-grade



Crews: Form, rebar, place concrete, sand

Figure 7-8. Subsystems and the production capacities for crews in the restaurant case.

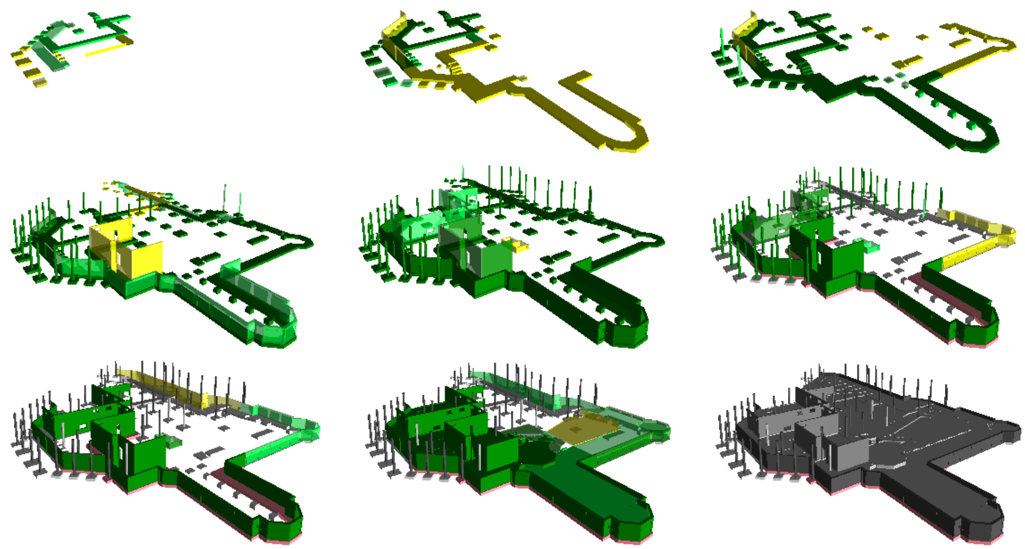


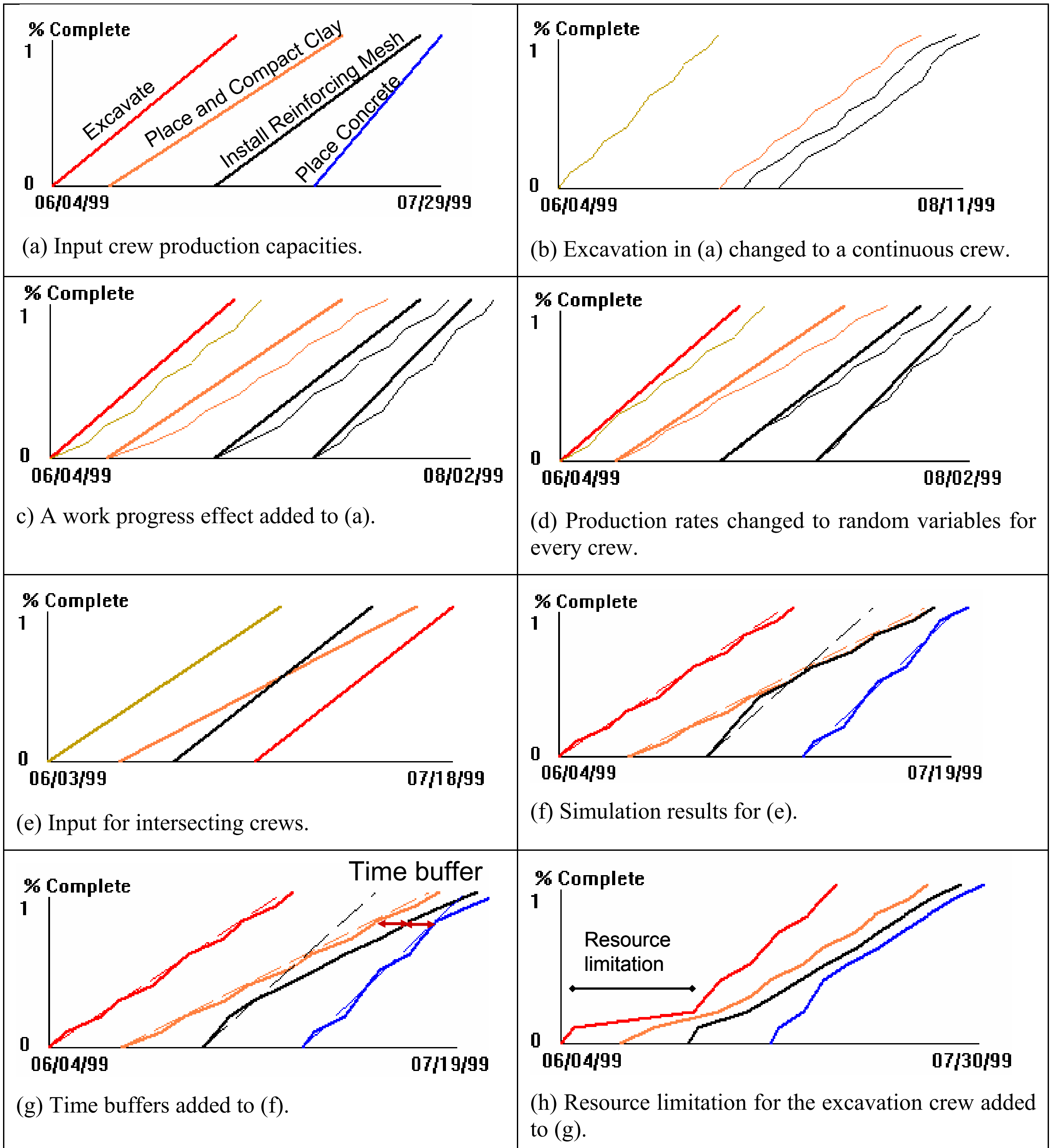
Figure 7-9. Snapshots from 4D visualization of the construction process simulation of the restaurant foundation components. Such 4D visualizations are an automatic output form the simulation of a GPM.

7.2.2. Evaluation of alternatives

The previous section shows the simulation of the process model using the parameters from the actual test cases. This section demonstrates the flexibility of GPM for the consideration and evaluation of alternative parameters for the lagoon case. The planners can evaluate process alternatives by changing the parameters in production rate functions, workflow strategies and interactions.

I obtain different simulation results for different production rate parameters on the lagoon, keeping the workflow strategies and interactions constant (Figure 7-10). Figure 7-10a shows the original production rate definition for the crews on the lagoon. Figure 7-10b shows the use of a continuous crew for excavation, i.e., no other crew can work on the lagoon before the scope of work for the excavation crew is complete. Figure 7-10c adds a work progress effect to emulate learning curves. To demonstrate that this modeling approach is extensible to stochastic models, I also tested random variables for the production rates of crews (Figure 7-10d).

Figure 7-10f demonstrates that GSim detects intersecting crews (for the input shown in Figure 7-10e) which causes the succeeding crew to slow down during simulation. Figure 7-10g shows that by adding a time buffer between every crew, planners can control the ripple effects of this slow down. Figure 7-10h demonstrates that by limiting the availability of a crew, the ripple effect to the other crews can be represented.



(a) Input crew production capacities.

(b) Excavation in (a) changed to a continuous crew.

c) A work progress effect added to (a).

(d) Production rates changed to random variables for every crew.

(e) Input for intersecting crews.

(f) Simulation results for (e).

(g) Time buffers added to (f).

(h) Resource limitation for the excavation crew added to (g).

Figure 7-10. Various simulation tests for the lagoon case obtained by changing parameters in the production rate function.

7.2.3. Other test cases

I tested different aspects of this research on two other projects to show the generality and scalability of the approach. The Element 5 exterior enclosure case of the Disney Concert Hall project (Figure 7-11) demonstrates modeling and simulation of construction processes for complex geometric shapes. I collected and defined different directions of workflow for each crew on the surface mesh representing the exterior enclosure, different unit work areas of each component. The resulting simulations describe the plan for the construction process for the exterior construction.

The Emeryville Bay Street project is the fourth test case for this research. This case is an application of the GPM approach to another foundation construction, on different components and using different construction methods and workflow strategies than the DCA restaurant foundation. Additionally, the Bay Street case demonstrates the use of the approach on a larger 3D model, with 13,097 components. GSim can successfully decompose this project geometry into regions and component types. Figure 7-12 shows the spatial decomposition of this project.

The main activities for this foundation construction are *drive piles*, *place pile caps*, *place grade beams*, and *slab-on-grade*. These activities follow each other. GPM can successfully represent the foundation process on this case. Figure 7-13 shows a result from the simulation.

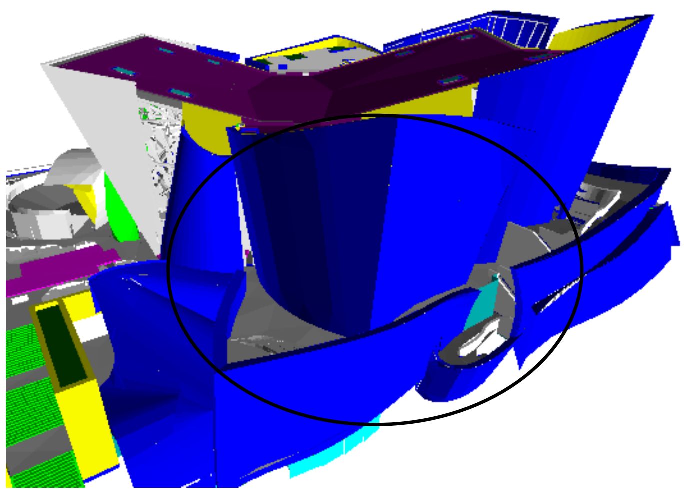


Figure 7-11. Exterior enclosure for the Disney Concert Hall.

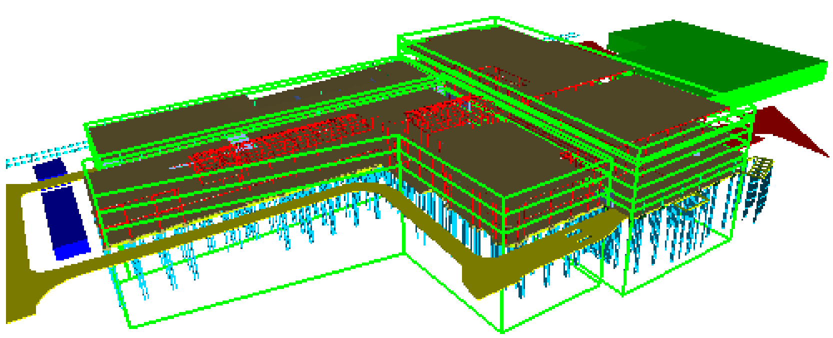


Figure 7-12. Hierarchical decomposition for the Emeryville Bay Street test case.

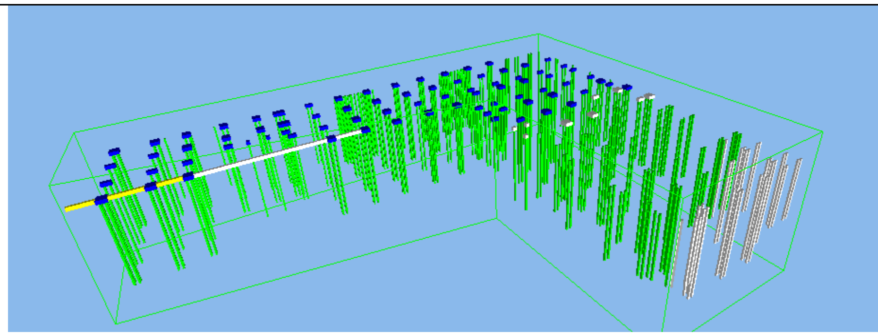


Figure 7-13. 4D snapshot of a simulation result for the pile foundation of the Emeryville Bay Street test case.

7.2.4. The power of the approach

As one piece of evidence for the power of the GPM approach, the previous sections have already demonstrated the flexibility of GPM to consider various process alternatives. This section gives two other ways to show the power of the GPM approach: model simplicity and scalability.

For model simplicity, I show that GPM can decrease the necessary user-defined parameters to describe process plans compared to current approaches, therefore GPM models are easier to generate, maintain and update. For this purpose, I compare the modeling requirements in GPM with current approaches to represent similar planning constraints and generate similar schedules using the existing CPM schedules and 4D models in the validation cases. Compared to CPM scheduling, GPM decreases the number of activities and precedence relationships. Compared to 4D models, GPM decreases the necessary number of links between 3D components and activities. Although the purposes of these models are not one-to-one comparable, the decrease in the amount of input the user needs to prepare and update is evident.

Table 7-2 demonstrates the decrease in activities and relationships compared to CPM for two cases. In the DCA restaurant building, the CPM schedule for the foundation contains 140 activities and there are 120 precedence relationships to describe the sequence of activities. Many of the precedence relationships in the CPM schedule reflect the sequencing of the same crew (e.g., the order in which the *form footing* activity performs work), relationships between crew sequences (e.g., the *rebar footing* activity must follow *form footing*), and relationships between different component types (e.g., the work on columns should start after the work on footings is complete).

GPM can model the physical conversions in the same process by defining the subsystems and interactions. A particular GPM example for the DCA restaurant building has 16 subsystems (every foundation quadrant containing the four component types as a separate subsystem). Note that the work locations in these subsystems are determined automatically using a spatial structure and the component types. Each crew in a subsystem corresponds to one or more activities in the CPM schedule. However, as a result of a simulation, the installation states for each component are similar to the activity periods in the CPM schedule. Additionally, the parameters and the interactions in GPM can represent most of the sequencing relationships in CPM.

Table 7-3 shows that GPM can generate detailed 4D visualizations with fewer links. Building detailed 4D visualizations requires many links between 3D components and activities. For example, the 4D model in the DCA restaurant requires 367 links to provide the visualization. In GPM, defining subsystems, assigning crews, and specifying production parameters automatically generates the detailed 4D model.

To demonstrate the scalability of the GPM approach, I simulate every subsystem in the DCA restaurant test case and measure the time for the simulation (Table 7-4). The results illustrate that, even on large models, simulation is possible in a short time.

Table 7-2. Decrease in the user-defined activities and precedence relationships compared to CPM.

TEST CASE	CPM SCHEDULE		GPM		
	# Activities	# Relationships	# Subsystems	# Parameters	# Interactions
DCA Restaurant Foundation	140	120	16	19	3
Emeryville Bay Street Foundation	25	42	9	9	2

Table 7-3. Decrease in the user-defined relationships between 3D components and activities in GPM compared to 4D models.

Test Case		Original 4D Model			GPM	
		# 3D Components	# Activities	# Links	# Subsystems	# Activities (Crews)
DCA Restaurant	Three Spatial Levels	2,103	844	367	83	186
	Two Spatial Level	2,103	844	367	27	74
Emeryville Bay Street		13,097	869	890	64	150
Lagoon	6 zones	6	24	24	6	24
	3 zones	3	12	12	3	12

Table 7-4. Comparison of simulation times for the test cases.

TEST CASE	# WORK LOCATIONS	# SUBSYSTEMS	# INTERACTIONS	SIMULATION TIME (IN SECONDS)
DCA Restaurant	1,876	26	3	5.2
DCA Lagoon (less refined mesh)	920	1	1	4.0
DCA Lagoon (more refined mesh)	3,291	1	1	18.0

7.2.5. Summary of the empirical validation

I have demonstrated the modeling and simulation of construction processes for four test cases. I have shown the generality, flexibility, model simplicity and scalability of the approach. The workflow strategy, production rate elements, subsystem interactions, simulation, and the geometric techniques work properly and can accurately represent the processes in the test cases. The users can evaluate process alternatives by changing parameters and quickly simulating the process model again. Direct visualization of the simulation results provides easy assessment of planning parameters and the resulting plan and schedule for a construction process.

One limitation of these test cases is their retrospective nature. Prospective test cases or intervention studies are necessary to improve on the validation. Section 8.5.1 suggests future work for more validation.

7.3. Validity of the construction process modeling abstraction

This section shows how to describe existing process models (CPM and linear scheduling) through GPM. GSim implements these conversions.

7.3.1. Conversion of GPM models to CPM networks

GPM models can be converted into CPM networks containing physical conversion activities and vice versa. CPM networks contain activities and precedence relationships (see Section 2.2.1), while GPM has subsystems containing crews and their interactions. However, after a GPM simulation, both models have similarities. The definition of an activity in GPM (Section 3.1) and the activity ordering interaction (Section 3.4.1) are designed with CPM networks in mind.

The GPM simulation results contain sufficient information to generate CPM network activities and precedence relationships. Figure 7-14 shows a screenshot for a CPM network automatically generated by GSim from a simulation of the DCA restaurant test case. Each subsystem contains an ordered set of crews. GSim can determine the duration for a crew in a subsystem after a simulation using state aggregation, thereby describing a CPM activity. Then, to create precedence relationships in the CPM network, GSim creates a start-start relationship with time lag for the crew sequence in a subsystem. The time lag is derived using the duration between the mobilization dates of the crews.

GSim also converts the interactions between subsystems into CPM network precedence relationships. Activity orderings between subsystems are finish-to-start relationships in CPM. For spatial crew ordering, an algorithm searches for crews affected by the ordering and creates start-to-start relationships with approximate time lags between activities representing these crews. For nearby work interaction, it may be necessary to create multiple activities corresponding to each crew.

Although not currently implemented, any CPM network with physical conversion activities and sequencing relationships can be represented with GPM. That is, it is possible to get a partial GPM model using a set of CPM activities and their relationships.

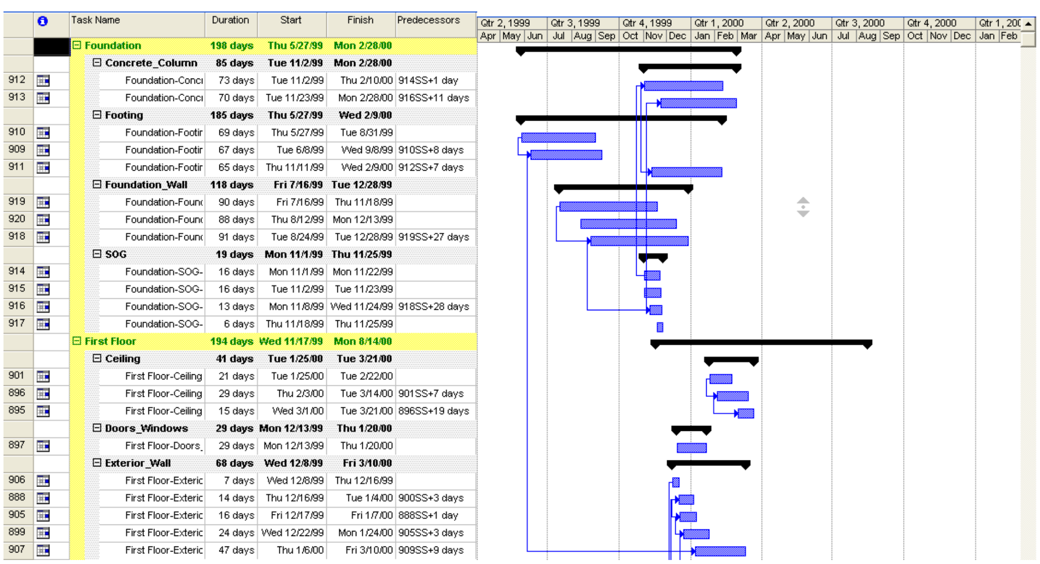


Figure 7-14. Automatically generated CPM activities and sequencing relationships from GPM simulation results.

7.3.2. Conversion of GPM models to line of balance models

One can also convert GPM and line-of-balance models to each other. This is closely related to the work balancing in 3D application.

Converting basic line-of-balance models to GPM subsystems is simple. LOB models have a mobilization date, a production rate and a workflow direction for each crew. Linear scheduling techniques assume that an activity flows linearly along a direction. LOB techniques have a user-defined ordering of work locations. These strategies are special cases of the workflow strategy in GPM.

Converting subsystems to line-of-balance models is similarly easy. The only requirement is to aggregate installation states to obtain activity durations for each crew and to divide durations by the total quantity to get a constant production rate.

7.4. Discussion

I described the validation of the contributions of this research. The validation uses theoretical and empirical parts. The results demonstrate that GPM has generality, flexibility, model simplicity, and scalability as described in the research questions (Section 1.3). The next chapter summarizes the specific contributions, practical implications and suggested future work for this research.

CHAPTER 8

SUMMARY OF THE CONTRIBUTIONS, PRACTICAL IMPLICATIONS AND FUTURE WORK

This Ph.D. research presents a geometry-based approach for modeling and simulation of physical conversions in construction operations. The results of this research include the GPM approach, the geometric techniques and GSim, the prototype implementation. During this research, I made use of research in different fields, specifically construction operations, planning/scheduling/control, discrete event systems and simulation, and geometric modeling/algorithms. I provided adaptations and extensions of research on geometric techniques. I applied discrete event systems theory and simulation to construction processes based on geometry. However, my contributions are mainly for construction management. The research results have implications and research opportunities for other fields.

Below are the specific contributions of this research, organized into three categories. The first category focuses on the contributions related to the construction process model: definition, inputs, outputs, and analysis. Chapters 3 and 4 explained these contributions in detail. The second category is on the geometric representation and algorithms to support this model, which is explained in Chapter 5. The third category depicts contributions on the applications of this model that includes the prototype software implementation, which are described in Chapter 6. For the remainder of the chapter, I summarize the practical and theoretical implications and suggest future work.

8.1. Contributions on formalization of a process model for physical conversions in construction based on geometry

The first category of my contributions relates to the geometric construction process model and is based on discrete event systems. This approach specifically considers the physical conversions in construction and provides a general, flexible and extensible way to integrate construction planning, simulation and visualization.

Various construction process abstractions and planning techniques are in use today. Techniques such as critical path networks, linear scheduling, 4D CAD and work task level discrete-event simulation focus on different aspects of the construction process at different levels of detail. CPM schedules determine the shortest possible paths and activity floats out of all possible paths. Linear scheduling techniques focus on work continuity but are limited to linear work progress over time. Birrell's conceptual model (Birrell 1980) among others explains the thinking process of construction professionals for construction operations without using a geometric or mathematical model. 4D CAD offers good visualization for the construction process but carries most of the limitations of CPM schedules. The use of discrete event simulation is mostly at the task level, focusing on specific parts of work instead of the complete process and lacking explicit reference to geometry. Individually, these different modeling approaches do not provide adequate support for consideration of the overall construction process including project-specific spatial complexities.

Discrete event systems and the theory of modeling and simulation use a group of techniques including: automata theory, modularity, hierarchy, discrete event simulation, performance analysis, control-feedback mechanisms and optimization of input variables. These techniques find limited use for the design and management of construction processes for a systematic approach to physical conversions because simple modeling elements that can represent the complexities of construction projects with reasonable effort are missing.

The first part of this section describes the contributions on the process model. The second part describes the contributions on the analysis and simulation.

8.1.1. Contributions on the process model definition

In Chapter 3, I provide a specific abstraction for the construction operations as installation state changes of work locations by crews. Each crew has certain parameters, including their production rate function and workflow strategy. A set of crews forms construction process subsystems. Coupling of a set of subsystems considering their interactions defines the complete process. Using this abstraction, geometric techniques and formal system theory concepts, I provide a general, mathematical process description for physical conversions in construction.

I made several contributions while formalizing this model. The first is the formal work location definition. I formally defined an atomic concept of *work location* based on geometry. I use it as the geometric unit of analysis for the process model. Previous construction process modeling techniques did not base their models on geometric structures and can therefore not relate the process model for a particular project to its project-specific geometric configuration. The common modeling and analysis unit in construction operations is the activity with limited consideration of geometry in describing construction processes.

Formal work location and crew definitions also allow adaptation of general state management techniques, such as finite automata, so that the states are always maintained correctly. I defined a set of state variables and their state spaces for work locations and crews in this model.

The second set of contributions for the model formalization is the input parameters for subsystems. I generalized linear scheduling and Birrell's conceptual model to describe a workflow strategy and a production rate function. I developed a production rate function for crews, capable of considering effects of shape, crew progress, nearby work and resource availability. Furthermore, I developed a general way to define workflow strategies for construction crews and use that definition to sequence work locations. Below are the specific contributions on the input parameters for crews.

Production rate function

I used the production rate function to specify at what rate crews can perform work at a specific location at a specific time instant. The main contribution here is showing that it is possible to combine various geometric and temporal production rate effects for crews as a single function for any possible work location. With such a production rate function for crews, the user can consistently model local effects of shape, nearby work, and resource availability. Since the work location definition includes geometry, it is also possible to use geometric properties for derivations in production rate calculations.

I defined a shape factor concept as a simple way to determine the local production rate changes caused by the shape. Although simplistic in its definition, this is an initial attempt to model the effects of geometric shape and condition of a particular work location on local production rate changes for construction processes. This is an improvement over previous research, which assigns constant production rate modifiers over large scopes of work for geometric effects.

The contributions for the nearby work for crews address the need to incorporate space conflicts as a part of the system description using geometric analysis. I use the existing research for the effect of nearby work on construction activities to automatically determine its effect on activity duration during simulation of the GPM.

Workflow strategy

Most of the previous research (Birrell 1980; Thabet and Beliveau 1994) describes directions of crew workflow as fixed (horizontal or vertical) or use manually sequenced work locations. Riley and Sanvido (1995) describe more complex directions, described as work area patterns, without computational support. This research generalizes a crew's workflow strategy as a function sequencing work locations. It defines generalized directions of workflow for construction crews and supports various workflow direction types.

Interactions between subsystems

Subsystems represent a decomposition of the overall process. I describe three general interaction types between subsystems as a set of parameters. I show that these interaction types provide support for modularity for various process decomposition types. Existing research did not provide a computational methodology to manage modularity using geometric techniques.

In activity network based methods (e.g. CPM), many sequencing relationships are necessary for detailed planning. These relationships need extensive maintenance after project changes. I defined *activity ordering* to apply CPM style sequencing relationships to subsystems. I also consider interactions not supported by CPM. *Spatial crew ordering* considers the spatial crew sequences on the geometric model using distance calculations. *Nearby work* considers the effects of crews working in close proximity over time using geometric analysis. I describe how to simulate multiple subsystems together considering these sets of interactions, adapting techniques from (Zeigler et al. 2000).

8.1.2. Simulation and analysis

The discrete event simulation in this research generates state trajectories for work locations and the crews as described in Chapter 4. The main contribution for the simulation is the automated generation of the simulation model, given the process model. Additionally, obtaining the state trajectory for both the work locations and crews provides information for performance analysis and visualization and is a contribution that was lacking in the previous research.

I defined a general automated reduction technique from definitions of subsystems to queueing networks. This allows the simulation of multiple crews acting on work locations. Previous work used discrete-event simulation for process analysis primarily at the work task level and separately from a geometric model of the work performed. The main limitations of these research efforts are the need to manually define the simulation model and the appropriate work locations. Birrell (1980) proposed a queuing network application to construction process planning at the macro level, where each produced unit should be a macro level space, such as a building floor in a high rise building or a house in a multi-unit housing construction. Ashley (1980) applied simulation to such a structure for repetitive unit construction, obtaining a simulation model similar to assembly lines in manufacturing. The simulation model in GPM permits extension of such simulation to more general construction processes.

8.1.3. Limitations of the process model

The GPM process model focuses solely on the physical conversions. It does not include other important aspects for construction process, such as costs, resource allocation, material management. The production rate model for crews is not comprehensive. Its components demonstrate that it is possible to automatically consider the localized effects of shape, geometric configurations, resource limitations, and nearby work on production rate. This research also did not analyze the interactions between different production rate modifiers.

The queueing network model is serial, although in reality, crews performing operations need not have a fixed sequence. There is limited support for feeding actual progress data back to update the model parameters.

The discrete-event simulation is deterministic. I also didn't provide a methodology for optimization of the described process model. In the future work section, I suggest ways to consider stochastic approaches and optimization.

8.2. Contributions on geometric techniques for the geometric process model

The next category of my contributions is the formulation of a set of geometric techniques for GPM and geometric solutions for specific cases by adopting and extending geometric techniques.

8.2.1. Contributions on the formulations of geometric techniques

I provide novel formulations for geometric techniques for construction process modeling and simulation. The application of many existing geometric representations and algorithms for construction process modeling is limited. I tested different geometric algorithms, adopting and extending and implementing those that enable the process model.

I use triangle meshes for geometric representation and analysis because of their flexibility and extensive existing research. Existing applications of geometric techniques for construction process modeling and analysis focus on prismatic representations. Triangle meshes are mainly used for visualization.

The main formulations I defined are geometry tessellation, geometric sorting, geometry analysis, and hierarchical space decomposition. These formulations are intertwined with the modeling and analysis contributions. Geometry tessellation manipulates, triangulates and tiles triangle meshes. Geometry sorting defines directions of workflow and sorts triangles accordingly. Geometry analysis describes crew production using geometric properties and distance calculations. Hierarchical space decomposition organizes geometric models for planning purposes.

8.2.2. Contributions on geometry tessellation applications to construction process modeling

I defined the geometry tessellation techniques to generate work locations and base structures, which are essential for process modeling and simulation. I formalized work location and base structure definitions on triangle mesh representation. Existing research relies on geometric representation of building components as input for use in automated planning or visualization.

I adopted constrained Delaunay triangulation and refinement techniques to triangulate surfaces to generate work locations. I defined a rectangular tiling technique, a simplified quadrilateral mesh generation technique, to represent quadrilateral work locations. I also introduced the use of structured grids and split/aggregate operations to define work locations on geometry.

8.2.3. Contributions on geometry sorting applications to construction process modeling and simulation

I computationally support the workflow strategy definition in this research for directional workflow of crews. Existing research does not geometrically describe the direction of workflow for construction crews in a general way.

I provide ways to generate direction of workflow on the geometry and to determine the work location ordering for each crew in the simulation. I adopted a surface sweeping technique (Turk 2001) to calculate the vector field representing the workflow on a triangle mesh surface, given a set of vectors. I defined a set of direction types to support common directions of flow in construction planning: directional, radial and edge-based.

8.2.4. Contributions on geometry analysis applications to construction process modeling and simulation

I described calculation of shape factors on triangle meshes. I provided general use of 3D distance calculation for nearby work and spatial crew ordering.

8.2.5. Contributions on the use of hierarchical space decomposition

Existing hierarchical spatial structures for construction process decomposition do not infer the enclosure information for building elements or split their geometry. For example, work block structure (Thabet and Beliveau 1997) uses fixed prismatic shapes for every floor.

I formulated the requirements for a hierarchical spatial structure. I developed a spatial structure called the region hierarchy that can automatically organize the building components spatially and define subsystems. It is a simple, user-defined, general geometric structure which can automatically determine enclosure information and can be used to split components. As a result, flexible decomposition of construction processes into subsystems using geometry is possible using this region hierarchy.

Section 5.6.1 describes the limitations of the geometric techniques.

8.3. Contributions on the applications of the process modeling approach

GSim is a prototype implementation that supports the interactive use of the described process modeling and simulation approach. GSim contains work balancing in 3D and zone generation applications.

A practical challenge is to plan accurately when and where a construction crew is working. This research describes an implementation for zone generation.

Work balancing in 3D is another contribution of this research. Linear scheduling techniques are limited to linear directional workflow. Using the workflow strategy and the production rate function definitions, I provide the basis for generalization of these techniques to process modeling with 3D geometric models and an implementation to allow users to balance work between crews and subsystems interactively.

8.4. Practical and theoretical implications

This research provides a new framework for modeling the construction process using 3D geometry, which can integrate planning, simulation, visualization and process analysis for construction operations management. GPM can relate the construction process to the design of a facility for better consideration of construction issues during design. The implications described in this section are closely related to the following section on future work.

8.4.1. Better project management

The results of this research (the GPM approach, the geometric techniques and GSim) have the potential to significantly improve construction operations management. I have defined a formal yet intuitive model for the physical conversions in construction processes. I have shown the use of workflow strategy and production rate for work balancing.

The described process model and its simulation supports work balancing in 3D, zone generation and process decomposition, all of which are important problems in construction operations management. Representing the conceptual thinking for the construction process computationally and mathematically is valuable, because it allows capturing and improving of existing processes in a systematic way. Being able to consider what-if scenarios and easy evaluation of planning alternatives with visualization are significant improvements for current practice.

A direct practical result is improved 4D visualization of construction processes. Most of the current 4D models use the project master schedule as a basis to represent the construction process at a macro level which is of limited value for daily operations management. Accurate 4D visualizations with hourly or daily temporal granularity can be valuable even without computational process analysis. Human visual perception can quickly detect important patterns and potential problems. GSim can quickly manipulate, reorganize, and triangulate geometric models. Based on a few parameters, it can generate detailed 4D models with a few parameters interactively and the user can interactively change these parameters to easily consider what-if scenarios.

Construction education can benefit from interactive applications in 3D that represent construction operations in a familiar video game style. Using existing 3D/4D models and process models from techniques such as CPM and line-of-balance, it is possible to generate scenarios to use GSim for construction education. The intuitive user interfaces in GSim would permit students to evaluate planning alternatives and see their effects on the construction process.

8.4.2. Relations to other phases of a project

Using the results of this research, project participants can consider construction process information during architectural and structural design. This research is similarly valuable for other aspects of project management such as estimating, progress payments and cost controls.

8.4.3. Implications for research

Research on construction process modeling and analysis

This research is based on or has relations to systems theory, geometric algorithms, discrete event simulation, and queueing theory. This enables the application of the existing research in these fields to construction process analysis and design. Many future improvements are possible for more detailed and robust process analysis.

This research brings geometric techniques to effective use for construction process modeling. It provides a bottom-up definition for a process model, starting from geometric primitives, work locations, crews, subsystems and the process system. At the same time, this is a new approach for geometry-based simulation techniques in construction. Most of the existing planning, scheduling and visualization applications use geometry as a fixed design attribute.

Research on computer graphics and geometric algorithms

With their complex spatial nature, processes and interactions, construction process models can provide a fertile application area for computer graphics,. Having a geometry-based process model opens up possibilities for better visualization techniques.

8.5. Suggested Future Work

Extensibility is one of the key attributes of the GPM. The following sections suggest various areas that have the potential to increase the theoretical and practical value of GPM and improve construction management. Figure 8-1 shows a structure for suggested future research.

The next section describes some possible improvements in the process model. Then, Section 8.5.2 discusses the possible uses and improvements of this research to automating the control of on-site construction performance. Automated process model generation by combining GPM with automated process planners and optimizing this process model for various criteria is a rewarding area to pursue (Section 8.5.3). Another research area is to improve construction process interactions with other phases of a project using GPM (Section 8.5.4). There is also a need for better visualization techniques with the collected and generated data using GPM (Section 8.5.5).

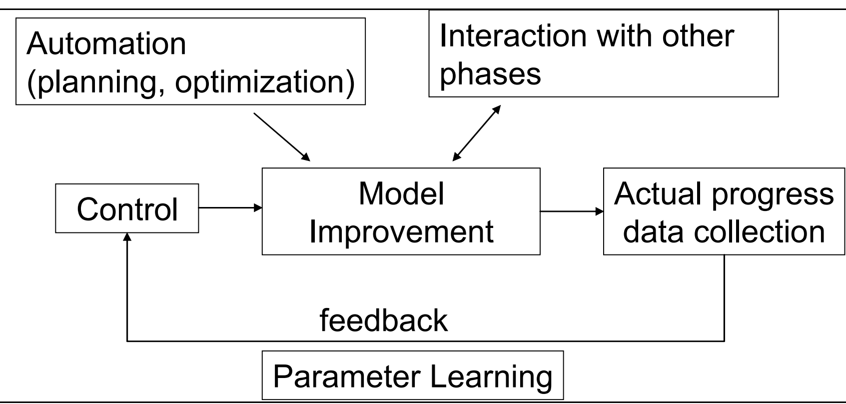


Figure 8-1. Structure for suggested future research.

8.5.1. Model improvement

The GPM process model is a start for more realistic and comprehensive process models based on geometry. One requirement is more validation. I conducted four retrospective case studies. Thomsen et al. (1998) suggest performing prospective cases with intervention studies to validate the usefulness of a model.

As mentioned earlier, the GPM production rate function demonstrates various effects on a crew's production rate without claiming to support all modifiers. One can improve this function to better describe variability of production and variations for different construction methods. Achieving this is closely related to the future work on data collection described in the next section.

The workflow strategies implemented are only directional types. It is possible to add dynamic and procedural workflow strategies without losing the generality of the process modeling technique. With dynamic and procedural strategies, one can design the crews in GPM as intelligent agents evaluating other crew and work location states during simulation to make dynamic decisions. Factors such as site access and equipment use as well as negotiations among different crews are possible candidates for future workflow strategy designs.

GPM assumes that crews are the sole processing elements. It currently does not consider resource allocation and sharing, equipment use, and material flows. By relating GPM to the supply chain for construction, starting from manufacturing design, and supply to assembly, one can better consider the spatial aspects of the construction process on site with the earlier stages and therefore provide better production designs. Application of and improvement to lean construction techniques (Alarcón 1997) using GPM is an interesting area of future work.

This research uses deterministic variables for crews. However, certain elements of the crew model are easily convertible to random variables, e.g., production rate elements, work location availability. Extending GPM using stochastic approaches is an area of improvement; construction projects are affected by many uncontrollable stochastic factors, e.g., weather and material delivery. Stochastic state variables representing site conditions can be assigned to work locations to represent such factors. Similarly, elements of the production rate function and the workflow strategy can be random variables. In such a stochastic simulation, one needs to clearly separate random elements of the construction process and the factors that are possible to consider with production rate effects. Additionally, analysis of stochastic simulation results considering geometry is a possible future research topic.

This research considers exclusively the work locations that are part of the finished project, ignoring temporary structures such as shoring, scaffolding and laydown areas and work space envelopes for crews. Automated generation of temporary structures and work spaces would improve this process modeling and simulation approach by better and more accurate consideration of such spatial constraints.

8.5.2. Feedback-control cycle

Building an effective feedback-control mechanism for construction process design/analysis/monitoring is an important practical need (Cheng and Chen 2002; Sacks et al. 2003). It requires better methods to collect actual on-site progress data, automated techniques to learn important parameters for construction work, and better project management using this information. Currently, it is challenging to achieve a good control for construction processes similar to the control described by system and control theory.

Actual progress data collection

Actual activity progress from construction sites is time consuming to obtain. A recent survey (Futcher 2001) showed that the need for data entry at the project level was the major obstacle to the success of a large-scale project management and control system. Even when the data is collected, it lacks the spatial information about the construction process.

Navon and Goldschmidt (2003) describe an automated labor monitoring technique using GPS data. Even with an integrated information model, this technique requires many decision rules to relate the actual process to the planned progress. GPM can mathematically relate the spatial and temporal information to the work parameters and decompose the process in a consistent way to better support such a labor monitoring technique.

Many construction sites today use webcams. When used in conjunction with a digital camera and when the correspondence between the image and the GPM model is established, it is possible to obtain progress information automatically. Using GPM, it is possible to define the estimated states for work locations over time. Extension of computer vision techniques of segmentation and tracking combined with statistical techniques to estimate the actual construction state and to compare to it to the planned states can provide such an application. This would enable a low cost technique for better observation and feedback from construction sites. I made a preliminary study for the feasibility of such an approach (Akbas 2002).

Parameter learning

Good data collection leads to better modeling. During this research, I collected limited data to fine-tune process model parameters. Each construction method has different parameters. Instead of manually describing the parameters every time, they could be collected automatically. Statistical learning and data mining techniques (Hastie et al. 2001) can improve the process of capturing parameters for reusable models. More data can provide better, more realistic process models. Similarly, one can build libraries for specific construction activity types and methods considering spatial effects. Process decomposition simplifies the learning process by focusing attention only to relevant parts of the project.

Project controls

Construction project controls should include defining input functions that will ensure that the construction process system will perform as desired under a variety of circumstances. Adding control mechanisms for GPM input variables and using performance parameters to evaluate how the system is actually performing, one can design construction models that can use techniques in systems and control theory.

For any simulation study, defining and analyzing performance parameters is crucial (Law and Kelton 2000). GPM uses a small number of performance measures (duration, idle time, etc.), which should be extended.

Consideration of multiple levels of construction process

Project planning and controls are hierarchical. Planning and process design start from a macro level, propagating to lower, more detailed (micro) levels. The actual work (and therefore progress data collection and project controls) is performed at the micro level. Ideally, a process modeling technique should support description of planning decisions at a high level propagating to detailed levels. It should collect the detailed on-site parameters from multiple crews and actual performance values back to the overall system.

Similarly organizational levels, e.g., contractors and subcontractors, require communication on planning information. The primary contractor should be able to define a high level schedule and distribute this schedule to the subcontractors. Subcontractors, using this schedule, should describe how they want to perform their scope of work. The primary contractor, collecting this information, should be able to update the plan accordingly. The prior work for changing the level of detail of the process is mainly for process planners or hierarchical simulation relating schedule activities and work tasks (Aalami 1998; Sawhney and AbouRizk 1995; Tommelein et al. 1994).

This research provides some aspects for this need. GPM provides automated ways to change the level of detail of the process utilizing geometry by manipulating geometry and relating the spatial and temporal aspects at micro levels. After a simulation, aggregating one or more crew states in a bounded space generates activities. GPM supports multiple levels of detail for geometric models (using mesh refinement) and work locations (each component or the assembly). A workflow strategy can propagate from macro to micro process levels and summarize information from micro to macro levels. Moreover, it provides flexible ways to decompose the process. Hence, using GPM to design better techniques to manage multiple levels of the construction process can be another future research area.

8.5.3. Process automation (planning and optimization)

Automated process planning

Although several automated process planners have been proposed for the construction domain (see Section 2.5.2), there is still a lot of room for improvement. This research supports various aspects of the planning process. It provides a physical organization and process elements of a construction project, which helps with definition of activities and sequences. GPM provides workflow strategy, which is a crucial aspect of a construction method definition. Assuming basic information on the crews and sequences is available, geometry analysis in GPM creates detailed flow sequences. GPM can also assist preparation of detailed time estimates by considering various geometric factors.

Combining existing automated planners with GPM is an interesting area of future work. For example, Construction Method Modeler (CMM) (Fischer and Aalami 1996) captures construction planning knowledge by explicitly modeling the relationships between product, resource, activity and sequence information and uses them to generate activities by employing a hierarchical construction planning process. However, Katz (1998) shows that significant manual product model reorganization is needed to generate appropriate levels of detail for components. This research can overcome this limitation of CMM by manipulating and reorganizing geometric models and incorporating spatial planning parameters effectively.

Another opportunity for future work is path planning for construction processes using the workflow strategy. In construction projects, site access constraints such as entry locations to a particular area commonly affect the workflow strategy. Existing planning techniques do not automate the effects of such constraints, therefore ignoring site accessibility issues. A simple approach is to apply basic path planning techniques (Latombe 1991) at time instants to update workflow directions for crews.

Automated spatial decomposition

In this research, the hierarchical region structure for spatial process decomposition is user defined. Determining good spatial decompositions automatically would be beneficial for planning. One can use constraints such as equal work duration and resource use for each region to guide the definition of such decompositions.

In their work (Winstanley and Hoshi 1993) decompose space into cubes and exhaustively test each cluster of cubes for user-defined cost and time criteria. A more effective approach would be using criteria, such as the number of regions at each level, workflow direction, boundary component types, and combine them with a cost function to determine the regions. Additionally, natural boundaries for each region such as walls and slabs should be included in spatial decompositions.

Parameter Optimization

Using spatial factors as a part of the process model description and process decomposition, one can consider more complex process models compared to prior work for construction process optimization. Each simulation result of GPM provides performance parameters. Using search and optimization techniques, one can search for the parameters that provide the optimum performance given a set of criteria (e.g., cost, resource use). However, optimization requires a well-established mathematical model and should be considered after successful modeling, design and analysis, control and performance evaluation (Cassandras 1999).

8.5.4. Interaction with other phases

During architectural and structural design, the results of this research can provide the project participants information on the construction process. For structural analysis, one research possibility is on better considering structural issues during the construction process. One can take into account multiple construction alternatives for structural analysis, for example by integrating finite element models for excavation with the construction process model.

8.5.5. Visualization

Better construction planning and scheduling requires better methods to abstract important features, especially when so much data is collected and generated. This research uses vector fields and color coding as particular ways of visualization. Further work is necessary to develop intuitive representations for workflow and production rate using color, textures, arrows or other techniques. Other visualization needs are representation of idle crews, work continuity and interactions between subsystems. One possible research question is whether realistic animation of crews performing work on geometry is valuable from the users' perspective.

8.6. Closure

In summary, the GPM approach offers a new basis for interactive construction process design. By explicitly considering the project-specific geometric configuration in modeling the construction process, it supports rapid evaluations of the effects of geometry or production parameters on the planned construction process. This allows users to explore the schedule impact of different project design options and to compare the use of different crews, workflow strategies, and other production variables. With the GPM approach, construction planners can be more proactive in addressing construction challenges on a particular project and can respond more quickly and accurately to changes in the project design or crew availability or capacity. The future work suggested in Section 8.5 can extend GPM for even better support of concurrent engineering in the AEC industry.

LIST OF REFERENCES

Aalami, F. (1998). "Using Method Models to Generate 4D Production Models," Ph.D. Thesis, Stanford University, Stanford, CA.

AbouRizk, S., and Mather, K. (2000). "Simplifying Simulation Modeling through Integration with 3D CAD." *Journal of Construction Engineering and Management*, 126(6), 475-483.

Akbas, R. (2002). "Automated Data Collection for Construction Progress from Webcam Images using Computer Vision Techniques." Unpublished Class Report in CS223B, Stanford University, Stanford, CA.

Akbas, R., and Fischer, M. "Construction Zone Generation Mechanisms and Applications." *2002, 19th International Symposium on Automation and Robotics in Construction*, NIST, Washington DC, USA, 293-298.

Akbas, R., and Fischer, M. A. "Examples of product model transformations." *Information Technology in Construction, CIB W78 Workshop*, Vancouver, BC, 2737-2746.

Akinci, B., Fischer, M., and Kunz, J. (2002). "Automated Generation of Work Spaces Required by Construction Activities." *Journal of Construction Engineering and Management*, 128(4), 10.

Alarcón, L. F. (1997). *Lean construction*, A.A. Balkema, Brookfield, VT.

Arditi, D., Tokdemir, B. O., and Kangsuk, S. (2002). "Challenges in Line-of-Balance Scheduling." *Journal of construction engineering and management*, 128(6), 545-556.

Ashley, D. (1980). "Simulation of Repetitive-Unit Construction." *ASCE J Constr Div*, 106(2), 185-194.

Ballard, G. "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.

Ballard, G. (2000). "Last Planner System of Production Control," Ph.D. Thesis, University of Birmingham, Birmingham.

Banks, J. (2001). *Discrete-event system simulation*, Prentice Hall, Upper Saddle River, NJ.

Berg, M. d., van Kreveld, M., Overmars, M., and Schwarzkopf, O. (2000). *Computational geometry: algorithms and applications*, Springer, Berlin.

Bertalanffy, L. v. (1969). *General system theory; foundations, development, applications*, G. Braziller, New York.

Birrell, G. (1980). "Construction planning - beyond the critical path." *ASCE J Constr Div*, 106(3), 389-407.

Blacker, T. D. (1991). "Paving: A New Approach to Automated Quadrilateral Mesh Generation." *International Journal for Numerical Methods in Engineering*, 32, 811-847.

Cassandras, C. G., and Lafortune, S. (1999). *Introduction to discrete event systems*, Kluwer Academic, Boston.

Cheng, M. Y., and Chen, J. C. (2002). "Integrated barcode and GIS for monitoring construction progress." *Journal of automation in construction*, 11(1), 23-33.

Cherneff, J., Logcher, R., and Sriram, D. (1991). "Integrating CAD with construction-schedule generation." *Journal of Computing in Civil Engineering*, 5(1), 64-84.

Chew, L. P. (1989). "Constrained Delaunay triangulations." *Algorithmica*, 4(1), 97-108.

Choo, H. J. (2003). "Distributed Planning and Coordination to Support Lean Construction," Ph.D. Thesis, University of California at Berkeley, Berkeley, CA.

Cormen, T. H., Leiserson, C. E., and Rivest, R. L. (1990). *Introduction to Algorithms*, The MIT Press, Cambridge, Massachusetts.

Darwiche, A., Levitt, R. E., and Roth, B. H. (1989). "OARPLAN: generating project plans in a blackboard system by reasoning about objects, actions and resources." *Technical Report Nr. 2*, Center for Integrated Facility Engineering, Stanford, CA.

Eastman, C. M. (1980). "Prototype integrated building model." *Computer Aided Design*, 12(3), 115-119.

Eastman, C. M. (1999). *Building product models: computer environments supporting design and construction*, CRC Press, Boca Raton, Fla.

Echeverry, D., Ibbs, C. W., and Kim, S. (1991). "Sequencing knowledge for construction scheduling." *Journal of Construction Engineering and Management*, 117(1), 118-130.

Edelsbrunner, H. (2001). *Geometry and topology for mesh generation*, Cambridge University Press, Cambridge.

Fischer, M., and Aalami, F. (1996). "Scheduling with Computer-Interpretable Construction Method Models." *Journal of Construction Engineering and Management*, 122(4), 337-347.

Fischer, M. A., Aalami, F., and Akbas, R. (1998). "Formalizing Product Model Transformations: Case Examples and Applications." Artificial Intelligence in Structural Engineering: Information Technology for Design, Collaboration, Maintenance, and Monitoring, I. Smith, ed., Springer, 113-132.

Foley, J. D., Van Dam, A., Feiner, S. K., and Hughes, J. F. (1995). *Computer graphics: principles and practice in C*, Addison-Wesley, Reading, Mass.

Frey, P. J., and George, P. L. (2000). *Mesh generation: application to finite elements*, Hermes Science, Oxford.

Froese, T. M., and Paulson, B. C., Jr. (1992). "Integrating project management systems through shared object-oriented project models." *Applications of Artificial Intelligence in Engineering*, 69-85.

Futcher, K. "User survey on a WAN portfolio MIS used for portfolio/project management in Hong Kong." *IT in Construction in Africa, W78 Workshop*, South Africa, 44-1--44 -14.

Gamma, E. (1995). *Design patterns: elements of reusable object-oriented software*, Addison-Wesley, Reading, Mass.

Gil, N., Tommelein, D. I., Kirkendall, B., and Ballard, G. "Lean product-process development process to support contractor involvement during design." *8th Intl. Conf. on Computing in Civil and Building Engineering*, Stanford, CA, 1086-1093.

Guibas, L. J., and Stolfi, J. "Primitives For the Manipulation of General Subdivisions and the Computation of Voronoi Diagrams." *Annual ACM Symposium on Theory of Computing*, Boston, Mass, 221-234.

Hall, R. W. (1991). *Queueing methods: for services and manufacturing*, Prentice Hall, Englewood Cliffs, NJ.

Halpin, D. W. (1977). "Cyclone--Method for Modeling Job Site Processes." *ASCE Journal of Construction Division*, 103(3), 489-499.

Halpin, D. W., and Riggs, L. S. (1992). *Planning and analysis of construction operations*, Wiley, New York.

Hastie, T., Tibshirani, R., and Friedman, J. H. (2001). *The elements of statistical learning: data mining, inference, and prediction*, Springer, New York.

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

Hopcroft, J. E., Motwani, R., and Ullman, J. D. (2001). *Introduction to automata theory, languages, and computation*, Addison-Wesley, Boston.

Hoschek, J., Kim, M.-S., and Farin, G. E. (2002). *Handbook of computer aided geometric design*, Elsevier, Boston, Mass.

Hoskins, E. M. (1973). "Computer aids in system building." Computer-Aided Design, R. W. Vlietstra, ed., North-Holland Press, New York, 127-140.

Institute, C. S. (1992). *Manual of practice*, CSI, Alexandria, VA.

Ioannou, P. G., Martinez, J., Kamat, V. R., and Martinez, J. C. (1996). "Animation of complex construction simulation models." *Computing in Civil Engineering*, 15(4), 620-626.

Kamat, V. R., and Martinez, J. C. (2001). "Visualizing simulated construction operations in 3D." *Journal of Computing in Civil Engineering*, 15(4), 329-327.

Katz, A. (1998). "Assessing Plan Reliability with 4D Production Models," Thesis submitted for the Degree of Engineer, Stanford University, Stanford.

Kavanagh, D. P., Stradal, O., and Cacha, J. (1985). "Siren: A Repetitive Construction Simulation Model." *Journal of Construction Engineering and Management*, 111(3), 308-323.

Koo, B., and Fischer, M. (2000). "Feasibility Study of 4D CAD in Commercial Construction." *Journal of Construction Engineering and Management*, 126(4), 251-260.

Koskela, L. (1992). "Application of the New Production Philosophy to Construction." *Technical Report No. 72*, Center for Integrated Facility Engineering, Stanford University, Stanford, CA.

Koskela, L. (2000). "An Exploration Towards a Production Theory and Its Application to Construction," Ph.D. Thesis, VTT Building Technology, Espoo, Finland.

Kunigahalli, R., and Russell, J. S. (1995). "Sequencing for concrete placement using RAG - CAD data structure." *Journal of Computing in Civil Engineering*, 9(3), 216-225.

Larsen, E., Gottschalk, S., Lin, M. C., and Dinesh, M. (1999). "Fast Proximity Queries with Swept Sphere Volumes." *Technical Report TR99-018*, University of N. Carolina, Chapel Hill.

Latombe, J.-C. (1991). *Robot motion planning*, Kluwer Academic Publishers, Boston.

Law, A. M., and Kelton, W. D. (2000). *Simulation modeling and analysis*, McGraw-Hill, Boston.

Lin, Y. (1999). *General systems theory: a mathematical approach*, Kluwer Academic/Plenum Publishers, New York.

Lo, S. H. (1985). "A new mesh generation scheme for arbitrary planar domains." *International Journal for Numerical Methods in Engineering*, 21(8), 1403-1426.

Mäntylä, M. (1988). *An introduction to solid modeling*, Computer Science Press, Rockville, Md.

Martinez, J. C., and Ioannou, P. G. (1999). "General-purpose systems for effective construction simulation." *Journal of Construction Engineering and Management*, 125(4), 265-276.

Meystel, A., and Albus, J. S. (2002). *Intelligent systems: architecture, design, and control*, Wiley, New York.

Microsoft. (2003). "Microsoft Project." Microsoft Corporation, Redmond, WA.

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

Morad, A. A., and Beliveau, Y. J. (1994). "Geometric-based reasoning system for project planning." *Journal of Computing in Civil Engineering*, 8(1), 52-71.

Mortenson, M. E. (1997). *Geometric modeling*, Wiley, New York.

Navinchandra, D., Sriram, D., and Logcher, R. D. (1988). "Ghost: Project Network Generator." *Journal of Computing in Civil Engineering*, 2(3), 239-254.

Navon, R., and Goldschmidt, E. (2003). "Monitoring labor inputs: Automated-data-collection model and enabling technologies." *Automation in Construction*, 12(2), 185-199.

O'Brien, J. J. (1975). "VPM Scheduling for High-Rise Buildings." *ASCE J Constr Div*, 101(4), 895-905.

O'Brien, W. (1998). "Capacity costing approaches for construction supply-chain management," Ph.D. Thesis, Stanford University, Stanford, CA.

Paulson, B. C., Jr. (1978). "Interactive Graphics for Simulating Construction Operations." *ASCE J Constr Div*, 104(1), 69-76.

Perera, S. (1982). "Compression of overlapping precedence networks." *ASCE J Constr Div*, 108(CO1), 1-12.

Primavera. (2000). "Primavera Project Planner." Primavera Systems Inc., Bala Cynwyd, PA, USA.

Project Management Institute. (2000). *A guide to the project management body of knowledge (PMBOK guide)*, Project Management Institute, Newtown Square, Penn., USA.

Riley, D. R., and Sanvido, V. E. (1995). "Patterns of construction-space in multistory buildings." *Journal of Construction Engineering and Management*, 121(4), 464-473.

Ruppert, J. "New and simple algorithm for quality 2-dimensional mesh generation." *Fourth Annual ACM-SIAM Symposium on Discrete Algorithms*, Austin, TX, 83-92.

Russell, A. D., and Wong, W. C. M. (1993). "New generation of planning structures." *Journal of Construction Engineering and Management*, 119(2), 196-214.

Russell, S. J., and Norvig, P. (2003). *Artificial intelligence: a modern approach*, Prentice Hall, Upper Saddle River, N.J.

Sacks, R., Navon, R., and Goldschmidt, E. (2003). "Building Project Model Support for Automated Labor Monitoring." *Journal of computing in civil engineering*, 17(1), 19-27.

Sanders, S. R., and Thomas, H. R. (1991). "Factors affecting masonry-labor productivity." *Journal of Construction Engineering and Management*, 117(4), 626-644.

Sawhney, A., and AbouRizk, S. M. (1995). "Application of hierarchical and modular simulation to a bridge planning project." *Computing in Civil Engineering*, 1, 727-734.

Selinger, S. (1980). "Construction Planning for Linear Projects." *ASCE J Constr Div*, 106(2), 195-205.

Shaked, O., and Warszawski, A. (1995). "Knowledge-based system for construction planning of high-rise buildings." *Journal of Construction Engineering and Management*, 121(2), 172-182.

Shewchuk, J. R. "Engineering a 2D Quality Mesh Generator and Delaunay Triangulator." *Workshop on Applied Computational Geometry*, Philadelphia, Pennsylvania, 124-133.

Shi, J., and AbouRizk, S. (1997). "Resource-based modeling for construction simulation." *Journal of Construction Engineering and Management*, 123(1), 26-33.

Skyttner, L. (2001). *General systems theory: ideas & applications*, World Scientific, River Edge, N.J.

Stradal, O., and Cacha, J. (1982). "Time Space Scheduling Method." *ASCE J Constr Div*, 108(CO3), 445-457.

Suhail, S. A., and Neale, R. H. (1994). "CPM/LOB: New methodology to integrate CPM and line of balance." *Journal of Construction Engineering and Management*, 120(3), 667-684.

Thabet, W. Y., and Beliveau, Y. J. (1994). "HVLS: horizontal and vertical logic scheduling for multistory projects." *Journal of Construction Engineering and Management*, 120(4), 875-892.

Thabet, W. Y., and Beliveau, Y. J. (1997). "SCaRC: Space-Constrained Resource-Constrained scheduling system." *Journal of Computing in Civil Engineering*, 2(1), 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*, 116(4), 705-726.

Thomas, H. R., and Zavrski, I. (1999). "Construction baseline productivity: Theory and practice." *Journal of Construction Engineering and Management*, 125(5), 295-303.

Thompson, J. F., Soni, B. K., and Weatherill, N. P. (1999). *Handbook of grid generation*, CRC Press, Boca Raton, Fla.

Thomsen, J., Levitt, R. E., Kunz, J. C., and Nass, C. I. (1998). "A proposed trajectory of validation experiments for computational emulation models of organizations." *Working Paper Nr. 47*, CIFE, Stanford, CA.

Tommelein, I. D., Carr, R. I., and Odeh, A. M. (1994). "Assembly of Simulation Networks Using Designs, Plans, and Methods." *Journal of Construction Engineering and Management*, 120(4), 796.

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*, 125(5), 304-310.

Turk, G. (2001) "Texture Synthesis on Surfaces." *Proceedings of the ACM SIGGRAPH Conference on Computer Graphics*, Los Angeles, CA, 347-354.

Winstanley, G., and Hoshi, K. (1993). "Activity aggregation in model-based AI planning systems." *Artificial intelligence for engineering design, analysis and manufacturing: AI EDAM*, 7(3), 209-228.

Wix, J. (1996). "Building Construction Core Model: Proposed ISO 10303 part 106, version S5.1."

Yu, K., Froese, T., and Grobler, F. "International Alliance for Interoperability: IFCs." *Congress on Computing in Civil Engineering, Proceedings*, Boston, MA, USA, 395-406.

Zeigler, B. P. (1984). "System-theoretic representation of simulation-models." *IIE Transactions*, 16(1), 19-34.

Zeigler, B. P., Praehofer, H., and Kim, T. G. (2000). *Theory of modeling and simulation : integrating discrete event and continuous complex dynamic systems*, Academic Press, San Diego, 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.