

A Multi-Agent Framework for General Purpose
Situational Simulations
in Construction Management

Amlan Mukherjee

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Amlan Mukherjee

and have found that it is complete and satisfactory in all respects,
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examining committee have been made.

Chair of Supervisory Committee:

Eddy M. Rojas

Reading Committee:

Eddy M. Rojas

William D. Winn

Joe P. Mahoney

Thomas Furness

Date:

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Abstract

A Multi-Agent Framework for General Purpose
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in Construction Management

by Amlan Mukherjee

Chair of Supervisory Committee:

Associate Professor Eddy M. Rojas
Department of Construction Management

There is a concern that the fragmented and decontextualized nature of the construction management (CM) curricula (McCabe et. al. 2000, Sawhney et.al. 2001) does not adequately prepare students for the industry. In order to do so we feel it is imperative to examine the nature of learning in the CM domain. How do novice construction managers learn? How do they build intuition through experience? Most importantly, what tools do we have that will allow us to train novice construction managers and provide educators with answers to the above questions. This research effort proposes that agent-driven situational simulations provide us with such tools, because they provide an interactive, dynamic, contextually rich, self organizing environment in which participants can explore “what-if” scenarios and test the validity of their decisions. The focus of this dissertation was to develop and test a general-purpose multi-agent framework that can be used by a community of developers to create situational simulations for the construction management domain.

Conceptually the framework is based on the understanding that problems in the construction management domain can be expressed as constraint satisfaction problems (CSP) and the constraints can be categorized as either temporal or resource constraints. The formal foundations of the multi-agent framework are set in the semantics of interval temporal

logic (Allen, J.F. & Ferguson, G.,1994) that allows us to represent construction activities and events as intervals that are bounded by time points. The framework provides a grammar for autonomous agents to use for their interaction. The autonomous agents can communicate and reason about the evolution of the simulation, while being sympathetic to user interaction. The grammar also forms the basis of an API that can be used by developers to create their own special purpose situational simulations. The Virtual Coach, an interactive situational simulation was implemented and tested using the proposed multi-agent framework in Sun Java 1.4.2 SDK.

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GLOSSARY

ACTIONS: Actions are triggers which create events and situations.

ACTIVITY: An activity is an emulation of a real life construction operation and is represented by an interval which has the same length as its' duration.

ACTIVITY CYCLE DIAGRAMS: A network used to represent the relationships between the activities, conditions, outcomes using directional arcs that go from condition to activity to outcome.

AGENT: An agent is anything which can perceive its environment through sensors and can act upon that environment through effectors. All agents in this dissertation are software programs.

CM: Short for Construction Management.

ENVIRONMENT: The environment sets the scene for the situational simulation. It is the participant's perception of the simulated construction project. It is interactive, temporally dynamic and virtual in nature. The environment emulates activities, events and processes pertaining to construction projects. It is characterized by a set of entities, each of which describes an unique aspect of the environment.

EVENTS: Events reflect the effects of real life episodes involving resource and precedence constraint violations within the construction management domain. Events are of two types: Independent Events and Dependent Events.

FIRST ORDER LOGIC: First order logic permits the formulation of quantified statements such as “there exists an x such that...” ($\exists x$) or “for any x , it is the case that...” ($\forall x$), where x is a member of the domain of discourse.

GPF: Short for General Purpose Framework

GPMAF: Short for General Purpose Multi-Agent Framework

MENTAL MODELS: Conceptualizations of the world that the mind builds by incorporating the individuals views of the world, of themselves, of their own capabilities and of the tasks that they are required to perform

SYSTEM DYNAMICS: A professional field that combines the theory, methods, and philosophy needed to analyze the behavior of complex systems using a common foundation that can be applied whenever we want to understand and influence the change of behavior over time

VARIABLES: A Variable is a symbolic representation of an entity.

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DEDICATION

To
My Dear Parents

Chapter 1

INTRODUCTION: BRIDGING THE DISCONNECT

1.1 Background

Barab et al. (2001) argue that the core of cognitive science and the resultant pedagogical models are based on the Cartesian philosophy of mind-matter dualism. This has resulted in a disconnect between the abstract and reflective mind and the material world in which the body is situated (Thelen 1995). As it is the case in other fields, this duality has resulted in a disconnect between the theory and practice of construction management (CM). In practice CM problems and crisis scenarios are complex and involve multiple resource interactions and feedback loops resulting from human decision making and its impacts on resource interactions. In contrast, the academic understanding of the domain relies on strategies that mostly focus on modeling construction operations as interactions between multiple resources (including material, equipment and labor), each of which can take finite states and where logical complexities are best described in terms of the conditions required to carry out the activities (Martinez and Ioannou 1999). Such methods isolate construction operations and processes from the human contexts in which they occur and thus do not analyze the impacts of decision-making on resource interaction.

The lack of a holistic approach to studying human-resource interactions in the CM domain has had implications in CM education. McCabe et al. (2000) argue that current civil engineering coursework teaches only the theories of CM and that students may encounter difficulties applying these theoretical principles when exposed to real world situations upon employment. Sawhney et al. (2001) suggest that civil and construction engineering curricula do not allow the inclusion of issues of importance to construction, nor the participation of practitioners or hands-on experience. AbouRizk and Sawhney (1994) recognize that

traditional teaching methods are not fully capable of providing students with all the skills necessary to solve real-world problems encountered in construction or conveying complex engineering knowledge. If construction education does not provide students with the skills to solve real-world problems or to apply theoretical concepts to practice, then the effectiveness of the problems studied or the methodologies applied in CM can be questioned.

Traditional CM classroom training methods deliver concepts that are presented as fixed, well-structured, independent entities. Classroom activities are disconnected from authentic context resulting in fragmentation and specialization of courses and educational experiences. This fragmentation of knowledge (Chinowsky and Vanegas 1996, Fruchter 1997) has resulted in a polarization of the learner and learning context and is not preparing students to apply theoretical concepts to real life construction scenarios (McCabe et al. 2000).

Meanwhile, as experienced construction managers are retiring there is an increasing knowledge void in the industry that cannot be easily replaced. Fledgling construction managers lack the skills that are gained through years of experience and the traditional CM curriculum does not expose them to any kind of training that allows appreciation of systemic dependencies in the construction domain and the ability to anticipate problems that arise during the project execution.

This disconnect between theory and practice is manifesting itself as a serious problem for the CM community. On the one hand academia is not appropriately preparing fledgling construction managers to meet the needs of the industry. This is furthering the notion that academic success is irrelevant to success in practice. Such notions feed back to reinforce the disconnect between theory and practice. On the other hand as experienced construction managers are retiring, the industry is losing expert knowledge workers who are leaving behind a void that fresh graduates are in no position to fill. In addition, there are few methods that allow us to analyze and study how expert managers engage in decision-making and capture their expertise in a way to enhance academic understanding of human decision-making and its impacts on the CM domain. This is not only widening the expertise gap in the industry but also reinforcing the disconnect between theory and practice. The widening gap in turn feeds back to enhance the original problem at hand: of studying the CM domain only as resource interaction instead of as a combination of human and resource interactions.

We have a systemic problem with the dual symptoms of a widening expertise gap and a widening disconnect between theory and practice. Unfortunately the system involves reinforcing feedback loops that are further reinforcing the symptoms at hand.

Efforts have been made to reduce the expertise gap by introducing case studies and construction site visits in the CM curriculum to generate usable and robust knowledge based in experience with partial success. Case studies can give the impression that there are easy-to-find and universally correct responses due to the necessary simplifications (Pennell et al 1997). Also site visits of large groups to construction sites may not be welcome, involve risk, and be unpractical (Echeverry 1996). Finally, case studies do not allow students to explore “what-if” scenarios and explore the validity of their decisions within the context of rapidly unfolding scenarios where they can directly find the impacts of their decisions. One could argue that internships often provide such opportunities, however in such situations students seldom enjoy positions of responsibility and cannot experiment with their decision making skills due to the real stakes involved.

A lot of work has been done in the field of simulations to explore their usefulness in bridging the disconnect between theory and practice. Researchers have explored alternatives in construction education using gaming and simulation environments such as Superbid (AbouRizk 1993), STRATEGY (McCabe et al. 2000), ICMLS (Sawhney et al. 2001) and VIRCON (Jaafari et al. 2001). Some of these efforts have been inspired by earlier research efforts in the area such as CONSTRUCTO (Halpin, 1970) and AROUSAL (Ndekugri and Lansley 1992). CONSTRUCTO has also provided the launching pad for a wide range of simulation frameworks that have been used to better understand CM operations and processes. The emphasis has been on developing specific purpose simulations of construction operations and processes and general purpose languages for developing simulations of operations. However, much of this work has limited human interactivity and is based on the understanding of the domain as an interaction of resources. While such efforts have had great successes in terms of furthering construction productivity, they have not really looked at bridging the disconnect.

1.2 *The Challenge*

The challenge is to systemically approach the CM domain by understanding the reasons which trigger the symptoms instead of the traditional approach which attempts to solve the dual inter-related symptoms of a widening disconnect between theory and practice and a widening expertise gap. Given that experienced decision-making plays a critical role in the success of construction projects, such an approach involves studying the CM domain as an interdependent system of human and resource interactions and better understanding research questions such as: How do experienced construction managers deal with critical problems and crisis scenarios? How can we analyze and leverage such information to develop the foundations of a systemic understanding of CM practices? How can we feedback such understandings into the CM curriculum to prepare students in the skill of decision-making and to better manage crisis scenarios? Given the recent advances made in computer science and the available computation power, what methods can we employ to answer the above questions?

The above questions, while being different approaches to the same challenge, involve a broad area of work spanning an understanding of CM, cognitive science and computer science and information technology. For the sake of this research effort it was imperative to identify the single question that is critical in developing a rigorous approach to studying and analyzing human-resource interaction in the CM domain, while enhancing construction education.

In a field such as CM where problems present multi-faceted situations dependent on context it is critical to develop dynamic, interactive, context-sensitive, adaptive experiential simulation environments. There is evidence from other fields (Windschitl and Winn, 2000, Oppenheimer, P. and Weghorst, S. 1999) that such environments can be useful for educational purposes. Also such environments can prove to be effective test-beds for collecting data regarding how experts deal with domain specific simulated scenarios and analyzing such information to learn about the impacts of human interaction in the domain.

The challenge that has been addressed in this research effort has been to develop a technology framework that can be used as a contextually rich education environment for

construction management while providing a test-bed to capture and analyze expert interactions in the domain, to generate knowledge that can in the long run add to the body construction management knowledge. This is no more than a stepping stone toward the bigger challenge of bridging the disconnect between the theory and practice of construction management.

1.3 Hypothesis and Objectives

I propose that situational simulation environments can be used as educational environments for construction managers while also providing a testbed to collect and analyze information about human interaction in crisis scenarios, thus allowing us to study the CM domain as a dynamic system, consisting of human and resource interactions.

Situational simulations simulate the CM domain as an interdependent system of human and resource interactions. They are dynamic, interactive, context-sensitive, adaptive environments powered by autonomous agents that can simulate future project scenarios that can arise out of resource and activity scheduling decisions taken by participants, consistent with rules that govern the CM domain and the project being simulated. In such environments, participants are exposed to diverse project management scenarios and situations rapidly unfolding in time and can explore what-if scenarios that may develop as a consequence of their decisions.

The necessity of situational simulation environments to have some sense of in-built autonomous agency requires them to be capable of expressively representing CM information and reasoning about wide range of construction scenarios. Also given the diversity of CM scenarios and projects, it is important to have a simple framework that can be easily programmed and extended to simulate different kinds of construction projects and scenarios.

The objective of this dissertation is to develop and implement a general purpose multi-agent framework for situational simulations for CM. Such a framework is driven by agents that have the ability to reason about CM scenarios and problems using the conceptual abstraction that all such problems can be modeled as constraint satisfaction problems and crisis scenarios are combinations of multiple constraint violations. The general purpose

framework makes the situational simulations extensible and reusable. It allows educators and construction managers to include project specific constraints, cost and schedule information and thus simulate different construction projects for different purposes without having to interfere with the underlying representation, reasoning and numerical models.

The specific objectives that were pursued are as listed:

- Conceptualize problems in the construction management domain and classify them into defined classes (such as a Constraint Satisfaction problem (CSP) or a planning problems).
- Develop a conceptual framework for situational simulations based on product, process and information models of construction.
- Develop an ontology that can be used to formally represent information pertinent to the construction management domain.
- Define a formal axiomatic system to describe the situational simulation environment using interval temporal logic.
- Develop inference rules representing agent reasoning.
- Develop a system dynamics approach to capture the concept of equilibrium during the implementation of a construction project.
- Suggest a model of the construction domain, which can be used by an agent to reason about the sensitivities of the simulated system to changes in the different aspects in the environment.
- Develop a multi-agent framework to create general purpose situational simulations in construction.
- Develop a framework that can be used as the foundation for the development of a programming language for general purpose situational simulations in construction.

- Implement a prototype of the proposed multi-agent framework.
- Develop a specific situational simulation to test the multi-agent framework.
- Experiment with the prototype system through interaction with expert and novice construction managers.

1.4 Contributions

The contributions of this research effort have a multi-disciplinary footprint. Beyond the immediate contributions to the field of construction engineering and management, this research also has contributions to the field of simulations and the cognitive sciences. This is apparent from the papers that have been published from this work in the American Society of Civil Engineers (ASCE) journals, the Winter Simulation Conference and the American Education Research Association (AERA) annual meeting. Specifically the contributions can be enlisted as below:

1. Construction Engineering and Management

- The development of a framework for independent developers to build customized situational simulations that suit their educational requirements
- The conceptualization of problems in the CM domain in terms of constraint satisfaction and planning
- The development of a formalism that provides an expressive language to represent and reason about construction knowledge
- The development of a collaborative environment that solicits participation from academia and industry and can be used for educational purposes and as a test-bed for conducting research on mental models of experienced construction managers
- The development of a system dynamics approach to understand meta-cognition in CM

2. Simulation Technologies

- The development of a multi-agent framework for interactive and adaptive simulations. Such simulations can be used for exploring “what-if” scenarios to impact policy making in areas such as the ocean sciences and urban planning. They can also be used to train responders to emergency situations like terrorist attacks

3. Cognitive Sciences

- The development of an understanding of meta-cognition of construction managers and a system dynamics/systems thinking approach to better understanding human cognition in the CM domain

This dissertation starts with a review of the literature in the areas of construction management simulations, agent technologies and the cognitive sciences. This is followed by a discussion of the conceptual and formal foundations of the general-purpose framework for situational simulations and details of the Virtual Coach, a particular implementation of the framework.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

The objective of this dissertation is to provide a technology framework that can be used across the academic and industrial branches of construction management for educational and research purposes with a long term goal of studying the CM domain more holistically. Such an effort requires a multi-disciplinary approach because the area of application of the research (CM) is not the same as the knowledge areas (information technology, education, cognitive science) that provide the theoretical underpinning. Therefore it is imperative to survey multiple areas of work and get an understanding of each of these areas to appropriately justify the work to be done and the methods to be employed.

The chief areas of work to be analyzed and the contexts in which they need to be analyzed are:

1. Simulation systems in construction: A survey of the existing simulation paradigms with a focus on simulations in construction. Why are these methods not appropriate for developing the multi-agent framework.
2. Agents: A survey of agents and the span of work relevant to artificial intelligence (AI) and agent driven environments similar to the envisioned multi-agent framework.
3. Education: A survey of the theory and evidence that exists in education literature to support the use of interactive and adaptive simulation environments for education
4. System Dynamics: A survey of the System Dynamics/Systems Thinking perspective and its utility in better understanding cognitive and meta-cognitive processes in CM

5. Mental Models: A survey of methods and research in understanding the differences between expert and novice knowledge organization patterns, and the usefulness of such an understanding in exploring the nature of expertise in CM.

In the rest of this chapter each of the above areas will be surveyed in detail.

2.2 *Simulations in Construction*

A survey of simulations in construction engineering and management suggests that they can be classified using three different approaches. The first approach classifies simulations based on whether they are simulating construction management processes or construction operations. While, Superbid (AbouRizk 1993), STRATEGY (McCabe et al. 2000), ICMLS (Sawhney et al. 2001), CONSTRUCTO (Halpin 1970) and VIRCON (Jaafari et al. 2001) are all examples of simulations which deal with construction management processes, Symphony (Hajjar et al. 1999) and STROBOSCOPE (Martinez et al. 1999) are examples of simulations which deal with construction operations like tunneling and earthmoving.

The second approach to classifying simulations is based on whether they are of a special purpose or a general purpose in nature. The difference between special purpose and general purpose simulations are:

- Special purpose simulations are restricted in scope (to a particular operation like tunneling or a particular management process like bidding)
- General purpose simulations unlike special purpose simulations allow for greater flexibility of scope since they are programmable.
- General purpose simulations can be used to promote new simulations and collaborations amongst developers.

A survey of current research indicates that there exist general purpose and special purpose simulation tools and techniques for simulating construction operations (Symphony: Hajjar, et al. 1999 and STROBOSCOPE: Martinez et al. 1999). All the simulations in the area of

construction management processes are special purpose in nature. They deal with specific problems in planning (Veshosky, et al. 1991) or bidding (AbouRizk 1993) or negotiation (Dubziak 1988).

The third approach to classifying simulations can be based on how interactive they are. I define situational simulations as temporally dynamic, interactive simulations. In their simplest form simulations of construction processes use a set of initial conditions and parameters, and a well defined model to project outcomes regarding the simulated operation. For example, given information regarding the availability of trucks and loaders, their unit costs and the amount of earth to be moved a process simulation would be able to project the total time and cost for an excavation operation.

2.2.1 Simulation Paradigms in Construction

Most simulations of design and construction processes are instances of discrete event simulations. Martinez and Ioannou (1999) explains in detail the essence of construction simulation systems and justifies the use of discrete event simulations for modeling construction operations. They go on to study the applicability of the Activity Scanning (AS) and Process Interaction (PI) simulation strategies to construction operations. Gil and Tommelein (2001) have also discussed the Event Scheduling paradigm. This section shall do a brief survey of the different simulation systems in construction.

Activity Scanning simulation models are based on a set of “activities” each of which has a set of defined conditions and outcomes. The “activity” in this context typically represents a single construction task and a construction operation can be simulated by a sequence of such activities. Hence an earth moving operation can be represented by the activities: *PushLoad*, *BackTrack*, *Haul*, *DumpAndSpread*, *Return* each of which has a condition and an outcome (Martinez and Ioannou 1999). An activity cannot occur if the condition is not fulfilled and when it occurs it always produces the predicted outcome. This scheme provides a way of representing simple networks which represent the relationships between the activities, conditions, outcomes using directional arcs. The direction of the arcs go from condition to activity to outcome. Such networks are referred to as Activity Cycle Diagrams

(ACD). The major languages used for modeling construction simulation namely CYCLONE and STROBOSCOPE, both use ACDs.

The Process Interaction paradigm uses processes or entities which compete for scarce resources as they flow through the system. The SLAM II simulation language uses the PI paradigm and can be successfully used for both discrete event and continuous simulations. A simulation begins with a network model or flow diagram showing the flow of entities. A SLAM II network is made up of nodes at which processing is performed. Common functions are entering and leaving the system, reserving resources, starting and stopping flows etc. Nodes are connected via ‘activities’ which define the routing of the entities. Time delays represent processing times, travel times, or waiting times. Entities proceeding from node to node have ‘attributes’ which determine their processing.

Finally, the Event Scheduling (ES) systems use event graphs which comprise vertices and edges where the vertices are associated with changes in states while the edges represent conditions and delays. The simulation language SIGMA is based on the event scheduling paradigm. It has wide applications in various simulation problems, including system dynamics problems (Gil and Tommelein 2001).

Situational simulation environments simulate the reality of the construction process. None of the surveyed methods can provide a framework to effectively represent situational simulations. In real life, events and activities take time to occur. Also, events are unpredictable, can occur simultaneously, have deterministic outcomes, are causal in nature and are motivated by a logic specific to the simulated domain. The discussed methods usually tend to treat time as a sequence of states or instantaneous events. This makes representation of parallel events over time very difficult. Different aspects within the domain also interact dynamically making it necessary that the simulation reflect the sensitivities of the system to changes in the individual aspects. Finally, a situational simulation is interactive and as time passes it evolves based on participant interaction and the events simulated within the environment. This means that the system should possess a perceptive reasoning ability. Therefore, in order to describe a situational simulation environment it is very important to have a framework which can represent and reason about events and activities within a formal temporal model. Based on the different functionalities a framework consisting

of multiple agents, can autonomously reason and perform different tasks in the simulated environment.

2.2.2 *Simulations of Construction Operations*

Each of the above paradigms are very useful for special and general purpose discrete event simulations where activities do not consume time or overlap in time or in which the simulation time changes *during* an event rather than in *between* events. The *Simphony* environment suggested by Hajjar and AbouRizk (1999) can be used to build special purpose construction simulation tools. AbouRizk et al. (1999) demonstrate a special purpose tunneling simulation template that was developed based on tunneling operations performed by the City of Edmonton Public Works Department for shielded tunnel boring machines.

Martinez and Ioannou (1999) use the STROBOSCOPE and later the EZSTROBE (Martinez 2001) to suggest a general purpose simulation system based on ACDs. An ACD can be used to represent resource flow and precedence between activities but it treats activities as instantaneous time points. This makes representation of parallel activities overlapping in time difficult to express. The multi-faceted nature of real-life construction situations require the ability to express multiple activities across multiple tasks which overlap in time. Clearly an ACD representation is not suited for representation of situations in a situational simulation. ACDs are very useful for expression of specific construction operations (like an earth moving operation) but not necessarily for the expression of multiple events occurring simultaneously during the construction process.

Simulations of construction operations built using STROBOSCOPE and Simphony are usually not interactive. They provide special and general purpose simulation environments for effectively simulating construction operations, however they are not very useful for building simulations of management processes which involve unpredictable and time consuming events within a system that evolves over time based on participant interaction and the outcome of events simulated within the environment.

2.2.3 Simulations of Construction Management Processes

The *Construction Management Game* and CONSTRUCTO are the earliest efforts at using games in to simulate construction management processes. The *Construction Management Game* developed by Au et al. (1969) is a simulation of the bidding process in construction and allows the participation of multiple teams. While a project management game developed at the University of Illinois by Halpin (1973) to integrate the effects of weather and labor productivity, using the CYCLONE simulation language. It simulates real life construction project scenarios facing construction managers. This was probably the very first attempt at a situational simulation environment. However, the lack of appropriate computing power at the time resulted in it not being interactive.

The Negotiation Game (Dubziak 1988) simulated contract negotiation between an utility and a design-build firm. Abourizk (1993) also developed *Superbid* which is a stochastic simulation of the bidding process in construction and trains players to increase profitability by optimizing bidding decisions. Beliveau (1991a, 1991b) also has conducted research efforts like the Lego Bridge Game and Road Building Negotiation Game which amongst other things, study the interactions between multiple team strategies in solving problems of negotiation and estimation in a competitive environment. These are fine examples of simulations of construction management processes dedicated to the special purpose of bidding and negotiation.

Veshosky and Egbers, (1991) developed a *Civil Engineering Project Management* game which deals with the planning phase of project management and allows students to undertake tasks specific to project design definition, specification reviews and scheduling and planning. STRATEGY (McCabe, et al., 2000) is another simulation environment that models the construction process for instructional purposes. It incorporates multi-team participation and situations, which raise random events. STRATEGY, is programmed in Microsoft Visual Basic, interfaced with Microsoft Access for database management. STRATEGY “borrows the bidding theme” from Superbid (Abourizk 1993), scheduling and planning from Veshosky and Egbers (1991) and the construction management aspects from CONSTRUCTO (implying that it uses the ACD simulation paradigm). It also uses MSBN, a

probabilistic expert system to provide intelligent guidance to the automation of stochastic functions within the program. While STRATEGY does provide limited interactivity, it is limited to the pre-planning phase and can be classified as a special purpose simulation.

The Parade of Trades (Choo, et al. 1999) game demonstrates to students the impacts of small variability of tasks on the construction environment. In the game, multiple trades are queued linearly and chained by dependency of input of each trade on the output of a previous trade. This is a special purpose simulation of a management process, and it does not allow users interact dynamically with it

Jaafari, et al. (2001) have worked at developing an interactive system for teaching construction management, VIRCON (VIRtual CONstruction), a system which combines traditional construction planning with 3D/4D models of the project. This system was implemented in classroom environments through student group projects for a class that taught project management. They used the C++ programming environment to provide an interface for data input as well as analysis and reporting. The system also implemented a non-immersive virtual reality visualization of the project through a module that would communicate with information stored in a database across a client server configuration. The system supports 'What-if' scenario analysis, integrates dynamic scheduling and estimation planning, is armed with stochastic analysis techniques and also provides for monitoring risks. Like STRATEGY, VIRCON also deals with simulating the pre-planning phase.

Sawhney, et al., (2001), have developed an Internet-based Interactive Construction Management Learning System (ICMLS), which is an advising and mentoring program that enhances participant involvement. The system uses multimedia, internet-based computing, databases and Virtual Reality Modeling Language (VRML) as their chief tools. ICMLS makes an approach to bridging the gap between the classroom and actual construction site using an interactive and adaptive learning environment, which "mimics the challenges faced by a construction manager on a real life construction project". The system is process-oriented (uses the the PI simulation paradigm) and makes use of discrete event simulation technology. Also, the environment simulated usually reflects a particular case study. The case studies are specific to construction operations chosen by a participant. The environment allows students to understand process interactions and equipment requirements for

the particular operation in the given scenario.

Amongst various in-class techniques that have also been reported recently is use of web-based tools to enhance collaborative learning by Rojas, (2002). The author explored the pedagogical and motivational goals behind the implementation of web-centric educational models while using MAESTRO, a software tutorial application, in a class of construction management graduate students.

Commercially there are various packages such as Primavera’s Project Planner P3e, which can be used within the classroom environment to expose students to techniques used in the field in areas of scheduling and planning. However, these are better classified as tools rather than simulations.

All the surveyed methods in this section are best classified as special purpose simulations.

2.3 Agents

An agent is anything which can perceive its environment through sensors and can act upon that environment through effectors (Russell and Norvig, 2002). Agents are also attributed a notion of intelligence. They can reason logically and act autonomously (free of human control) towards a goal. They are aware of the repercussions of their actions on the environment and dynamically integrate their experiences into existing reasoning mechanisms. In the computer mediated simulation domain there can be two kinds of agents: software agents (programs) and humans (interacting with a computer mediated environment). In a situational simulation environment, the “coupled” agent is a human while the “outside” agents are software agents. Each agent handles a specific reasoning aspect of the environment.

A problem solver is a component of an agent (Talukdar 1998). Problem solvers perceive problems in the environment and solve them using a set of defined tools. In the quest for an abstraction of processes in the construction management domain, I decided to use a hypothetical problem-solver and a hypothetical agent. While the problem solver allows us to abstract the classes of problems involved, the notion of intelligence in the agent allows us to grasp the underlying threads of reasoning in the world of construction.

Agents exhibit autonomous behavior. Autonomy gives an agent the ability to behave free

of human intervention. Autonomous decisions cannot be taken by agents which function by looking up matching facts from a set of built in assumptions and knowledge, because that limits the agents' ability to deal with undefined situations. Autonomy of an agent calls for an 'intentional stance' (Woodridge and Jennings, 1995). To take an intentional stance is 'to be the subject of beliefs, desires, etc.,' (Seel, 1995) and intentional notions are abstraction rules which allow us with a convenient way of describing, explaining and predicting behavior. For instance, some simple abstraction rules for the construction environment are 'Bad weather adversely affects productivity', 'productivity affects duration' etc. These intentions are essentially attitudes which represent the agent and influences its behavior. The attitudes can be information attitudes or pro-attitudes. While information attitudes are related to the knowledge that an agent has about the world, pro-attitudes guide the agent's behavior. The agent has to have access to both these attitudes in behaving autonomously and rationally within the environment. The Waffler architecture (Anderson and Evans 1996) is an instance of an agent architecture that adopts and applies intentions under resource and time constraints. It uses the concepts of a 'long-term memory' and a 'working memory'. While the former provides the conceptual knowledge possessed by an agent specific to the domain and the simulated project, the latter includes its awareness of the environment based on its perception.

The literature provides a rich variety of agent based frameworks that have been used in distributed environments. The Generalized Partial Global Planning (GPGP) (Lesser et al. 2002) and its associated TAEMS hierarchical task network representation were developed as a domain-independent framework for coordinating the real time activities of small teams of cooperative agents working to achieve a set of high-level goals. Coordination between multiple agents running different algorithms has been exploited to develop efficient solutions to complex problems. A-Team (Talukdar et al. 1996), a scale-efficient network of distributed computer agents were used to solve non-linear algebraic equations in a shorter time, using the Newton-Raphson and Genetic Algorithms as agents, than the individual processes. The M-RAM (Soibelman et al. 2000), a multi-reasoning model uses an agent-like approach to develop modules, each of which is specialized to perform particular tasks. The M-RAM model was used to support the conceptual phase of structural design and to study the

applicability of agents to support the sub-processes of a divided structural design process. This dissertation looks at using agent modules, each of which are specialized to perform a particular thread of reasoning pertinent to the implementation phase of the construction project. The autonomous reasoning and problem solving capabilities of the agents allow us to efficiently design situational simulation environments for the construction domain.

Agent architectures have also been used in synthetic, software and testbed environments. However, as Tambe et al. (1995) explains, though closely related the concept of using agents for synthetic environments differs from software (Etzioni 1993), robotic (Brooks 1991) and testbed (Hanks, Pollack, Cohen 1993) environments distinctly. The most significant difference between software and synthetic environments is that, the latter requires real time behavior in dynamic, limited information worlds, and therefore cannot be strongly dependent on traditional planning. Unlike robotic environments synthetic environments don't need to deal with low-level motor control and perception. Test-bed environments differ from synthetic environments often because of the domain of problems they handle. Synthetic domains tend to handle real life domains (like construction in this case) while test-bed environments tend to deal mostly with domains, which often tend to have greater complexity than test-bed domains where developers can "prestructure the environment, choose which aspects of behavior, or instrument the domain for experimental purposes." (Tambe et al. 1995).

There has been a great deal of investigation in the use of agents in interactive simulation environments, which are very similar to situational simulation environments. The obvious benefit of using agents is that they can replace humans when a large number of entities are needed to populate a virtual world (Tambe et al. 1995). Notably, Cremer et al, (1994) suggested the use of intelligent agents in traffic simulators, to simulate scenarios involving slowing and speeding of vehicles, pedestrians, traffic jams and other complex traffic patterns. Tambe et al.(1995), have explored the use of intelligent automated agents for battelfield simulation environments. Their environments are based on *Distributed Interactive Simulation* (DIS) technology, in which large scale interactive simulations are built from a set of independent simulators linked together by a network. They developed independent, intelligent automated pilots in the environment based on the underlying SOAR

integrated architecture for general intelligence (Laird, Newell and Rosenbloom 1987). The SOAR architecture is investigated in greater detail in the next section.

SOAR has an explicit symbolic representation of its tasks which it manipulates by symbolic processes. Domain specific knowledge is also symbolically coded and used as a guideline for behavior. Intentions are represented by a general scheme of goals and sub-goals. Goal formulation is achieved by finding a desired state in a problem space, which is defined as a space with a set of operators that apply to a current state to yield a new state (Laird, Newell and Rosenbloom 1987). Thus all goal formulation tasks can be completed using some heuristic search technique. If knowledge to immediately formulate a goal (say select an operator) is insufficient, then a sub-goal is created which in turn can further create sub-goals. Hence the behavior of SOAR involves a tree of sub-goals and problem spaces. The ability to recursively create sub-goals allows SOAR to learn continuously and automatically by storing the “results of its sub-goals as productions.” For example, if at any point more than one operator can be chosen, a sub-goal is created to break the tie, and the final result of problem solving within this sub-goal creates a *preference* which resolves the tie. The operator sequence is stored as a *production* and is delivered as the *preferred* solution in a relevantly similar situation. In this way the architecture uses a production system for single memory organization of all long term knowledge. The SOAR architecture was illustrated by the authors using the Eight Queen Puzzle problem amongst other problems.

The reason why the SOAR architecture is of great interest to us is because, Tambe et al.(1995) have successfully used it to create situational simulations for the air-combat domain. They created pilot agents that participate in battlefield simulations using ModSAF (Calder et al. 1993) a distributed simulator that has been commercially developed for the military. Using DIS technology, copies of ModSAF are used to simulate a number of different fighter aircraft, across a network of workstations. The aircraft can participate in simulated combat with or against each other. The simulation is run by ModSAF sequentially invoking each agent. The simulation model is affected by action of all agents across the network, and allows predictions regarding future states of the simulation. Depending on the predictions and the actions of the agents the simulation is updated at the end of each cycle. The SOAR architecture has been used to implement this environment. The states in the SOAR

architecture represent situations and operators represent actions, which can be in the form of simple primitive actions that modify internal states or arbitrarily complex ones.

At this point it is important to compare the SOAR multi-agent architecture with the proposed multi-agent architecture for situational simulations in construction. The SOAR architecture represents situations as states. Operators facilitate state transformations. This means that in such an architecture time is represented as a sequence of states. Also the operators which represent actions in the real world will tend to be instantaneous. Intervals can be defined as a sequence of states, but it would make representation of multiple overlapping events difficult. As in the case of the interactive simulation developed for the air-combat domain by Tambe et al.(1995), the simulation of multiple interacting simulated aircrafts is achieved using DIS technology, which involves running multiple copies of the simulation over a network and coordinating them in parallel. In the construction domain, this would entail running multiple copies of the simulation for each construction activity. However, in the absence of DIS technology the agent framework that I propose intends to use temporal reasoning based on an interval representation of time (Allen and Ferguson 1994) to represent parallel activities within the construction domain. The proposed architecture ascribes operations to agents. However, the operations are not defined to create transitions between states. Instead the agent operators change attribute values of entities which are logical aggregates of variables. Each variable defines some aspect of the environment. The time interval reasoning allows the description of an aspect of the environment as an assertion about a variable attribute over a time interval. Different entities are affected at different times by different agent operations and at any time it is possible to have persistent states of variables or multiple operators acting on multiple entities each specific to a particular context or activity.

Tambe et al. (1995) argues that finite state machine (FSM) languages are too restrictive to represent human like intelligence. Similarly, situational calculus, an FSM language, is inadequate for representing information about the parallel nature of events in the construction domain. Even though the situational calculus approach was used in the air-combat domain, parallelism and simulation of multiple fighter planes could be achieved through DIS technology. By running multiple copies of ModSAF, they were running multiple FSMs

in parallel. The proposed framework runs multiple finite state machines (for each activity context) within a single simulation model. This has been explained in detail in chapter 4.

There are many formal agent theories. A very good survey of these theories has been done by Wooldridge and Jennings (1994). Agent theories use formalisms which can be used to effectively capture the desirable properties of agents. All formalisms need two independent attributes: a language of formulation and a semantic model. The two fundamental formulation languages used are (i) a language which uses non-truth functional modal operators, which can be used to qualify formulae and (ii) a meta-language, which is some kind of a first-order language containing terms that denote formulae about some other object language. The semantic problem can be also resolved through two basic approaches: the possible worlds semantic model and the sentential or interpreted symbolic structures approach. The possible worlds model is formulated using modal logic and deals with an agent's belief characterized by the different directions in which the present world can evolve in future. In the sentential approach an agent's beliefs are viewed as symbolic formulae explicitly represented in a data structure associated with it.

The agent framework proposed in this thesis will develop a formalism which uses first-order logic syntax and semantics based on a deduction model of belief (Konolige 1986). Konolige's model is based on the observation that a knowledge-based system is based on the two components of (i) a data base of symbolically represented 'beliefs' (this could include rules, frames, semantic nets or logical formulae) and (ii) a logically incomplete inference mechanism. He defined this observation in terms of a deduction structure which can be expressed as $d = (\Delta, \rho)$ where Δ is a base set of formula in some logical language and a set of inference rules representing the agent's reasoning mechanism. Deductive closure of the agent's base beliefs under its deduction rules is given by the function $close()$ which is given by:

$$close((\Delta, \rho)) = \{\varphi | \Delta \vdash_{\rho} \varphi\}$$

where $\phi | \Delta \vdash_{\rho} \phi$ means that ϕ can be proved from Δ using only the rules in ρ .

An autonomous agent framework appears to be suitable for a situational simulation environment. As the simulation proceeds, the agent takes intentional stances while au-

tonomously generating events. It can also perceive the state of the environment at any point of time and be able to predict the outcomes based on its knowledge of the domain. It should be noted the reasoning involved in this process is rule based rather than case based. The knowledge base associated with an agent is a repository of rules and definitions regarding the causal nature of events. The environment is coded in terms of variables and defined by a set of axioms which always hold true. The variables define aspects of the environment by taking up values from a discrete set of attributes. Depending upon the values of the set of variables, and its knowledge of the inference rules, the agent can reason about the unfolding situations and accordingly plan the future evolution of the environment.

2.4 Education

The prevalent approach to understanding how people learn has been the computational approach to human cognition. Such an approach assumes that the world can be represented by static structures of discrete symbols, and cognitive operations are essentially discrete, sequential and instantaneous transformations from one structure to the next. However, criticisms that cognitive activity is contextually situated (Brown, Collins and Duguid, 1989) and is not simply a mapping of external events to an internal symbolic system (Maturana and Varela 1987) has lead researchers to study the context and culture in which cognition occurs (Winn 2002). The more recent constructivist school of thought has explained learning in terms of students evolving to a greater contextualized understanding of their experiential world. It holds that learning is a process in which individuals construct their own meanings of the world they observe, and that the psychological processes involved are “essentially the same as the epistemological processes by which new knowledge is constructed by professionals in a discipline” (Novak 1993).

With the advances in the fields of information technology, virtual environments have proved to be extremely good test beds for the constructivist approach to learning. The Virtual Gorilla Project at the Atlanta Zoo (Allison et al, 1997) and the Virtual Puget Sound (Windschitl and Winn, 2000) and the Surgical Simulator (Oppenheimer, P. and Weghorst, S. 1999) efforts at the Human Interface Technology Laboratory, at the University

of Washington are just a few instances. However, critics of constructivism argue that it borders "towards relativism, or towards treating the justification of our knowledge as being entirely a matter of socio-political processes or consensus, or towards the jettisoning of any substantial rational justification or warrant" (Phillips 1995).

Winn (2002) provides an alternative framework, for describing learning in artificial environments, based on the three concepts of embodiment, embeddedness and adaptation. One of the implications of the framework is that it couples the learner and the environment into "one evolving system rather than two interacting ones." Learning thus can be thought of as a "self-organization by the system and new knowledge as an emerging property of that self-organizing activity." This is of great significance with respect to educational environments in construction. The success of a construction project (a system which evolves from start to completion) in terms of time and budget is dependent on the skill of the construction manager (the learner in our environment). As students learn within the environment, their performances improve and directly affect the evolution of the environment itself. It allows us to conclude that a successful learning environment in construction would have to conceive the learner and the environment as a coupled system.

The framework (Winn 2002), also resurrects the importance of the computational approach to cognition. Understandably, virtual environments being computationally generated need to be represented and reasoned about. The computational approach to cognition allows us to decompose an intelligent agent's reasoning mechanisms within complex domains (Beer, 1995). It also allows us to develop a representation for the domain which defines the context as well as reflects the dynamic nature of such environments. The framework also proposes that the environment be an adaptive one. It should be perceptive to the level of the participant's abilities and simulate situations, which challenge them accordingly, thereby providing the necessary scaffolding to the student.

2.5 The System Dynamics/Systems Thinking Perspective

In this dissertation I have argued that in order to effectively educate CM students to face real world scenarios, it is necessary to understand learning as a cognitive activity and how

it happens in the CM domain and I suggest the adoption of a systems perspective in better understanding cognition and meta-cognition in CM.

As explained by Richmond (1994), systems thinking can be explained as a paradigm and a learning method. The paradigm provides us with a vantage point of view of the domain and a set of thinking skills, which focus on understanding the underlying structure of a system in terms of reciprocal inter-relationships of the components and how they unfold in time. The learning method supports the paradigm. I have used the Virtual Coach, a situational simulation of the CM domain, as our method to explore the usefulness of employing the systems thinking paradigm in CM. The success of such an environment lies in providing students with the above mentioned “vantage point.” At the same time it is also important for the researcher to be able to study the human-resource interaction in the simulation environment from a similar “vantage point.” At this point it is important to analyze the system dynamics perspective in greater detail.

The systems perspective has its origins in the domains of System Dynamics / Systems Thinking (SD/ST). A system is defined as a group of interacting, interrelated, or interdependent elements acting as a complex whole. A complex system is one in which the elements interact to create multi-loop non-linear feedback. Most social systems can be classified as complex systems. Jay Forrester, considered to be the father of the field of system dynamics, defines it as a professional field that combines the theory, methods, and philosophy needed to analyze the behavior of complex systems using a common foundation that can be applied whenever it is necessary to understand and influence the change of behavior over time (Forrester 1991, 1994). System dynamics involves interpreting real life systems into computer simulation models that allow us to understand how the structure and decision-making policies in a system create its behavior.

Richmond (1991, 1994) has defined systems thinking as the art and science of making reliable inferences about behavior by developing an increasingly deep understanding of underlying structure. He explains that the systems thinking is system dynamics with an aura, that is, it provides a laymans approach to understanding the emergent behavior of complex systems, without being intimidated by the mathematical methodologies employed in analyzing system dynamics.

Richmond (1991) further goes on to explain that SD/ST in practice is a continuum of activities, which range from the conceptual to the technical. On the far left is the purely conceptual systems viewpoint, that is arrived at by standing back far enough from a system in both space and time to see the underlying web of ongoing, reciprocal relationships which are cycling to produce patterns of behavior. Proceeding rightwards along the continuum, the emphasis shifts toward implementing the viewpoint and becomes more analytical. This involves the use of influence diagrams and formal models to conceptualize and eventually mathematically express the inter-relationships and feedback loops that are present in the system. Finally, the formal mathematical models can be used to power simulations that can allow us to simulate and verify the models, explore what-if scenarios and forecast emergent behavior of the system.

The main advantage of using a SD/ST approach in order to understand a domain is that it allows researchers to stand back and be able to adjudge the impacts of events and decisions that are often not limited locally in time. It also helps in developing solutions to problems by getting a better understanding of the feedbacks and counter-actions that occur because of the immediate problem at hand. Forrester (1971) analyzes the counter-intuitive behavior of social systems, and explains that orderly processes in creating human judgment and intuition lead people to counterintuitive decisions arising out of a conflict between the goals of a component of the system and its greater good. Sterman (1992) explains why the domain of CM is counterintuitive. For example, a delayed project tends to get even more delayed when more resources are added to it. This kind of behavior is typical with respect to complex and highly interacting systems.

The SD/ST approach is also critical in better understanding meta-cognition¹ in a domain as it can be used to analyze cognitive processes. As discussed in the previous section, the computational approach to human cognition ignores that cognitive activity has a dynamical component and as Port and Van Gelder (1995) explains, the computational approach to cognition fails to recognize that “cognitive processes and their contexts unfold continuously and

¹The term “meta-cognition” in this dissertation refers to the researcher’s understanding of cognition in a particular domain. Thus it still refers to the second order cognition (cognition about cognition) but in a sense that is different from that traditionally used in education literature.

simultaneously in real time.” They conclude that an alternative approach to understanding cognitive processes is by treating natural cognitive systems as dynamical systems.

This echoes Winn’s (2002) notion of the learner and the learning environment being a coupled system and strengthens the argument that human cognition is not only contextualized and adaptive, but also dynamic. Knowledge is an emergent property of the coupled dynamical system consisting of the learner and the learning context. This is particularly significant with respect to the CM domain, because of the critical role of human decision-making in it.

The construction management domain can be studied as a complex system, which has multiple interacting components (schedule, cost, resource distribution and availability, etc.) with multiple feedback loops. Using the SD/ST approach to model CM projects is not an entirely new idea. Sterman (1992) correctly asserts that attributes of construction projects are complex, consisting of multiple inter-dependent parts, involving multiple feedback processes and non-linear relationships. He explains that system dynamics can be used to capture the interdependencies in the CM domain so that causal impact of changes can be traced throughout the system.

The success of a construction project (a system which evolves from start to completion) in terms of time and budget is dependent on the skill of the construction manager (the learner in our environment). As students learn within the environment, their performances improve and directly affect the evolution of the environment itself. Hence, a learning environment for the CM domain that aims at bridging disconnect between fragmented presentation of theory and practice in CM courses needs to be interactive and adaptive and it should present the CM domain to the students as a dynamical system. This would facilitate and aid the process of learning by helping students cognitively better understand the systemic nature of the CM domain.

2.6 *Mental Models*

A long term goal of situational simulation environments is to serve as test-beds for capturing expert interaction in simulated crisis scenarios to facilitate the exploration of expert

mental models. Besides, giving us a picture of how experts deal with crisis scenarios, such explorations will also help us understand the shift between expert and novice mental models and the nature of expertise among construction managers. Such knowledge when integrated with the curriculum will prevent the loss of expert knowledge from the industry and thus help in bridging the disconnect between theory and practice in the long run. Thus it is important to understand mental models and their relation to expertise.

Experiential learning allows expert construction managers to develop an intuition that sets them apart from novice construction managers. There is provocative evidence in Education literature to support the above claim. Studies of experts and novices in Physics (Chi et al. 1982), exploring organization of knowledge structures have found that in representing a schema for an inclined plane novices tend to concentrate on the surface features of inclined planes, while experts connect the notions of the inclined plane with laws of physics and the conditions under which such laws apply. Experts notice features and meaningful patterns of information, which cannot be reduced to isolated facts and propositions but are instead 'conditionalized' to specific circumstances (Bransford et al. 2000). The process of conditionalizing allows experts to develop the expertise that guide their decision making processes. Experts also have the ability to retrieve information on a selective basis befitting the context of the problem at hand.

More than fifty years ago, Craik (1943) suggested that the mind constructs "small-scale models" of reality that it uses to anticipate events (Johnson-Laird and Byrne 2000). Such models are conceptualizations of the world that the mind builds by incorporating the individuals views of the world, of themselves, of their own capabilities and of the tasks that they are required to perform (Norman 1983) and are referred to as mental models. Individuals construct mental models of themselves and the environment that they are required to interact with from perception, imagination, the comprehension of discourse, or, more importantly for this study, as they solve problems. Mental models provide predictive and explanatory power for the understanding of such interaction, and experts, unlike novices, have them already in place to draw on. They underlie visual images, but they can also be abstract representations of situations that cannot be visualized.

Mental models research is fundamentally concerned with understanding human knowl-

edge about the world (Gentner and Stevens 1983). Specifically, scientists have studied mental models to explicitly reveal human understanding of limited content domains. Hutchins (1983) has used mental models in explaining the cognitive structures involved in Micronesian navigation techniques. De Kleer and Brown (1983) developed a framework for investigating the structure of peoples mental models of physical devices. Other related work on expert cognition includes Chi et al. (1988) investigation into the nature of expertise and Noices (1997) investigation into the expertise of professional dancers.

The shift from novice to expert is a shift from one system of beliefs about the world, one set of concepts and one set of problem solving capabilities to another (Carey and Wiser 1983). I believe that such a shift is in essence a shift in the underlying mental models of novices and experts. By studying the differences in the mental models of novice and expert construction managers, the critical differences in their problem solving approaches can be understood.

In the next section we have reported a pilot study that was conducted to explore and understand the expertise of construction managers by exploring their mental models.

2.6.1 Exploring Mental Models of Construction Managers

The scope of this dissertation is in developing general purpose simulation environments. However, in keeping with what motivated this research effort, I have also made a preliminary exploration into existing tools and methods that can be used to analyze and learn about expertise from human decision making data. In this chapter I have investigated the nature of expertise in construction managers by exploring experimentally the existence of a difference in the mental models among construction managers.

A group of construction managers with varying levels of experience were asked to respond to a construction management crisis scenario. Using the **ConProFac** software to calculate an index i indicative of the structuredness of the responses I found a significant correlation between i and the number of years of experience of the respondent.

Methodology

Traditionally, mental models research focuses on either developing a knowledge representation for a particular domain or a phenomenological understanding of human thinking. The former method involves the development of knowledge representation networks using computer simulations, while the latter involves the psychological experimentation (Gentner and Stevens 1983). Meanwhile, research on novice-expert development has been characterized by two approaches: diagnosis of novices systematic misconceptions about content and how that affects problem-solving and differences in information processing analyses of problem solving procedures between experts and novices (Carey and Wiser 1983).

We have used a methodology that analyses the differences in problem solving approaches of novice and expert construction managers. This involves testing human subjects and quantitatively studying the results using ConProFac, a program that creates descriptions of how people organize their ideas and qualitatively analyzing their responses.

We gave a group of 7 construction managers, with different levels of experience, a construction scenario and documented and analyzed their reactions to the scenario at hand. The scenario described the construction of a \$104 million project of a state-of-the art library facility, to be built over a period of 24 months. The scenario was based on real life construction projects, and was developed in collaboration with GLY Construction, a Seattle based general contractor. The information provided in the scenario included relevant project information like schedule and budget information, project participants, current delay on the project, recent information exchanges with the owner, budgetary constraints and space constraints on project site. (Complete project scenario is available in Appendix B.)

The participant assumed the role of a construction manager with First Construction, a GC/CM At-risk contractor. The project scenario presented the participant with a 60% completed project that should have been 67% completed at the time of the situation. The project had been delayed due to an act-of-God event, a snow storm. The owner, the City of Seattle, had in response provided a 15-day extension on the schedule after which First Construction would face liquidated damages of \$15,000 per day of delay. In order to finish by the new deadline, First would need to complete installation of curtain walls on schedule

to enable the interior decoration sub to finish on time.

First Construction had been brought onto the project because of their reputation in curtain wall installations. However, clerical errors in specifying the nature of the prefabricated curtain wall material requirements had resulted in delivery of inappropriate material. Space constraints demanded that the delivered material be installed to avoid delay on the project. Labor constraints threatened a situation in which First Constructon would not have access to skilled labor because of a delay in the wall installation and the constraints on cost and schedule had to be attended to, while maintaining the reputation of First Construction.

The participant was required to analyze the information that had been provided and devise the best possible plan of action subject to the situational constraints. Based on their plan they were required to respond to a set of questions that required them to explain their plan of action and justify their priorities. Information about the project provided in the scenario was incomplete and insufficient to answer all the questions in the questionnaire. However, the ambiguity had been deliberately designed as I expected the participants to answer the questionnaire based on what they intuitively felt about the situation at hand. They were encouraged to make suitable assumptions and draw conclusions based on them writing all their assumptions in the space provide.

We identified four distinct areas of concern: Space Management, Schedule Management, Labor Management and Materials Management. For each of these areas, each participant was required to indicate briefly his/her plan of action, using available information. For example a decision to hire skilled laborers would be a plan of action to manage labor, while a decision to crash activity X would be a plan of action to manage schedule. Participants were also required to rank, on a scale of 1-10, how they believed their plans of action would affect the project schedule, project cost and the reputation of the company, for each of the four areas of concern listed above. A value lower than 5 would indicate an adverse impact, while a value higher than 5 would indicate a positive impact. A value of 5 would indicate maintaining the as-planned schedule.

We used the ConProFac software to calculate an index i indicative of the structuredness of the numerical responses, while qualitatively analyzing the plans of action that the participants keyed in. In the following section I have briefly discussed how the ConProFac

software works and how it was utilized to analyze the user inputs.

ConProFac

The ConProFac program creates descriptions of how people organize their ideas about a content area at different levels of generality: CONcepts, PROpositions or FACets. It can be used with any information about how collections of concepts are connected by predicates to form propositions. For example, “cat” and “mammal” are connected by “is a” to form the proposition, “cat is a mammal” or “bad weather” and “construction delays” can be linked causally to give, “bad weather causes construction delays.” The truth of propositions about concepts can either be binary, that is either true or false, or weighted to express the likelihood that the proposition is true, or that a participant believes it to be true.

Propositions and their associated values can be obtained in a number of ways. The simplest one is to ask subjects to rate the truth of a set of propositions on a scale. Data can also be gathered from distance metrics applied to concepts placed at nodes in concept maps, whose inter-node connections are named, from free verbal associations given to sets of concept names, and even from analysis of freely-composed text. ConProFac can either create tables of proposition values from the propositions themselves, entered as strings, or can accept numerical tables directly that have been prepared by the researcher.

ConProFac uses standard methods (for example, see Rumelhart & McClelland, 1986) to calculate the strengths of associations (weights) in a network among all the concepts in the content area, and to place them in a matrix. These weights express the probability that if one concept becomes active, others will too. The network can then be queried, by activating a single concept or a group of them, to determine which concepts are associated with which others and how strongly. Also, the network can be trained to recognize patterns.

Most relevant to this study is the comparison of the pattern of weights across matrices derived from individual subjects. ConProFac calculates the structuredness index i that can be used to compare differences among the ways subjects organize their ideas and how these change over time, using standard statistical procedures. The value of i always lies between 0 and 1. A mental model that reflects a very high level of structuredness with absolutely

no ambiguity would have $i = 1$, while a mental model which is completely ambiguous and incapable of exhibiting any consistently structured response would have $i = 0$.

We constructed a three by four matrix to tabulate the participants responses regarding how they thought of their plan of action, with respect to the four areas of concern identified namely, space, schedule, labor and material management effected project cost, project schedule and company reputation. I analyzed each of these matrices using ConProFac to calculate the structuredness index i for each of the participants by using their numerical inputs as indications of how important they thought the sensitivities were of each of the matrix items. Analysis of the data as explained in the following section and the value of i allowed us to analytically understand the mental models of the participants.

Results

The table (2.1) lists the relevant statistics generated from the participant responses, the values of i , the time taken by the participant to complete the responses, and the experience (in years) of each of the participants. The question is, what kind of statistical correlation exists between experience and the structuredness index of the participants, and how reliable are the available data points. I used a third metric, the time taken by each participant in completing the responses after having read the scenario to assess the reliability of their response. As is obvious from the table, the rather short interval of time taken by participant 7 and the rather long interval of time taken by participant 1 clearly attract attention.

It is clear from the responses of participants one and seven, that participant seven took a very short while to complete the test (indicating possible lack of interest) and that participant one has provided detailed involved replies. Hence, in calculating the correlation coefficient I have excluded participant 7. The correlation coefficient so calculated is 0.77. If I do discount participant one and seven as extreme cases, I get an even higher correlation coefficient of 0.90.

Qualitative analysis of the participants plans of action shed more light on the differences in the mental models of experts and novices.

The responses of participants one and three both with comparable lengths of experience

Table 2.1: Structuredness Index, Experience of subjects and Time Taken

Participant No.	Structuredness Index ($0 < i < 1$)	Experience in Years	Time Taken(mins)
1	0.685	19	41.09
2	0.512	10	14.37
3	0.968	18	10.42
4	0.50	10	19.31
5	0.512	7	22.37
6	0.609	8	16.03
7	0.50	14	4.06

have the following in common:

- Enumeration of possible situations that might arise from the scenario and expectations of outcomes from such possibilities e.g.:

First I would approach the owner to determine if they would accept the incorrect glass. I would assess the time it would take to replace the glass and determine the impact to the schedule and the extent of further liquidated damages (Participant 1)

1. Review whether materials can be more efficiently organized on site to allow continued storage of glazing materials. 2. Review costs for an off-site warehouse to store the materials. 3. Review whether local installer has space in their warehouse/yard to store materials. (Participant 3)

This is markedly different from responses of participants with fewer years of experience, who emphasize more on what needs to be done immediately to solve the problem at hand, e.g.:

The glass that is not correct should either leave the site or be installed in order to close the building in. (Participant 5)

Throw away the glass since it is defective. This will provide area for the other subs to store materials (Uninvolved Participant 7)

Call surrounding parking lots and/or open spaces to see if space can be secured. Look at roof space, possibly haul other material to our yard and have our own forces deliver the material, possibly at night time where streets could be possibly used (blocked off). (Participant 2)

- Off the cuff calculations to support and evaluate decisions e.g.:

The 7% delay represents approximately 35 day delay after the 15 day extension is taken. This is approximately \$525,000.00 in LD. In addition, a month of general contractor overhead (at First Co.) expense would be about \$65,000 that cannot be recovered. Clearly, any steps to improve the schedule are very important. (Participant 1)

Based on the above observations it can be said that, with experience, construction managers tend to base their decisions and plans on apprehensions of different possible outcomes of current situations. They also tend to support their decisions by rough calculations using thumb rules, even in situations with incomplete information. The thumb rules that they use are usually based on cost patterns that they tend to recall from previous project experiences. In contrast, managers with fewer years of experience tend to concentrate more on immediate actions without considering long-term impacts.

2.6.2 Discussion

This pilot study presents the tip of an iceberg and is a preliminary investigation of mental models of construction managers. Based on this study, I can conclude that there exists a high correlation between levels of structuredness of thought and knowledge organization between expert and novice construction managers. This indicates that over periods of time, experience helps in fine-tuning the mental models of construction managers. A qualitative analysis also indicates that experts tend to apprehend the future impacts of their plans while deciding, as compared to novices. It also indicates that even in situations of limited

information, experts tend to make “complete” calculations using rules of thumb drawn from situations that they have encountered before.

This study also suggests that there is a correlation between experience and how construction managers organize their knowledge. On a particular problem, even though experienced construction managers might differ on the particulars of an optimal solution, it is highly probable that their organized approach to the problem is very similar and distinctly different from that of a novice. In turn this supports the otherwise anecdotal ground that motivates this work: that retiring expert construction managers are leaving a void in expertise that is difficult to replace without understanding the nature of expertise.

Understanding the way experienced construction managers work can be very useful in creating more meaningful curriculum in civil and construction engineering and management academic programs. For example, by the most part, the current construction management curriculum does not provide students with a platform to explore “what-if” scenarios on construction projects, or train them in long-term decision making. Studies like this should motivate changes in curriculum that provide students with a platform where they can test their decision making skills and be able to evaluate the long term impacts of decisions on cost and schedule. The understanding that experienced decision-making requires long-term apprehension of impacts and events could in no small way direct research in developing interactive simulation environments that can allow students to get “virtual experience” and mimic the mental models of experienced professionals before they graduate.

The significance of these results is not in their novelty, but in the fact that mental models can be used to analytically quantify the knowledge that comprises expertise among construction managers, which are difficult to formalize. There is a dictum that “expert construction managers often don't know what they know.” This study provides us with methods that can be used to ascertain such knowledge.

That being said, this study is far from complete. The results are based on a sample of only seven construction managers, all of whom work at the same construction management firm. Also, the data are correlational, which precludes conclusions about causal relationships between experience and structuredness. But it is important to understand that the study is examining a nascent topic and establishing correlation is a first step toward studies of causal

relations. Also, the study goes a long way in setting the agenda for using mental models, a method that cognitive scientists have been using for a long time, to better understand the human and resource interaction in construction management. Long-term studies along these lines would require greater support and a collaborative environment shared by both universities and industry. Hence this study can be used as a springboard for further research in this field.

Chapter 3

CONCEPTUALIZATION

This chapter will examine the conceptual models that provide the foundations to situational simulations. There are two major focuses that need to be understood and conceptualized. Firstly, the product, process and information models which govern the situational simulation environment and secondly a classification of problems in the CM domain to conceptualize the foundations of the general purpose framework.

3.1 *Conceptual Framework*

Construction management is a nontrivial process which encompasses a series of complexities that must be represented in any model. The conceptual framework introduced in this section is a representation of the construction management process, which serves as the foundation for the development of situational simulations.

The components of this framework are shown in Figure (3.1). There are three major models:

- The process model
- The product model
- The information model

The process model is a representation of the building process, the product model is a representation of the physical facility, and the information model is a representation of the data environment. In addition, this conceptual framework also includes a visualization mechanism to provide process and product feedback to the participant. A brief description of all the models is included in this section to provide a comprehensive view of the entire framework.

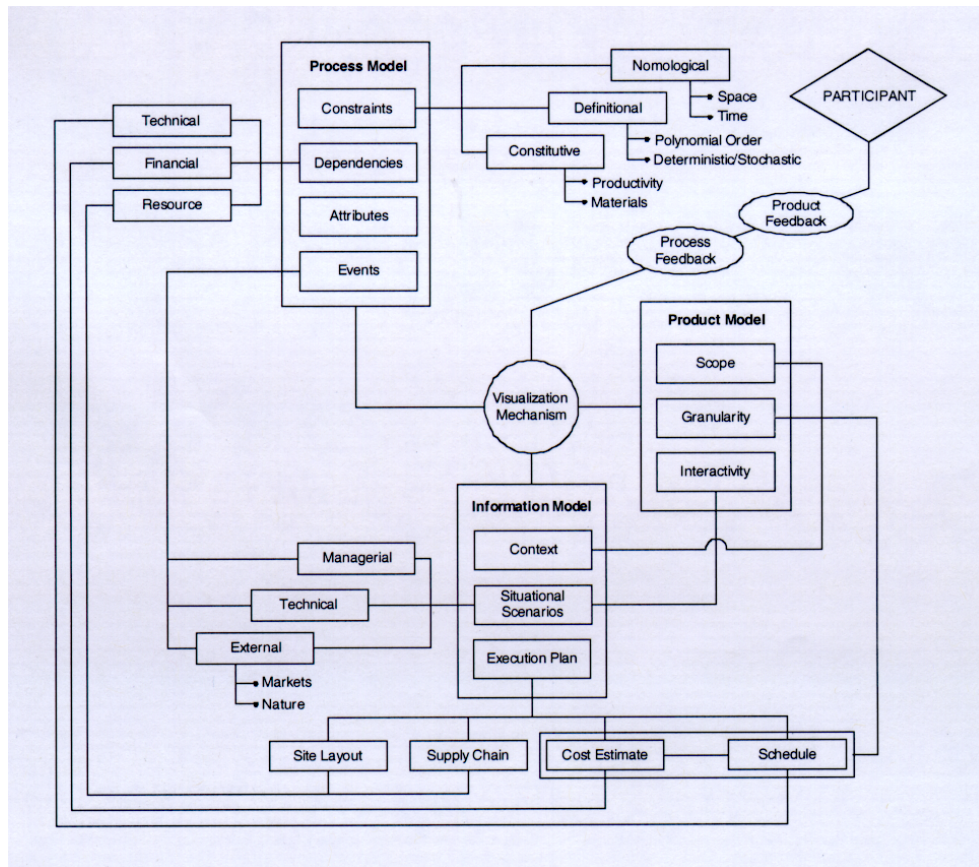


Figure 3.1: The Conceptual Framework

3.1.1 *Process Model*

As depicted in Fig. 3.1, the process model is defined by constraints, dependencies, attributes, and events. Constraints are limitations to the process given by nomological, definitional, or constitutive principles. Nomological constraints are nonnegotiable limitations that must be satisfied because they are dictated by natural law. Two instances are space and time. For example, in the process model, two materials cannot occupy the same space at the same time, nor can the total amount of materials stored at the site exceed the available space.

Definitional constraints are limitations imposed by mathematical relationships. Two instances are the polynomial order of the equations and the deterministic/stochastic nature of the variables. All equations in the process model are first-order polynomials, which simplifies numerical calculations as linear relationships are used to extrapolate and interpolate data. In addition, all variables in the process model are deterministic, further reducing computation requirements.

Finally, constitutive constraints are limitations imposed on the process model by choice. Two instances are productivity and materials. Productivity is represented in the process model as dollars per unit of time, rather than squared feet, cubic yards, or any other production metrics per unit of time. This limitation was imposed to provide a single unit to measure the variable and thus facilitate the application of events that impact the productivity of a variety of activities. Materials is another variable for which a limitation was specified. The number of different materials in a typical construction project could run into the thousands. In order to reduce the data storage requirements of the process models, materials were classified into two categories: driving and nondriving. An activity-based material tracking system for driving materials is implemented in the process model. Driving materials are defined as the biggest cost drivers in an activity. This self-imposed limitation on the process model significantly reduces that number of materials to be tracked, as it is often the case that only a handful of materials comprise most of the material costs of an activity, even if several dozens are required. Non-driving materials are bundled into one variable and are immune to changes in prices.

Dependencies are relationships among variables given by technical, financial, and re-

source enslavements. Technical dependencies are given by the construction schedule and represent the hard and soft logic sequencing of a project. Financial dependencies are dictated by the cost relationships among variables. For example, indirect costs are dependent on the duration of a project and the supply chain structure implemented. Resource dependencies are determined by the relationships among the different variables and resources such as materials, labor, and equipment. As an illustration, the rate of consumption of resources by an activity is related to its scheduled duration. If the activity duration is to be compressed, the rate of resource consumption increases.

Attributes are the specific characteristics that identify a variable. For example, a material may have attributes such as quantity, cost, procurement data, equipment required, and trade required, among others. Labor may have attributes such as crew size, wages, benefits, mark-ups, category, and efficiency.

Events are particular occurrences of situational scenarios. For example, an event could consist of the receipt of a test report from a concrete pour of several columns, in which the experimental results from a three-day compression test are 25% below the expected strength. The participant as decision maker can disregard the results, order new tests, wait for the seven-day compression tests, demolish and reconstruct the columns, and so on. The specific action taken by the participant, as well as its cost calculated through dependencies and constraints, determine the impact the decision has on the original schedule and other relevant factors.

3.1.2 Product Model

The product model is a representation of the physical facility and is defined by its scope, granularity, and interactivity. The scope relates to the percentage of the actual facility that needs to be represented by the product model. This decision is dependent on the information and process model needs. For example, some situational simulations may focus only on a few activities rather than on an entire project. When this is the case, there is no need to model the entire physical facility, as a model of the physical structure associated with the preceding activities and those required by the simulation exercise should suffice.

In addition, the scope of the product model can also be limited by proper restriction of the interactivity of the model. There is no need to model those aspects of the physical structure that are not going to be experienced by the participant. In essence, the same principles that apply to the design of movie sets also apply to the definition of the product model: build/model only those items that the viewer/participant is going to be exposed.

Granularity is related to the level of detail on the model of the physical facility. The granularity of a product model is intrinsically associated to the project schedule in order to support 4D visualizations of the process. However, granularity is also linked to the situational scenarios, as different scenarios may require different levels of detail in the product model. For example, a situational simulation could be developed to expose participants to the 1981 Kansas City Hyatt Regency Hotel disaster (Sweet 1999). This simulation should include fully developed details of the steel connections for the second and fourth floor walkways according to both the original design and the proposed modification.

This level of detail would be of essence for the success of such a simulation. However, if a similar facility is modeled for simulations without events related to the steel connections, then the product model does not have to provide such level of detail and details about the connections of steel members could be omitted altogether from the model.

Finally, interactivity relates to the ability of the model to be customized to better serve the participant. The interactivity of the product model is correlated to the scope and the level of granularity required. The technology selected to present the product model to the participant is also a limiting factor of the degree of interactivity of the model. For example, immersive virtual reality models are more interactive than nonimmerse ones, and these in turn are more interactive than nonvirtual reality models.

3.1.3 Information Model

The information model is made up of the context, the situational scenarios, and the execution plan. The context provides the participant with information related to the construction project, including scope definition and business plan. It also provides data about the site in which the project will be erected, including information such as local availability of re-

sources, labor, materials, equipment! and local regulations. This context information offers the participant a general understanding of the project goals and restraints.

Situational scenarios provide the participant with specific information about managerial, technical, and external events. An important factor that differentiates situational simulations from games is reality of function. Reality of function occurs when participants accept their roles and fulfill their responsibilities seriously and to the best of their ability. In order to accomplish this, a situational simulation must provide sufficient information so that participants can behave in a professional manner. The objective of the scenarios is to convey to participants the magnitude, severity, and timelessness of the problem or opportunity as well as all the relevant facts to encourage an analytical rather than a heuristic response.

Finally, the execution plan introduces participants to the original resource-loaded schedule, cost estimate, site layout, and supply chain arrangements. Participants are free to deviate from the original plan while managing the simulated construction process if they believe that the process can be improved. However, the original plan serves as a benchmark to evaluate the appropriateness of their decisions. Deviations from the original plan can also occur when events happen and participants are expected to adjust the different parameters under their control to go back to the original plan.

3.1.4 Visualization Mechanism

The participant interacts with the process, product, and information models through a visualization mechanism that provides process and product feedback. Process feedback provides the participant with access to the vital signs of the construction process. Sample feedback data includes actual cost and scheduling information and comparisons with estimated values. Product feedback provides visual information about the status of both the as-built and the as-planned physical models.

3.2 Conceptual Foundations of the General Purpose Framework (GPF)

In this dissertation I have developed a framework that encapsulates the abilities of the process, and product models into a framework that be extensibly used to simulate a range

of construction scenarios by only changing the information described in the information model. In this section, I have developed the conceptual foundations to the framework.

In developing the foundations of the GPF, I studied the CM domain and tried to classify the pre-construction and construction phase processes into specific classes of problems. Deciding on a common abstraction for problems in the CM domain is the first step toward developing a general purpose framework. In doing so I analyze the nature of problem solving during the pre-construction phase and during project execution.

During the pre-construction phase the problem at hand is that of creating a resource loaded activity schedule, also referred to as the “As-Planned” schedule. This can be classified as a constraint satisfaction problem (CSP). Such problems can be solved using a search based constraint solver. A number of research efforts support this claim. Succur and Grobler (1996) suggested a CSP formulation for construction project planning. They developed a structure that can represent precedence constraints (which they refer to as temporal constraints) and implicit resource constraints; and they provided a solution to the CSP using forward-checking constraint propagation algorithms like pruning and conflict resolution. Hammond et al. (2000) suggested the use of a partitioned dependency structure matrix (DSM) to represent information about a schedule, which on closer analysis proves to be a CSP in which each matrix is a state representation of precedence and resource dependencies in a schedule. WorkPlan (Choo et al. 1999) also used resource and precedence constraint satisfaction in the WorkPlan implementation. It is safe to claim that given the appropriate constraints, the “As-Planned” schedule can be generated using search based constraint solvers that return sequences of state transformations between an initial state representation of a schedule and a goal state representation (a resource loaded “As-Planned” schedule) while assigning resources to all activities, in keeping with resource and precedence constraints.

During the construction phase managers aim to complete the project within constraints of budget and time as encoded in the “As-Planned” schedule. However, in reality, circumstances seldom permit the “As-Built” schedule to be identical to the “As-Planned” schedule. Projects get derailed from the “As-Planned” implementation because of violations in resource and precedence constraints caused by unexpected events like labor strikes,

undelivered material and bad weather. Construction managers face the challenge of completing the project while constantly making critical decisions that satisfy the constraints encoded in the “As-Planned” schedule by reallocating resources, rescheduling activities and making time-cost trade offs. Hence, the manager’s job during the construction phase is akin to a planning problem.

Planning problems make use of domain structure to generate relevant plans. Unlike search based problem solvers which are dependent on a specific set of successor functions to affect the environment, planners have a greater degree of autonomy and can create plans which are sensitive to context specific information. Specifically, during the construction phase, managers are responsible for maintaining constraint satisfaction by taking corrective measures and dynamically updating the plan based on context specific knowledge of the present and anticipated futures of the environment.

The CM domain can thus be abstracted to a CSP during the pre-planning stage and a planning problem during the execution stage. Thus the process of developing the GPF reduces to developing a framework that can expressively represent construction information and reason about the same using constraint satisfaction and planning techniques. In the next chapter I have developed a “language” that can be used to expressively represent and reason about construction information. The reasoning processes are driven by autonomous agents which have been dealt with in detail in chapter 5.

This most important contribution of this dissertation is the development of a general purpose framework that has its foundations in an expressive representation scheme within a framework of autonomous agents that are can reason at a level of abstraction applicable to a diverse range of scenarios in the construction management domain. This lends extensibility to the framework and allows it to be used for simulating diverse construction processes.

3.3 Summary

In summary, this chapter provides the conceptual foundation for this dissertation. In the first part I have discussed the process, product and information models that help us to understand the functioning of situational simulations. In the second part I have laid the

conceptual foundations of a general purpose framework that brings together the requirements of the product and process models and provides a platform to simulate a diverse range of construction processes and scenarios.

This chapter also develops the conceptual understanding that the CM domain can be abstracted to a planning problem during the implementation phase and a constraint satisfaction problem during the pre-construction phase. It involves satisfaction of resource and precedence constraints, and reasoning processes, which govern actions and events in the construction environment.

This sets the scene for chapter 4 in which I develop the representation scheme that can be used to expressively represent and reason about CM information. Chapter 5 completes the development of the general purpose multi-agent framework the conceptual foundations for which have been developed in this chapter.

Chapter 4

REPRESENTATION AND REASONING: THE LOGIC OF TIME

4.1 *Time*

It can be assumed that within the bounds of human perception there is consensus that time is always in passage and indeed always moves in the forward direction. Most importantly the passage of time is common to all experiences (of course, this discourse is limited to non-relativistic experiences only). Indeed, an agreement on a temporal metric provides a common canvas for agreement and a language for commitment across a wide range of experiences. For example if two parties can agree on the length of an unit of time (a second) and define a standard reference to calibrate the passage of time (a calendar) then they can agree on the start date and end date of a commitment. The interval in between can be broken down into multiple sub-intervals each of which can further define sub-parts of the commitment.

Construction contracts, the resource loaded schedule and the budget are really resource and temporal commitments. Construction projects happen within intervals of time that are easily defined and always closed. Hence, a temporal representation can indeed be useful and expressive. The interval defined by the duration of the entire project serves as the parent interval of all events in the project and is finitely bounded. There may be alterations in the completion date to express delay. All activities and events can be defined as sub-intervals within the project.

Also, as time passes the status of a commitment (complete, partially complete, etc) needs to be updated to reflect the impacts of events that can rapidly change the situation at hand. A temporal representation can be used to express information about events and changes in the status of activities by appropriately defining entities and commitments, assigning them variable characteristics and monitoring and registering all variations in status. The abil-

ity of the simulation to monitor and register all changes in properties and infer consistent conclusions about events and their impacts presumes domain knowledge and autonomous reasoning. This chapter develops a representation and reasoning method that allows software agents in the simulation to access domain knowledge and reason about activities and events.

For example, events like a period of snowy weather can be defined by an interval that spans the period over which the impacts of the event effect the construction site. Activities impacted by a weather event will show changes in related properties. For example, the *productivity* variable associated with all activity intervals, that have the *outdoor* flag set to *true*, and overlap with the interval of snowy weather, will be changed to a reflect a reduction in productivity due to inclement weather. Similarly by changing the properties of variables associated with activities across intervals of validity of different events, fairly complex information can be expressed and consistently reasoned about using the common language of time.

In developing a general purpose framework for situational simulations its imperative to develop an expressive “language” that allows us to represent and reason about a diverse set of construction scenarios. The universal nature of time and the important role it plays in the execution of construction projects provides us with a starting point. In this chapter I have used semantics of temporal intervals to represent and reason about construction information.

4.2 Background

As surveyed in chapter 2, the dominant paradigm for construction management simulations is Activity Cycle Diagrams. It has provided the basis for CYCLONE (Halpin 1970) and more recent general purpose simulations like STROBOSCOPE and EZSTROBE (Martinez and Ioannou 1999, Martinez 2001), all of which have been successfully used to simulate construction operations. Such simulation systems use a time point representation to express information about events. Each event is represented by a point in time and the simulated timeline is a progress from one discrete time point event to the next.

This kind of a representation is unsuitable for representing multiple over-lapping events and activities. For example, if both activity A and activity B are represented by a single time point, then it becomes difficult to represent the precedence relationship: *Activity B starts after activity A is 50% complete*. In a later section in this chapter I have analytically explained why a time point representation is unsuitable. The suggestion is to move on to an interval representation of time to more appropriately represent such relationships and simulate the time line as a series of contiguous discrete time points some/all of which can bound intervals that can overlap and provide greater expressive power.

It should be very clearly understood that the contention here is not with a time point representation. Such a representation is very useful in simulating construction operations, like earth-moving or tunneling, where the focus is on simulating the sequence of activities and events of particular operations, for estimating model parameters. In situational simulations the focus is instead on simulating processes as they rapidly unfold in an interactive environment. It is important to easily represent and reason about multiple overlapping events.

It should also be very clearly understood that all representations are equivalent and the ACD paradigm can be used to develop situational simulations. The suggestion is that in order to do so, the modifications necessary would eventually lead to an interval representation of time. Hence in this chapter I have developed a suitable way to represent and reason about construction information using the semantics of interval temporal logic.

4.3 Representation

This section uses the language of First Order Logic to formally represent information about situational simulations for the construction domain. First order logic can be used to represent domains which are composed of objects which have individual identities and properties that distinguishes them from other objects (Russell & Norvig, 2002). The objects are also related to each other by relations and functions. Knowledge representation and reasoning is widely studied using first order logic.

To start with, the situational simulation environment is formally defined and character-

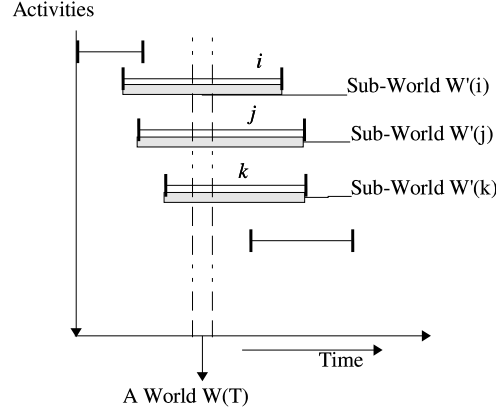


Figure 4.1: Worlds and Sub-Worlds in the Activity-Time Plane

ized. The second part of this section looks at notions of an interval representation of time. Based on definitions of the environment and axioms of time, actions and events are defined. The section concludes with a justification for using an interval representation of time in representing actions and events in the situational simulation.

4.3.1 Definitions

Time-points and Time Intervals

Time-points are always represented by positive integers, and signify specific points in the continuum of time. In the simulation it is defined as the smallest discrete interval of time within the scope of the simulation and is referred to as the *discrete granularity*(ϕ).

A series of consecutive time points make up a time interval. Every time interval is associated with an ordered pair of integers. The integers define the start and end time-points of the time interval. Hence, a time interval i which stretches from the third day to the fifth day of the simulation, will map onto the ordered pair $\{3, 5\}$ where the discrete granularity of the simulation is a day. When a time interval represents an activity, the time-points represent the early start and early finish points for the activity.

$$\forall i \cdot \exists J, K \cdot J < K. \quad (4.1)$$

The interval duration is given by $K - J + 1$

$$i : \{J, K\}; i.start = J, i.end = K$$

The convention followed in this paper is that all time points are represented in the upper case, while all time intervals are represented in the lower case.

Environment

The environment sets the scene for the situational simulation. It is the participant's perception of the simulated construction project. It is interactive, temporally dynamic and virtual in nature. The environment emulates activities, events and processes pertaining to construction projects. It is characterized by a set of entities, each of which describes a unique aspect of the environment. For example, weather and production rate are entities in the environment.

Activity

An activity is an emulation of a real life construction operation and is represented by an interval which has the same length as its' duration. Activities take time from start to completion. Activity intervals are dynamic in nature, as activity durations may change during the construction process.

A two-dimensional time-activity plane, Figure (4.1), is helpful in visualizing how activities span time. It is similar to the Gantt Chart representation of the activity schedule. The time-activity plane has simulation time represented on the x-axis and the activity intervals on the y-axis. The y-axis is discrete and each unit represents an activity. On the time axis, each unit represents the discrete granularity of the simulation which is the smallest unit of time in the simulation and is represented by a time point.

Variables

A Variable is a symbolic representation of an entity. They are discrete in nature and can only take up values from the discrete finite domain $[s_1, s_2, s_3]$ which is the set of all possible

attributes of the entity described by the variable. Every entity has an unique set of attributes. Hence, every variable maps on to an unique domain. A set of variables completely characterizes the environment. Precedence and resource constraints are relationships between the variables and determine the values taken up by the variables. The environment (E) being a composition of the entities is expressed as a set of the variables defining its entities.

$$E = [v_1, v_2, v_3, \dots v_n];$$

$$\text{where Domain of } v_i = [s_1, s_2, s_3]$$

In the above equations the symbol v_i is a variable which describes an unique entity v_i in the environment. There is a closure on the set of variables in the environment. Hence as the simulation progresses, the set of variables may take up different attributes from the domain, but new variables may not be added to the set.

A combination of n such variables completely defines the simulation environment, as expressed in the second equation. As the environment changes, variables take up different values from their domains to reflect the change. This information is expressed through boolean predicates, which state the truth regarding time intervals over which variables hold particular values. The truth that the entity represented by the variable v_i has the attribute value s_1 over the time interval t is represented by the predicate:

$$v_i(s_1, t)$$

For example, the entity Weather is represented by the variable *weather* which can take values from the domain $[sunny, rainy, snowy]$. The predicate $weather(sunny, t)$ signifies that the weather in the environment will hold sunny over the time interval t .

Reasoning in the environment uses conditions which are conjunctive clauses of the predicates. Hence, the condition representing snowy weather and null productivity over the interval t is represented by the sentence:

$$weather(snowy, t) \wedge prod(null, t)$$

Variables are homogeneous over the time intervals in which they hold. Unless otherwise

altered, it may be assumed in the above example that the weather will hold snowy for the entire interval t .

Variable Classification

Just as entities in the environment are represented by variables, similarly activities are represented by variables too. Often these variables are specific to the activities that they describe. This calls for a classification of variables in the environment. All variables which describe entities specific to particular activities are *Activity Specific Variables*; variables which describe entities that are relevant to the whole time-activity plane are *Global Variables*. For example, weather is a global variable since its effects can be felt across activities. However, the availability of a particular material or special equipment may be specific to a particular activity. The unavailability of earth-moving equipment will not effect a concrete pouring operation, even though it may delay a concurrent earth moving operation.

It is possible for more than one concurrent activity to have instances of the same variable with differing values at the same point of time. For example, the labor efficiency for an activity might be 100%, while that of a concurrent activity may be 80%. Thus, the activity specific variable representing labor efficiency can take up two different values in two different contexts at the same time. We define *contexts* as dynamic time intervals identical to the activity intervals. For all intents and purposes, the contexts are set by activities. Activity specific variables are always in context to the activity which they define and at any point of time there can be multiple instances of the same activity specific variable, each in context to a different activity. However, within the same context no variable can have multiple instances, as that would mean an entity having more than one attribute at the same time.

This understanding helps us formally define *Activity Specific Variables* as variables which can have multiple instances across contexts at the same time, and *Global Variables* as variables which can only have a single instance across all contexts at every point of time.

World

A world is a snap shot of the environment at a specific time point T , as shown in Figure (4.1). The time point is the granularity of the simulation and is usually represented as a day. Progress from day to day in the real world translates to progress from time point to time point in the simulation. The simulation thus moves from one world to the next. Symbolically the world at the time point T is denoted by $W(T)$ which is given by the set of all variables which defines the environment at that time point.

$$W(T) = E|_T$$

Sub-World

The set of all variables in the environment which belong to the same context is defined as a sub-world. The sub-world is therefore a subset of the world where all the variables are specific to a particular activity which defines the context, as shown in Figure (4.1). For the context defined by the activity interval i the sub-world at the time point T is the set of m variables which describe entities in the activity and is denoted by:

$$W'(i) = \{v_{i1}, v_{i2}, \dots v_{im}\} \in E|_T$$

At any time point T if the ongoing activity intervals defining the concurrent contexts are i, j, k then it can be said that the set of environment variables is given by:

$$W(T) = [W'(i) \cap W'(j) \cap W'(k)] + W'(\mathcal{G})$$

and $\mathcal{G}$ is an uniquely defined pseudo context for global variables.

$$W'(\mathcal{G}) = \text{Set_of_Global_Variables}$$

4.3.2 Axioms Representing Time

This section investigates the interval representation of time as proposed by Allen and Ferguson (1994). A review of their axioms has not been reproduced here due to limitations of space. On the basis of the axiomatic relations *Meets*, *Before* and *After* defined on intervals by Allen and Ferguson, precedence relations between intervals have been axiomatized

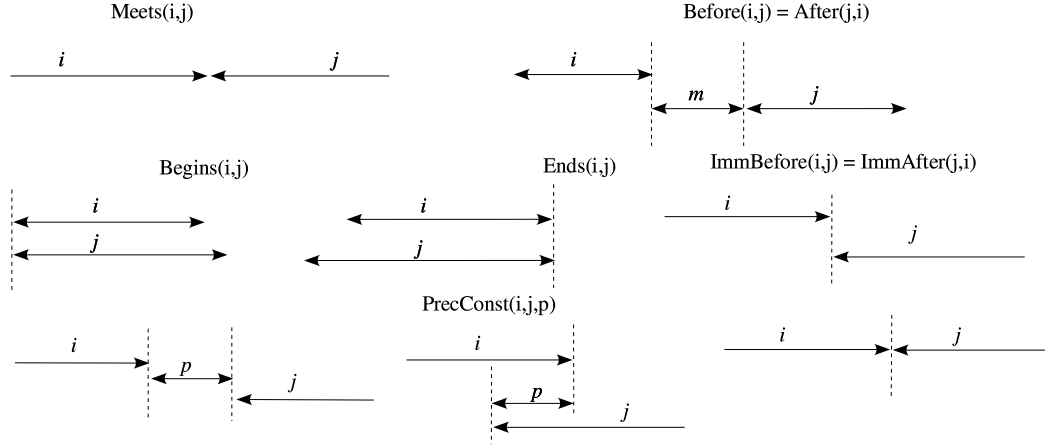


Figure 4.2: Axioms defined on Intervals

to aid representation in the situational simulation domain. A diagrammatic representation of the axiomatized time intervals can be seen in Figure (4.3.2). The precedence relations developed include consequence, coincidence, precedence and concurrence. A brief review of the relations *Meets()*, *Before()* and *After()* has been provided below.

Meets: Two time intervals *i* and *j* are said to meet if and only if *i* precedes *j*, and yet there is no time between *i* and *j* and *i* and *j* do not overlap. In terms of discrete time points this can be axiomatized as:

$$\begin{aligned} \forall i, j \cdot \exists I, J, K, L \cdot (i = \{I, J\}) \wedge (j = \{K, L\}) \\ \wedge (J = K - 1) \Rightarrow Meets(i, j) \equiv i : j. \end{aligned} \quad (4.2)$$

It can be proved from this axiom that a time interval cannot meet itself, excepting when $\{I, J\}$ coincides with $\{K, L\}$, in which case the intervals *i* and *j* collapse and become time points. This rules out possibilities of circular models of time.

Before: A truth value for *Before(i, j)*, implies that interval *i* starts *before* interval *j* and can be expressed as:

$$\begin{aligned} Before(i, j) \equiv \exists m \cdot Meets(i, m) \wedge Meets(m, j) \\ \equiv i \prec j. \end{aligned} \quad (4.3)$$

The inverse of *Before* is *After*, which is defined as:

$$\begin{aligned} \text{After}(i, j) &\equiv \exists m \cdot \text{Meets}(j, m) \wedge \text{Meets}(m, i) \\ &\equiv i \succ j. \end{aligned} \tag{4.4}$$

Precedence constraints between time intervals representing activities, actions and events as described in this paper will be based on the definitions of the following axioms.

Consequence Axiom 1 *An interval i is said to be immediately before another interval j if i precedes j and meets it. Inversely, the interval j is said to be immediately after the interval i*

$$\begin{aligned} \forall i, j \cdot \text{ImmBefore}(i, j) &\Rightarrow (i \prec j) \wedge (i : j) \\ &\equiv \text{ImmAfter}(j, i) \Rightarrow (j \succ i) \wedge (j : i). \end{aligned} \tag{4.5}$$

Coincidence Axiom 2 *Intervals i and j are said to have a coincident point of beginning if there exists a time interval t which comes immediately before both i and j . Similarly, if there is a time interval which comes immediately after two time intervals i and j then they are said to have a coincident point of ending.*

$$\begin{aligned} \forall i, j \cdot \text{Begins}(i, j) &\Rightarrow \exists t \cdot \text{ImmBefore}(t, i) \\ &\quad \wedge \text{ImmBefore}(t, j). \end{aligned} \tag{4.6}$$

$$\begin{aligned} \forall i, j \cdot \text{Ends}(i, j) &\Rightarrow \exists t \cdot \text{ImmAfter}(t, i) \\ &\quad \wedge \text{ImmAfter}(t, j). \end{aligned} \tag{4.7}$$

Precedence Axiom 3 *Any two time intervals i and j will always have a finish to start precedence relationship defined by the time interval p .*

Combining (4.5,4.6 & 4.7):

$$\begin{aligned}
& \forall i, j, p \cdot PrecConst(i, j, p) \Rightarrow \\
& (ImmBefore(i, p) \wedge ImmAfter(j, p)) \\
& \vee (Begins(j, p) \wedge Ends(i, p)). \\
& \forall i, j \cdot PrecConst(i, j, 0) \Rightarrow i \prec j
\end{aligned} \tag{4.8}$$

Concurrency Axiom 4 *Given that $\wp_{now}$ is the discrete granularity which represents the current time in the simulation, all time intervals which span across it are said to be concurrent.*

$$\forall t ConCurrent(t) \Rightarrow \wp_{now} \subset t \tag{4.9}$$

4.3.3 Actions, Events and Situations in Situational Simulations

Temporal logic has been used in this section to expressively represent actions, events and situations.

Actions are triggers which create events and situations. Some outcomes of actions are bad weather, material delivery, reallocation of resources, labor strikes etc. In the simulation environment actions occur instantaneously in time, at the starting time point of the interval of the event they trigger.

Events reflect the effects of real life episodes involving resource and precedence constraint violations within the construction management domain. Events are of two types: Independent Events and Dependent Events. Independent events are generated in the situational simulation on a stochastic basis without being triggered by any participant interaction legacy. They are triggered by actions taken by the agent. For example a snow event is an independent event and based on the geographical location of the simulated project the number of snow events created will reflect real weather records (Buffalo, NY during January has a higher probability of getting a snow even than Seattle, WA). Dependent events on the other hand are triggered by actions taken in the environment by participants or due

to an existing feedback from previous participant interactions. Dependent events and their impacts, need to be consistently detected and inferred, are at the focus of this chapter.

All events span time intervals. Each event is associated with three sets of variables: the *Pre-Condition* set, the *Event Condition* set and the *Consequence* set and is triggered by a unique action. Member variables of the event condition and pre-condition sets are identical. However, the variables in the two sets must have different attribute values. The change in attribute values is triggered by actions. The event is reflected by the event condition set of variables. Future effects of the event, are captured in the consequence set, which is a set of assertions about values of variables in the future. The compound predicates $Pre_Cond(t)$, $Event_Cond(t)$, $Consequence(t)$ are conjunctive clauses of simple predicates which assert attributes of the member variables over the time interval t during which the conditions specified by the pre-condition, event condition and consequence sets hold, respectively. They are also homogeneous over the time intervals in which they hold.

For example, in the event of a labor strike that lasts for the time interval t , productivity (represented by the variable $prod$) for all activities is reduced to 0 due to a 0% availability of labor (represented by the variable $labor$). In this case the event condition set is $\{labor(null, t), prod(null, t)\}$ across all activity contexts. The pre-condition set is $\{labor(100\%, t'), prod(100\%, t')\}$ where the predicate $Meets(t', t)$ is true. This event represents a violation in a resource constraint. The action to create the labor strike event can only be taken if the pre-condition set is fulfilled in the immediately previous time point. This is expressed as:

$$\begin{aligned} \forall t \cdot Act_Labor_Strike(t.start) \Rightarrow \\ \exists t' \cdot labor(100\%, t') \wedge prod(100\%, t') \\ \wedge Event(Labor_Strike, t) \wedge ImmBefore(t', t) \end{aligned}$$

The fact that the pre-condition set is a necessary condition for an action to occur and that every action triggers an event is used to axiomatize the definition of an action as:

$$\begin{aligned} \forall t \cdot Action(t.start) \Rightarrow \exists e, t' \cdot Pre_Cond(t') \\ \wedge Event(e, t) \wedge ImmBefore(t', t) \end{aligned} \tag{4.10}$$

The converse of the above axiom does not hold, however, if the pre-condition set holds, then it may be concluded that the action may probably be taken. This is axiomatized as:

Axiom 5 *A specific action can be predicted to probably occur at $T + 1$ if for all contexts concurrent at both T and $T + 1$ there exists at least one context i such that $W'(i)$ at T has a subset of variables which satisfy the pre-condition set of the action.*

The pre-condition set could have also included other non-null values of productivity and labor, for the logical precondition of a labor strike to be fulfilled. However, in order to avoid disjunctive reasoning in the present level of research, the precondition set is being limited. This limitation will be dealt with in future.

Consequences of an event are assertions about the future that are direct outcomes of the event. The consequence set is a set of variables that assert attributes of entities in a future time interval, which is directly affected by the occurrence of the event. For example, in the case of the event *Labor Strike*, the productivity of all activities may take a while to recover, and continue to be at 50% for the time interval t'' immediately after the *Labor Strike* event is over. The time intervals t and t'' are tied by the precedence constraint predicate. Hence, the labor strike event may be defined in first order predicate logic as:

$$\begin{aligned} \forall t \cdot Event(Labor_Strike, t) \Rightarrow \\ \exists t' \cdot labor(null, t) \wedge prod(null, t) \\ \wedge prod(0.5, t'') \wedge PrecConst(t, t'', 0) \end{aligned}$$

This allows us to generalize the definition of the event as:

$$\begin{aligned} \forall e, t \cdot Event(e, t) \Rightarrow \exists t', p \cdot Event_Cond(t) \\ \wedge Consequence(t') \wedge PrecConst(t, t', p) \end{aligned} \quad (4.11)$$

Information about actions and events stored in the knowledge base is based on event and action definitions discussed here.

If the pre-condition and event condition sets of variables for an event belong to the same context, then the event is specific to a particular context and is effectively an *activity or context dependent event*. However, if the pre-condition and event condition sets of variables

are Global variables only, then the event is a *global or independent event*. For example, because weather is a global variable, an event related to it will be a global event. By definition variables in the event condition and pre-condition sets have to be either global or context specific. They cannot be mixed. The consequence set may, in both cases, still have variables from across activity contexts.

Situations are events which result in immediate constraint violations and demand immediate user intervention to carry on with the simulation. All events may not create immediate constraint violations, and hence may not create situations.

Types of Events

The second function of the agent in the system is to generate events. As is obvious from the previous section, the possible actions forecast for a particular day provides the set of actions from which the agent chooses some actions based on a stochastic model to generate the corresponding events. The stochastic model is Bayesian in nature. The probability of an event occurring is conditional on circumstances and also to the frequency of occurrence of that event. This model is to be developed in greater detail in future. Currently the simulation runs a very naive model which generates events based on simple probabilistic inputs. For example the probabilistic input for a snow event in Seattle, WA is derived from local weather records.

4.3.4 Participant Interactions and Agent Actions

Participants interact with the environment by changing values of the variables that represent specific entities. By changing the contexts or resource variables, participants can reallocate resources between activities. Participants can interact only with variables within their jurisdiction. Global variables are beyond their control (e.g., the participant cannot change the weather). Access is limited to context specific variables which describe the resource requirements of the activities.

The agent has greater access to variables than the participant does. It can access all global variables and context specific variables. However, in taking actions that affect the

environment, the agent is not allowed to change eternal truths about the environment (e.g., the agent may not change the attribute of an excavation activity from outdoor to indoor).

All agent actions are essentially operators which transform a set of pre-conditions to a set of event conditions. Because participant interactions are limited to resource reallocation and replacement within the environment, they cannot directly create events in the environment. However, reallocation of resources might result in resource constraint violations which, when perceived by the agent, will indirectly create events. Hence participant interactions can only create the *Pre_Cond()* set, but only agent actions can transform a *Pre_Cond()* set to a *Post_Cond()* set.

4.3.5 Interval vs. Time Point Representation

The axioms and definitions described so far have been based on a representation which uses time intervals rather than time points. Time intervals can be represented as a series of time points and the simulation itself traverses from time point to time points. This section uses the constructs of finite state machines to justify the use of intervals over time points.

The situational simulation can be looked upon as a Finite State Machine (FSM) which is defined as a model of computation consisting of a set of states, a start state, an input alphabet, and a transition function that maps input symbols and current states to successive states. It can be described by the tuple:

$$\mathcal{M} = \langle \mathcal{S}, \mathcal{I}, \mathcal{R}, \mathcal{L} \rangle$$

where $\mathcal{S}$ is a finite set of states, $\mathcal{I} \subseteq \mathcal{S}$ is the set of initial states, and $\mathcal{R} \subseteq \mathcal{S} \times \mathcal{S}$ is the transition relation, specifying the possible transitions from state to state. $\mathcal{L}$ is a function that labels states with the atomic propositions from a given language. Such a tuple is called a Kripke structure (Kripke, 1962).

States in the situational simulation environment are expressed using sets of variables. The two sets of variables defined so far are the world set $W(T)$, which characterizes the environment at each time point, and the sub-world set $W'(i)$ which characterizes the environment, in terms of intervals, over activity contexts. Closure on the set of variables and the attribute domains, limits the number of possible worlds and sub-worlds to a finite number.

The set of all worlds is denoted by $\mathcal{W}$. If there are n variables, each of which can take up at most m attributes, then the cardinality of the set $\mathcal{W}$ is at most n^m . In reality the number is lower, because there will be many worlds which are mathematically accountable but absurd in reality.

We can also define the set of all possible sub-worlds specific to a particular activity context i . This is denoted by $\mathcal{W}_i$. This set does not completely define the activity environment, because it leaves out the global variables. However, if augmented with the set of global variables, it results in a set of states that completely defines the context. This is denoted by $\mathcal{W}_i^+$.

$$W^+(i) = W'(i) + W(\mathcal{G}); \quad W'(i) \in \mathcal{W}_i$$

$$\mathcal{W}_i^+ = \{W^+(i)\};$$

$W^+(i)$ is the augmented sub-world. $\mathcal{W}$ and $\mathcal{W}_i^+$ are equivalent to $\mathcal{S}$ in the Kripke structure. $W(T)$ ($W(T) \subseteq \mathcal{W}$) corresponds to an initial state defined on a time point. Similarly, $W^+(i)$ is a an initial state defined on the interval i .

An action in the environment creates transitions in state. Differences between attributes of variables, in the pre-condition and event condition sets of an event triggered by an action, indicate a transition in state. The critical question is, do the actions create changes in states defined in $\mathcal{W}$ or in $\mathcal{W}_i^+$?

Actions creating dependent events operate on variables specific to the context specific sub-world. Actions creating independent events operate on the set $W(\mathcal{G})$. Since the set of variables in the sub-worlds have been augmented with the global variables, independent events are essentially multiple instances of the same action across all contexts. Hence, actions creating context dependent and independent events can create state transitions in $\mathcal{W}_i^+$. This representation allows multiple state changes to occur in the environment, each in a different context, at any point of time. In other words, an interval representation allows simultaneous context dependent events across different activity contexts without breaking the semantic structure.

It is very difficult to define unique state change actions as operators on $\mathcal{W}$, without breaking the semantic structure. Only actions triggering independent events can be ex-

pressed as state transitions. Simultaneous context specific dependent events cannot be expressed by this representation within the defined action-event semantics. Hence, state transitions defined by actions are best suited for the set of states $\mathcal{W}_i^+$ that uses an interval representation of time.

The Kripke Structure that can be defined for the context i in the simulation environment is:

$$\mathcal{M} = \langle \mathcal{W}_i^+, \mathcal{I}, \mathcal{R}, \mathcal{L} \rangle$$

where,

$$\mathcal{I} = W^+(i); \mathcal{R} \subseteq \mathcal{W}_i^+ \times \mathcal{W}_i^+$$

$$\mathcal{L} \in Set_of_all_Events$$

In effect it is an FSM for each context allowing simultaneous activities and events; actions serving the purpose of state transition operators and events providing a language to express changes in state. This is the rationale behind using an interval representation of time.

4.4 Agent Reasoning

4.4.1 Overnight Inference

The agent comes into play between every consecutive discrete time point in the simulation, in other words, between any two consecutive 'days' during the simulation of the project. Hence, the name 'overnight inference'. The agent infers after the time point T and before the time point $(T + 1)$. It has complete access to information in the environment encoded in terms of sets of variables $W(T)$ and $W(T - 1)$.

Since sub-worlds cannot change state during the inference process, the agent's inference environment is static. It is also discrete, since there are a finite number of possible states. The environment is also non-episodic, because the agent needs information from $W(T)$ and $W(T - 1)$. Finally, from the agent's point of view, the environment is non-deterministic as it cannot predict all user interactions or event generator decisions in the immediate future.

The Reasoning Mechanism

It may be noted here that for every event, the set of event conditions may be referred to as the post-condition set for the action triggering the event. The pre-condition set of the action and event are identical. The following assumptions of closure can also be made:

- **Event Closure:** An occurrence of an event implies that an action occurred. This is expressed as:

$$\forall e, t \cdot Event(e, t) \Rightarrow \exists Action(t.start) \quad (4.12)$$

- **Attribute Closure:** This reflects a closure on the attributes and variables and implies that any change in attributes of variables implies that an event has occurred. This is expressed as:

$$\begin{aligned} \forall t, t' \cdot Pre_Cond(t') \wedge Post_Cond(t) \\ \wedge Meets(t', t) \Rightarrow \exists e \cdot Event(e, t) \end{aligned} \quad (4.13)$$

On the basis of the definition of an action (4.10), definition of an event (4.11), variable unification (Variables unify when they both describe the same entity and take up the same attribute value, two sets of variables unify when there is a one-to-one unification between the members of the sets) and the assumptions of closure (4.12 & 4.13), the following theorem can be stated:

Theorem 1 *A specific action can be inferred to have occurred in between time points $(T-1)$ and T if for all contexts concurrent at both $(T-1)$ and T there exists at least one context i such that $W'(i)$ at $(T-1)$ has a subset of variables which unify with the pre-condition set of the action and $W'(i)$ at T has a subset of variables which unify with the post-condition set of the same action.*

Given a context i for which there exists sets S and S' which unify with the pre-condition and post-conditions sets of the same Action at $(T-1)$ and T respectively, it is required to prove that there was an $Action(T)$.

Proof: It is known that $S \subset W'(i)$ at $(T - 1)$ and $S' \subset W'(i)$ at T . By definition, the member variables of S and S' are identical but have different attribute values. Let us assume that S and S' are homogeneous over time intervals m and n . A change in the values of variables occurs at $(T - 1)$ and at T . Therefore, $m.end = (T - 1)$ and $n.start = T$. Hence by (4.2) it can be said $Meets(m, n)$. Now by (4.13)

$$S(m) \wedge S'(n) \wedge Meets(m, n) \Rightarrow Event(e, n)$$

by (4.12)

$$Event(e, n) \Rightarrow Action(n.start)$$

Hence, there was an $Action(T)$.

Corollary 1 *For every Action taken there is a set of assertions which predict the future of the simulation environment.*

This is proved because of the fact that every action implies an event, which, in turn, implies a consequence set (4.10 & 4.11). Prediction by the agent for possible future actions follows Axiom 2.3.1.

4.4.2 Implementation and Correctness

A theorem prover was implemented for the stated theorem using the Forward Chaining algorithm (Russell & Norvig, 2002). Given the perceptions of the world in terms of $W(T)$ and $W(T - 1)$, the agent classifies the variables into sub-worlds specific to contexts that are concurrent in both (T) and $(T - 1)$. It then isolates all contexts in which variables have registered changes in attribute values. Then for each of these contexts it unifies the variables with action and event definitions in the knowledge base (KB). All inferences are added as facts to the Assertion set, thus allowing reasoning in future worlds to be based on perceptions and outcomes of the past. Figure (4.3) illustrates the algorithm.

All agent inferencing and reasoning is done on the basis of assertions about actions and events in a knowledge base of facts. The inference mechanism is sound and complete within definitions of actions and events defined in the knowledge base. Hence, if an action is defined in the knowledge base, then it will always be predicted everytime its pre-condition

```

Agent (Assertions, KB)
{ Perceive  $W(T)$ ,  $W(T-1)$  from Assertions
  {For each context  $i$  concurrent in  $W(T)$  and  $W(T-1)$ 
    {if  $W(i)$  at  $T \neq W(i)$  at  $(T-1)$ 
      {For each event  $e$  in the KB
        {Check for unification of  $Pre\_Cond$ 
          and  $Post\_Cond$  set of  $e$  with  $W(i)$ ;
          Infer actions taken in  $T$ ;
          Infer Consequences of actions in  $T$ ;
          Predict possible actions in  $(T+1)$ ;
          Add inferences to set of Assertions;
        } }
      } }
  }
}

```

Figure 4.3: Agent Algorithm

set is fulfilled. Also, an event defined in the knowledge base will always be inferred if it has occurred. However, if there is a combination of variable attributes which the participant can change but which are not documented in the knowledge base, then they will simply go unnoticed. Hence, an efficient implementation of this agent lies in developing an accurate knowledge base of facts, and creating appropriate closures on participant interaction.

4.5 Summary

In this chapter I have developed a scheme to represent construction information using an interval representation of time. Given the importance of autonomous reasoning in a situational simulation environment and the need for agency that is sympathetic to user interaction and capable of consistently generating events using construction domain specific information, I have also developed a way to reason about construction events.

The representation and reasoning techniques developed in this chapter, besides being the first step toward the development of a general purpose framework, also provides a stepping stone towards developing an ontology that can be used to represent and share construction information seamlessly across different construction and project management software.

Chapter 5

THE MATHEMATICAL MODEL

In the last chapter I have explored ways of representing construction information and reasoning about it using construction management domain specific information stored in a knowledge base. The domain specific information is stored in the form of high-level relationships between entities in the environment. For example, the indisputable relationships between the impact of bad weather on productivity on site and its long term impact on schedule and budget. While such relationships help reasoning in the environment, they are incapable of expressing the exact decrease in productivity or the exact nature of the delay.

A decision maker needs to have access to both qualitative and quantitative information in an environment to efficiently monitor progress of a construction project and test the validity of their decisions. Hence the need for a mathematical model that works in tandem with the reasoning agent and influences its reasoning. For example, when the reasoning agent reduces productivity in a particular activity by 50% the model gets updated to reflect a delay in the activity by the same number of days as the remaining duration. If such a delay over-runs the available float for the activity, the project gets rescheduled to reflect the delay and its impacts on the budget and space on the construction site.

The emerging picture is the need for yet another agency in the simulation environment. One that complements the logical reasoning agent by communicating with it and consistently updating and computing the quantitative variables in the simulation environment. At the basis of this agency is a mathematical model that has been discussed in my MS thesis (Mukherjee 2000) and published subsequently (Rojas and Mukherjee 2003). I have discussed it in section 5.1.

This chapter focuses on the relational nature of the mathematical model and how it allows the mathematical agent to compute and update production rates, costs and durations in the simulation environment, while calculating the differences between “As-Planned” and

“As-Built” project performance.

5.1 Mathematical Agent Reasoning: Unite and Compute

The mathematical agent reasons about the sensitivities of the simulated environment to its inter-related component aspects [*Total Direct Cost(TDC)*, *Total Indirect Cost(TIC)*, *Remaining Duration(RD)*, *Production Rate(PR)*] due to dependent and independent events which create constraint violations. Such events have the ability to deflect the progress of a project from its planned path. For instance, a delayed material delivery can delay a particular activity and all dependent activities and, in turn affect indirect and direct costs and the remaining duration of the project.

The mathematical agent maintains a direct quantitative comparison between the “As-Planned” and “As-Built” values of each of the above quantities during the execution phase of the project. In a manner of speaking, it provides an accurate picture of the *stability* of the simulated system. Delays in the “As-Planned” schedule indicate that there have been constraint violations in the project implementation and are therefore a pointer to instability in the system. The mathematical agent provides the participant to get a systemic By taking corrective measures to satisfy constraints, the decision-maker aims at maintaining stability in the system.

Rojas and Mukherjee, (2003) explain the mathematical model which defines the relationships between direct cost, indirect cost, remaining duration and production rate during the construction process. The equations are time dependent. In the simulation environment each of the equations are computed by programs. Each program is denoted by a function. The most basic parameters taken by the functions are the independent variables (defined over continuous domains), which describe the availability and quantities of materials at any point of time during the simulation. Given the unit costs of materials, the total direct cost at the time point T is given by

$$TDC[T] = \sum_i C_{i,T} \quad (5.1)$$

$$TDC^P[T] = \sum_i C_{i,T}^P, \text{ where } \forall i \cdot T \subset i$$

$TDC^P[T]$ and $TDC[T]$ are values of the total direct cost across all context intervals as calculated from the 'As-Planned' database and the total direct cost across all context intervals as calculated from the independent variables generated from the simulation respectively. $C_{i,T}$ indicates the total cost of material, equipment and labor used in the context interval (activity) i during the time point T . The superscripted cost $C_{i,T}^P$ denotes the "As-Planned" cost. Based on the mathematical model, the relationships between Total Cost(TC), Total Indirect Cost(TIC), Remaining Duration(RD) and Production Rate(PR) (the dependent/derived variables in the mathematical model) can be functionally expressed.

We have used a denotational way of expressing the inter-related operations. The expressions of the form:

$$Y[M] = x_{-} * (p_{*}, Y[M] \dots) \text{ where } M = \{[i, T], [i], [T], \perp_0\} \text{ and } x = f, F \quad (5.2)$$

will denote a program x which takes in independent and derived parameters (p_{*}) and returns a value $Y[M]$. Y is a derived variable, and $[M]$ denotes the aspect of Y that the value describes. That is, Y can be described across contexts at a particular time point or only specific to a time activity element $[i, T]$. M can take up a value of $\perp_0$ only when it denotes a value which has been derived from static planned data. $Y[M]$ can in turn be fed as a parameter to some other function as a derived parameter. In keeping with the above semantics the following equations can be written.

$$TC[T] = TIC[T] + TDC[T] \quad (5.3)$$

$$TIC[T] = f_1(TIC[T - 1], RD[T]) \quad (5.4)$$

$$RD[T] = f_2(RD'[i, T]) \quad (5.5)$$

$$RD'[i, T] = f_3(PR[i, T]) \quad (5.6)$$

$$PR[i, T] = f_4(PR_0, \eta) \text{ where, } prod(\eta, i) \quad (5.7)$$

$$PR_0 = TDC^P[i] = C_i^P, (constant) \quad (5.8)$$

where $TDC^P[i]$ is the total planned direct cost for the context interval i . $RD'[i, T]$ gives the remaining duration for the activity represented by the context interval i . The function f_2 represents a program which returns the remaining duration of the project at time T , $RD(T)$ given the remaining durations of the concurrent activities. The set of equations can also be used to calculate the same parameters for the “As-Planned” implementation of the project.

In the above equations the values which can be considered as ‘raw data’ or the independent variables are the components of the cost variable, the resource requirement (“As-Planned”) and the actual resource usage/availability (“As-Built”) data. This information can be read off from $W(T)$ within the simulation environment in case of the actual resource usage/availability and from the “As-Planned” database in case of the planned resource allotment/requirement. The value of $prod(\eta, i)$, the productivity of workers during the context i , is a discrete environment variable which is read from $W'(i)$. The raw data computes to C which can be calculated across all contexts for a particular time point ($\sum_i C_{i,T}$) or across a particular context from the “As-Planned” database (C_i^P). The information from the “As-Planned” database is static and is used only as benchmark constants. PR_0 is a constant. So it can be said:

$$\sum_i C_{i,T} = F_1(W(T)) \quad (5.9)$$

$$\eta = F_2(W'(i)), \text{ therefore} \quad (5.10)$$

$$PR[i, T] = f_4(PR_0, \eta) = f_4(F_2(W'(i))) \text{ (absorbing the constants)} \quad (5.11)$$

where F denotes a program. Note that PR_0 is a constant. Thus the whole system can be reduced to:

$$TC[T] = F_1(W(T)) + TIC[T] \quad (5.12)$$

$$\text{or } TC[T] = F_1(W(T)) + f_1(TIC[T-1], f_2 \circ f_3 \circ f_4) \quad (5.13)$$

$$\text{or } TC[T] = F_1(W(T)) + f_1(TC[T-1] - F_1(W(T-1)), f_2 \circ f_3 \circ f_4(F_2(W'(i)))) \quad (5.14)$$

The symbol $\circ$ denotes inter-connections, (i.e. $f \circ g$ implies that the value returned by g is passed as a parameter to f). Equation (Eq. 5.14) is a systemic representation of the simulation. It provides a single relationship, which reflects the progress in the simulation system at any time T dependent on the state at $T-1$. Each of the quantities when calculated for both “As-Planned” and “As-Built” information will provide comparative trends, which can be used to detect instabilities in the system. The values for the former will be constants across all simulations of the same project, while the variations in the values of the “As-Built” will show the expertise of the participant.

The mathematical agent functions within the vocabulary of the functions defined above. The functions denoted in the lower case f are collectively represented by the $\otimes$ operator. They are programs which compute within the mathematical model. The functions denoted in the upper case F are collectively represented by the $\oplus$ operation. They are programs which unite the appropriate values to the appropriate variables in the mathematical model. The need for this arises since the same programs compute the “As-Planned” derived variables as well as the “As-Built” derived variables. While the data for the “As-Planned” calculations come from the “As-Planned” database, the “As-Built” independent variables come from the simulation environment.

5.2 Variable Synchronization

Chapter 3 focused on reasoning about variables that are discrete in nature and take up values from finite sets. The reasoning also involves variables such as production rates, direct costs, indirect costs and efficiency which take up % values from finite sets. For example, production rate can take up discrete values from the set $\{0\%, 25\%, 50\%, 75\%, 100\%\}$. However, in this chapter I have introduced the workings of a model that can calculate an exact value for production rate as a real number. Clearly, there is a need to map the continuous value of production rate as calculated by the mathematical agent to a discrete value that can be used by the logical agent to reason about the state of production rate of an activity.

The process of mapping the real values of continuous variables to discrete values is referred to as variable synchronization. Thus entities like production rate, direct cost, indirect

cost, total cost and remaining duration always have two variable avatars: one discrete and one continuous. The continuous variable stores and updates real values as calculated and monitored by the mathematical agent. The discrete variable stores a discrete finite % value that reflects the real value of the continuous variable. The % value is calculated by the mathematical agent and reflects the relative “As-Built” value of the entity as compared to the “As-Planned” value. The percentage so calculated is rounded off to the nearest discrete percentage value less than it. This synchronization process allows the mathematical and logical agents to work in tandem and complement each other.

Chapter 6

THE GENERAL PURPOSE MULTI-AGENT FRAMEWORK

The discussion in chapter 3 focused on the conceptual foundations of a general purpose framework for situational simulations in construction. The first step towards developing a general purpose framework is to classify the problems in the construction management domain. Having abstracted the domain to a planning problem during the implementation phase and a constraint satisfaction problem during the pre-construction phase, I classified problems related to construction processes as resource and temporal constraint satisfaction problems with the understanding that events occur when such constraints defined in the scheduled implementation plans are violated.

The next step was to develop “language” that could be used to represent mathematically construction information and be able to reason about the same using domain information so that constraint violations can be detected as the simulation evolves and the impacts of all user interaction can be incorporated in the updated future project implementation plans. Using the semantics of temporal intervals and first order logic I developed such a representation and reasoning scheme in chapter 4.

Chapter 5 further explored the mathematical model driving the situational simulation and the agency involved in consistently calculating and updating the values of cost and schedule in the simulation. It also explains the synchronization system allows the mathematical and logical agents to function at tandem and complement each other in consistently evolving the simulation system.

Chapter 2 introduced the idea of agency and surveyed different agent based simulation systems. It was also argued that a general purpose framework consists of multiple agents that can autonomously reason and perform different tasks in the simulated environment. Having conceptualized the different classes of problems and developed a way of representing and reasoning about construction information, in this chapter, the discussion is well poised

to explore the different functionalities of situational simulations that merit such agency and provide the building blocks for a multi-agent framework.

6.1 The General Purpose Framework (GPF)

The GPF is a protocol that can be used by developers to put together different simulations using the conceptual foundation of constraint satisfaction, planning and the semantics of interval temporal logic to represent and reason about the CM domain. It is akin to an API for a programming language that can be used to program situational simulations for the CM processes. Hence, the GPF components will belong to one of the following fixed classes: agents, entities, operators and bases. Members of these classes can combine according to a well defined grammar to form operations, which are the basic building blocks of any situational simulation programmed using the framework. In this section each of the four mentioned classes have been defined and the grammar that governs the framework has been discussed.

An agent is anything that can perceive its environment through sensors and can act upon that environment through effectors (Russell and Norvig 2002). In the context of this paper all discussions about agents will refer to *software agents*. Software agents are programs which can autonomously create changes in their environment based on its understanding of the condition of the environment. The *environment* is the formal definition of the semantics underlying the software simulation as defined in Chapter 4. Agents reasoning logically and acting autonomously (free of human control) toward a goal, can be attributed a notion of intelligence. They are aware of the repercussions of their actions on the environment and dynamically integrate their experiences into existing reasoning mechanisms. In the suggested multi-agent environment, each agent handles a specific reasoning aspect of the environment.

Agents are responsible for simulating the environment by generating current events that are an outcome of past participant interactions or, by randomly generating seed events. Secondly, the agent can predict future consequences of present circumstances; as warning flags for the participant and also as a guideline for effectively planning the future of the

environment. Finally, the agent can depict the sensitivities of the environment to user decisions. This allows it to portray differences between the “As-Built” and the “As-Planned” trends. In order to accomplish the first two duties, the agent needs to be perceptive to changes in the environment effected by the participant as well as be able to effect changes in it. It must also have awareness regarding the context specific causal reasoning about actions and events, which governs the environment.

Each agent has a finite set of operators associated with it. Operators are reasoning mechanisms attributed to each agent. Agents use operators to reason autonomously and make changes to the environment. Changes to the environment are made by changing values of variables and/or variable collections which are referred to as entities. Entities are defined as the different classes of information in the simulation environment. Every agent operation takes an information entity as an input and transforms it to another information entity (Fig. 6.1). Atomic entities can be combined to create super entities when the super entity is a logical parent of the atomic entities.

The nature of variables and their classification has been discussed in chapter 4. Variables can be classified into discrete and continuous variables depending on the nature of the values they take up. Each variable can also be classified as activity specific (defines an aspect of a specific activity) or global (defines an aspect of the environment applying to all activities). Combinations of variables can also be classified into the following sets of disjoint entities.

- As-Planned Data, As-Built Data
- Activity Dependent Events, Global Events

Agents function by implementing operators to change the values of entities

Pro and Information Attitudes (Woodridge and Jennings 1995) (inferred and factual information) are inherited by agents from knowledge bases (KB), databases (DB) and feedback from user interaction (UI). This allows the agent to reason autonomously. Knowledge bases contain event definitions and data bases contain “As-Planned” cost and schedule information about the project being simulated. The framework consists of utility functions which are not operators but can allow any of the agents to access the bases or to do routine

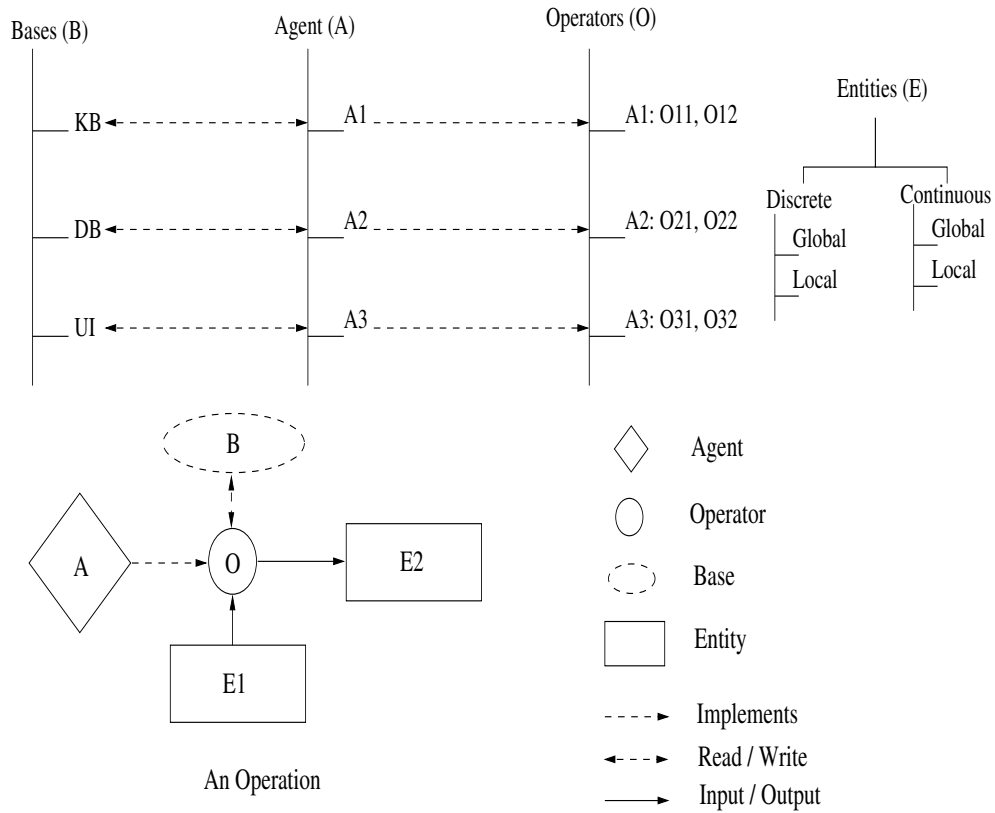


Figure 6.1: The Agent-Operator-Entity-Base Framework

repetitive tasks like calculating remaining durations of activities or updating the floats on the schedule.

The basic unit of the GPF is an operation. In an operation an agent inputs an information entity and outputs it to another information entity using a specific operator. Situational simulations built using the GPF can be expressed as a combination of operations, in series and/or parallel. This sets the grammar for creating simulations using the Agent-Operator-Base-Entity components of the framework, as illustrated in the Figure (6.1).

In the parlance of the Java programming language the GPF can be expressed as:

```
public interface Operation1{
    void O11(Environment E);
    void O12(Environment E);
    . . .}
```

```

public class Agent1 implements Operation1{...}
public abstract class Variable{
    . . .
    //Status of a variable: global or local
    public boolean global_local;
    . . . }
public class DiscreteV extends Variable{...}
public class ContinV extends Variable{...}
public class Environment{
    . . .
    //List of Discrete variables
    public DiscreteV discrete_list;
    //List of Continuous variables
    public ContinV contin_list;
    . . . }
public class Simulation() implements Runnable
{
    public static Agent1 A1;
    public static Agent2 A2;
    public static Environment E;
    . . .
    run(){
        . . .
        //A typical operation
        A1.O11(E);
        . . . }
    public static void main(String Args[]){
        run();
    }
    public static void utility1(){ ... }
}

```

An implementation of such a framework would have definitions of multiple *Agents* each implementing a particular *Operation* interface. The current implementation of the framework

called the Virtual Coach, has three agents: Logical Agent (LA), Mathematical Agent (MA), and the Visualization Agent (VA). The VA was developed specifically for the Virtual Coach and will be discussed in Chapter 7.

The Virtual Coach implementation also has the following events defined: bad weather, poor quality work, labor strike, no material delivery and cost hike. Each of these events represents a resource constraint violation. The implementation also includes utility functions which read from the data base, the knowledge base, runs the scheduler and calculates remaining duration. The next chapter discusses the Virtual Coach implementation in greater detail.

There are three interfaces to the developed framework. One is the programmer's interface, the second one is the developer's interface and the third one is the user interface to the developed situational simulation. I will discuss the third interface in the next section. The first two interfaces that allow the framework to be extensible. An implementation of such a framework will require the developer to input the following to simulate a specific project of their choice:

- “As-Planned” cost and schedule information
- Definitions of variables characterizing the simulation (they can add to the defaults)
- Definitions of anticipated events using pre and post conditions for the associated constraint violations
- Realistic probabilities of defined events based on historical data to enable the simulation to generate reasonable scenarios.

The developers will be using a web interface that will allow them to feed the above information in a structured format directly into the database and the knowledge base. While this interface is currently very limited, in future it will be further developed to be interoperable with typical project management software like MS Project.

Programmers have access to the source code and are free to add more operations to each of the existing agents and/or to add more agents to the framework with dedicated

operators. Thus the developer can either use the functionalities provided by the current implementation of the multi-agent framework to simulate projects of their choice or they can add more functionality to extend the current framework.

6.2 Summary

The motivation of this dissertation is to provide a general purpose platform that can be used both in industry and academia to better train fledgling construction managers while, also allowing academic researchers to collect and analyze human resource interaction data.

In this chapter the general purpose multi-agent framework for situational simulations in construction management was introduced. This framework is the most important contribution of this dissertation. The following chapters focus on implementing a situational simulation using the developed framework and testing its' usefulness as a learning environment.

Chapter 7

THE VIRTUAL COACH: IMPLEMENTING AND TESTING THE GENERAL PURPOSE MULTI-AGENT FRAMEWORK

So far the focus of the dissertation has been in developing conceptual and technical foundations of the general purpose situational simulation environment for construction management. In this chapter the focus shifts to implementing a situational simulation, the Virtual Coach, using such a framework and then studying its usefulness as a learning environment.

7.1 The Virtual Coach Implementation

The Virtual Coach is a particular implementation of the discussed general purpose multi-agent framework (GPMAF). It is a situational simulation that is run by three agents: the Logical Agent (LA), the Mathematical Agent (MA) and Visualization Agent (VA). The Virtual Coach implementation currently runs a situational simulation for a twelve activity hypothetical project with realistic constraint violations and event information. It was implemented in Java using a PostgreSQL database server.

MA operators are Unite and Compute (as discussed in chapter 5), while LA operators are Inference and Event Generation (as discussed in chapter 4). Systemic reasoning in the Virtual Coach is based on a mathematical model as discussed in chapter 5. It deals with reasoning about how events affect the net equilibrium of the system. If the project is executed “As-Planned”, then the system equilibrium is not affected. However, every time there is an event, which results in a crisis, the equilibrium is disturbed. This allows the simulation to constantly give the participant feedback regarding progress as compared to the “As-Planned” implementation. These graphs can be seen in the lower left corner of the “As-Planned” vs “As-Built” screen.

The logical agent can create events and also infer events, which follow as a result of

user interactions with the simulated environment. It can create events in the situational simulation by violating developer defined constraints. It can also predict future constraint violations based on its ability to infer from facts in the knowledge base. A default knowledge base can be used or developers can create their own knowledge bases. In Virtual Coach, events could be generated as a result of the following constraint violations:

- No work can be done unless necessary material and labor are available
- Outdoor activities cannot be productive during snowy weather
- Overworking a labor crew reduces productivity and increases chances of rework
- Labor hired on an emergency basis costs more and is less productive
- Schedule constraints

7.1.1 System Architecture

The “As-Planned” project data and the domain specific information in the knowledge base were stored in a database that provides back-end support to the simulation environment. The architecture of the system was designed keeping the following constraints in mind:

- The simulation system will have to query the database in real time to access “As-Planned” project information and the knowledge base while recording “As-Built” project information and participant interaction.
- People who develop simulations will need to have access to the database, but simulation participants will only need to work with the simulation engine embodied by the agent framework.
- At any point of time one or more participants should be able to work on the simulation (independently or as part of a collaborative effort).
- Optimize space requirements

The above requirements motivated the decision to utilize a client-server protocol for the Virtual Coach. In general the client-server protocol allows a client site to send a request to another site, the server, which sends an answer as a response to this request. In a strict client-server system each site has a fixed role of always acting either as a client or a server. In such cases the server is the data source and the client is the query source.

In the Virtual Coach, the client is the participant's workstation and the server contains the "As-Planned" information regarding the virtual construction project that is being simulated. The client queries the server on demand. The advantages of choosing a client-server system are as follows:

- Only data on server machines need to be backed up.
- Security issues can be addressed by controlling only the server machines and client-server communication links.
- Client and server machines can be equipped according to their specific requirements.
- Hence, while the clients can be simple desktop PCs with good support for GUIs, the servers could be more powerful machines with higher processing capacity and better I/O performance.

The point of concern remains how to distribute the computing load between the client and the server.

Kossmann (2000) surveys the commonly used approaches in exploiting client resources, and discusses the trade-offs between them. He presents the alternatives as Query Shipping, Data Shipping and Hybrid Shipping. While the query shipping technique conducts query processing on the server and sends the results to the client, the data shipping technique ships all the relevant data tables to the client and conducts the query processing on the client. Hybrid shipping offers the flexibility to execute query operators on both client and server.

The Virtual Coach aims at shifting most of the computing load onto the client and using the server only to host the As-Planned database for the simulated project, which will be

queried on demand. Since the database will, under typical situations, contain up to half a million data points, shipping data from the server to the client is not a very good idea. Hence even though all computations dealing with the queried information will be carried out on the client, the query processing will occur on the server. Precedence information regarding the project schedule will be stored in a Directed Acyclic Graph (DAG) (Cormen et al 2001), which will be dynamically updated during the simulation, as it will contain relative validity intervals between activities. The timestamps for data relevant to activities subject to delay will need to be dynamically updated to maintain temporal consistency.

The Hybrid-shipping alternative turns out to be the most useful under the circumstances. Therefore, while in response to requests from clients the server will only ship the relevant results queried from the As-Planned database, the DAG for each project coding the precedence information will be shipped from the server to the client at the beginning of each simulation.

The distributed nature of the Virtual Coach will provide a framework for future research to extend the system to cater to multi-participant construction project simulations. The participants involved could be distributed across different geographical locations and yet collaborate and learn from each other's experiences within a shared virtual environment.

7.1.2 Information Visualization

Visualization is the graphical presentation of information with the goal of providing the participant with a qualitative understanding of the information content. Proper information visualization is extremely important for creating effective non-immersive environments that can provide the participant with a fulfilling learning experience.

Efficient visualization is made of two important components. The first component is the accurate mapping of information to visual entities. This involves technical challenges of analyzing and understanding the data semantics and developing the best way to represent them. The second component involves an understanding of human interfacing with the visual information.

An accurate mapping of information to visual entities involves the following steps:

- Analysis of information to be represented. The information can be classified as raw data and/or as derived/processed data. The relations between different types of data and how they interact with each other require analysis. It is also very important to verify if the data is successfully encapsulating all the pertinent concepts.
- The next important step is to create a mapping from data sets to graphical entities.

This will involve an understanding of how best to represent the data sets. The graphical entities might be simple points and lines or more complex objects like audiovisual files, image files, graphics, CAD objects, text etc. All data sets which represent 3D information is probably best represented via audiovisual files.

The second component will involve an understanding of issues of human computer interaction with the visual experience in perspective. Bertin (1983) developed the Image Theory, which deals with the psychological and perceptual aspects of visualization. He considers the image to be the most fundamental perceptual unit of visualization, and assumes that an ideal visualization consists of a single image, to optimize efficiency and speed with which an observer can extract information. Even though Bertin's theory deals with visualization through a single image, some of the concepts developed in his treatise are relevant to visualization in general.

Currently, in the Virtual Coach information visualization and user interactivity are handled by the visualization agent (VA). The function of the VA is to make sure that the information being displayed to the user is consistent with the information in the simulation. The VA is also responsible for encoding participant reactions and passing them onto the other system agents in a format that can be easily processed.

While this section identifies the factors driving information visualization and interface design, the Virtual Coach interface is very preliminary and was developed as a research interface for testing the framework and the usefulness of situational simulations in training construction managers.

Figures (7.1) and (7.2) provide screen shots of the Virtual Coach. Figure (7.1), is the resource allocation screen, which informs the participant of the total available resources in the environment and the total resource requirements specific to each ongoing activity in the

simulation. Each activity panel also has a graph showing the “As-Planned” rate of work completion versus the “As-Built” rate of work completion. The participant is allowed to assign more or less than the planned requirements depending on availability to accelerate or decelerate the project.

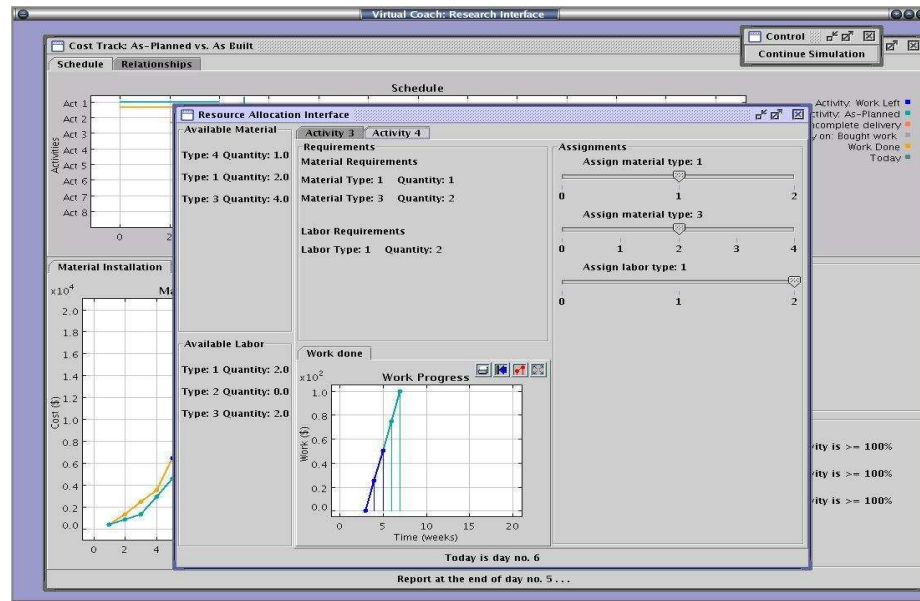


Figure 7.1: Resource Allocation Interface

In the absence of the necessary resources, the participant is also allowed to hire more labor and purchase more material at a premium price. This allows the participant to accelerate the project, at a higher cost, and is often an option to keep the project on schedule. While the direct costs go up, the participant does gain in terms of indirect costs by saving time.

Finally, Figure (7.2) illustrates the report about progress at the end of a week. The participant can view the current state of the schedule compared to the “As-Planned” schedules. He/she can also keep track of direct costs, indirect costs and space requirements by following the graphics at the lower left hand corner of the viewer. The lower right hand corner of the viewer allows the participant to monitor the values of discrete and continuous environment variables and keep track of the possibilities of events that may occur in

the near future. They can also keep track of recent events that have just occurred. This is important in allowing them to make future resource allocations. The final goal of the participant is to steer the project through generated scenarios and complete within budget and time constraints.

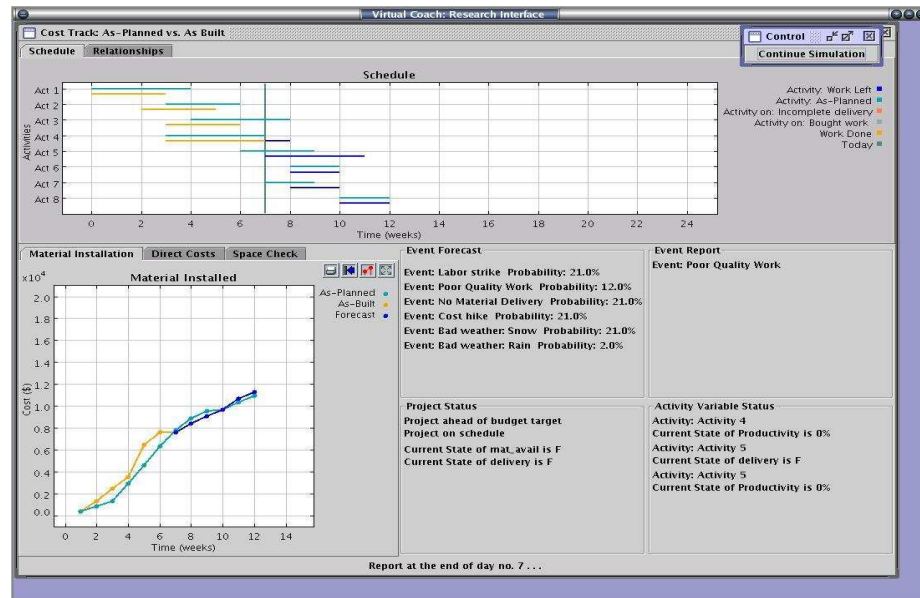


Figure 7.2: End-of-day Report

7.2 Testing the Virtual Coach

A pilot of the Virtual Coach situational simulation environment was tested with a group of 19 senior level construction management students, as part of a Project Management class at the University of Washington. The pre/post test protocol was used.

The pilot implementation of the Virtual Coach simulates a twelve activity hypothetical project with realistic constraint violations and event information. Participants have the ability to allocate, reallocate, or procure resources from the market place. They are presented with the challenge of quick decision-making amidst rapidly unfolding events. By exploring “what-if” scenarios, participants can also test the sensitivities of the system to their decisions in a dynamic environment. At the end of each simulated week the program

creates a progress report with information regarding the current state of the schedule as compared to the “As-Planned” schedule. Such information helps participants in monitoring their progress and perceiving the system dynamics of the CM domain. The final goal of participants is to steer the project through generated scenarios and complete it within budget and time constraints.

The students took pre and post-tests (see Appendix A) before and after they participated in the simulation. It took the subjects between 25-30 minutes to complete the pretest and the posttest. Before running the simulation and after the pretest, the subjects were provided about half an hour time to practice on the simulation and gain familiarity with the interface. Participating in the simulation took the subjects between an hour and seventy five minutes on an average. The posttest was administered after the simulation and the test session was completed with a fifteen minute long debriefing session during which the students were required to complete a survey and provide their comments. Students were also required to think aloud their decisions and their perceptions of what was happening during the exercise. All comments made during the simulation were recorded (audio only).

The pretest and posttest presented the students with a construction crisis scenario (see Appendix A) and required the students to rank (on a scale of 1-10), in their opinion, the importance of a list of provided factors in developing a plan for a 12 week period of the construction scenario. They were also provided with a list of constraints governing the scenario and the necessary project information. The constraints included schedule considerations, budget limitations and the possibilities of events such as bad weather, material delivery delays and labor shortage.

The performance of the students in the pre and posttests, an analysis of their feedback during the debriefing session and their recorded thoughts were used as metrics for evaluating the performance of the system. In the next chapter we have discussed the results and conclusions in detail.

Chapter 8

RESULTS AND DISCUSSION: UNDERSTANDING COGNITIVE AND META-COGNITIVE PROCESSES IN CONSTRUCTION MANAGEMENT

There is evidence (McCabe et al. 2000, Sawhney et al. 2001, AbouRizk and Sawhney 1994) that the construction management curriculum is fragmented and de-contextualized in nature and does not adequately prepare students for the industry. As discussed in chapter 1, the inadequacy of construction management education is greatly responsible for the widening disconnect between the theoretical understanding and practice of construction management. In order to create a more appropriate curriculum, I think it is imperative to examine the nature of learning in the CM domain. This chapter discusses our observation of the students interacting with the Virtual Coach, a situational simulation environment.

Section 2.4 surveys work done in using simulation environments for training purposes and their usefulness. Literature in education and the cognitive sciences which investigate learning as a cognitive activity have also been explored. In tandem I also surveyed work done in applying system dynamics/systems thinking concepts to better understanding counter-intuitive behavior and interactions of the sub-components of complex systems. Based on observations of student interactions with the Virtual Coach I have tried to evaluate the usefulness of the Virtual Coach in training construction managers and understanding cognitive and meta-cognitive processes from the system dynamics/systems thinking perspective.

8.1 *The Hypothesis*

Two categories of student interactions with the Virtual Coach were analyzed. The first one is the differences in their performances in the pre- and posttests. As explained in the previous chapter the tests required students to rank (on a scale of 0-10) how important they

thought a set of factors (See Appendix A) were influencing their decision making process. A positive difference between the ranks ascribed to a factor (posttest rank - pretest rank) is referred to as an *improvement* and implies that the subject regarded the factor more critically after going through the simulation. A consistent pattern in the areas of improvement in performance, backed by qualitative thought analysis and the feedback provided by the students would allow us to conclude the efficacy of the Virtual Coach as a learning environment.

The hypothesis of this study was that students will show significant improvement in factors that deal with resource and constraint satisfaction. On a meta-cognitive level I proposed that students learn by better understanding resource and temporal constraint satisfaction and apprehending constraint violations. In the next sections, I have discussed the findings based on a statistical analysis of student performance on the pre and posttests and a qualitative analysis of thoughts and recorded interactions.

8.2 Pretest/Posttest Performance Analysis

Four of the priority ratings assigned by the students, before and after using the simulation, were summed and compared using a paired-sample t-test. The ratings selected for analysis were those that related to the schedule and resource constraints and the need to anticipate delay on a project (giving priority to critical activities in case of delay, attention to space restrictions on site, anticipating future material delivery delays, accelerating activities to create buffer for anticipated delay.) The difference between the ratings was significantly different:

Pre-Test: Mean = 21.26 Std. deviation = 4.92

Post-Test: Mean = 25.31 Std. deviation = 4.70

T-statistic: $t(18) = 3.32$ p-value < .01.

8.3 Think-Aloud Analysis and Feedback

A qualitative analysis of the participants thoughts (as recorded during the simulation) and the feedback provided in a post simulation survey provided us with valuable insight

into what the students learnt from the experience. Below is a list of selected reactions from the students after the simulation was over. They have been reported verbatim and are representative of the general feedback that provided by the students. The highlighted sections of the responses emphasize the fact that what impressed the students most was the ability to get the bigger picture and the inter-relationships between labor, budget, schedule and the impact of their decisions on the environment.

*Participant 1: I liked the fact that **I was able to see what my actions were doing to the budget and schedule.** In the industry you are always trying to pick up a few critical days in the beginning to counteract unforeseen setbacks in the future.*

*Participant 2: Virtual coach was a good simulation and put together the critical elements of managing a project, labor , materials, schedule, and cost. I feel that it **provides a good way of actually controlling a schedule and seeing the effect one change can have on all the variables.***

*Participant 3: I like how the project did not go according to plan. I think it was a good way to communicate as to how unforeseen events happen thus **you need to change the way in which you approach your already existing constraints.***

*Participant 4: The virtual coach does a good job with giving **students a better idea of the big picture.** . . . I felt like I needed to **understand how the relationships between the material and labor allocation were determined and being used before I really put a lot of trust into the Virtual Coach.***

*Participant 5: I thought the Virtual Coach is really interesting in the fact that it accounted for the **many outside parameters that may affect the construction process** of a project.*

*Participant 6: The real time cost allocation and schedule **allows one to see where they are at and where they are going is great.***

*Participant 7: I think that virtual coach is a great activity for us to use. it **gets you to think about resource, management, estimating and scheduling together.** I think it could be improved by letting us see the differences in unit costs, and how much our decisions affect the project. . . for example, it would be nice to see **how much more expensive it is to hire labor at a premium.** other then that it is a great program, any schoolwork I*

have done so far has not taught resource managing as well as this has.

Participant 8: Virtual coach did an excellent job of forcing me to see the big picture or suffer the consequences of lost productivity, lost \$, etc. I feel that the scenarios and interaction with the program as far as the percentage of likelihood of certain events was fairly true. For example, if I worked the workers too hard they would be more likely to perform poor work or strike.

Participant 9: I thought Virtual Coach was an educating experience. I thought that it showed and allowed the students to have a good understanding of the decisions they made and how the decisions influenced the schedule and the budget.

Participant 8 also emphasizes the bigger picture and recognizes some simple dependencies that create the underlying structure in the CM domain. Participant 7 suggests that the program should be further developed to reflect in greater detail the sensitivity of their decisions on the project. Clearly this is an example of the students having realized that resource, management, estimating and scheduling are related, function together in a system, and therefore it is necessary to evaluate the sensitivity of the system to the each decision.

Participant 4s response also highlights the understanding gained of the bigger picture and the understand the relationships between material and labor allocation. It is also very encouraging to note that the student feels the need to know the workings of the simulation model.

The recorded reactions of participants during the simulation helped us detect the various “Ah-ha” moments that reinforce the belief that the simulation was helping students achieving a systemic view of the CM domain. It was very interesting to note how the students were reacting to delays in the schedule. The most common reaction was to accelerate the activity at hand, without paying attention to where it was on the critical path. There was also a general tendency to increase the productivity of labor on a delayed activity without anticipating a feedback in terms of rework or labor unavailability in the future. It was interesting to note a student comment when he realized that a project impacted by an event toward the end of the schedule is a lot more difficult to recover from than a project delayed early on.

The “Ah-ha” moments happened when the unexpected feedback came back to make the

user rethink a decision taken earlier on in the simulation. The understanding that there exist lag times between action and feedback motivated the students to stand back and get a bigger picture of how sensitive the system was to their decisions. It also helped them perceive that problems are often not just localized disturbances, but results of structural causal relationships, which are reciprocal in nature (Participant 8).

8.4 Discussion

Based on qualitative feedback (post simulation survey) from the students, where 16 out of 19 thought that the Virtual Coach was a useful educational tool; the statistical significance of the differential between the post- and pre-test results as discussed above, it can be concluded that an intervention using situational simulations can be useful in construction education. Also based on our observation of the students interacting with the Virtual Coach we have concluded that students in CM learn by developing a better understanding of the inter-relationships of the sub-components of the CM system (cost, schedule, and resource availability) and its evolution over time.

From this study it can also be concluded that students tend to learn better by understanding the underlying constraints present in a project and apprehending their violations while making decisions. Our analysis shows that the way students feel better equipped to apprehend such constraint violations is by getting a systemic view of the CM domain and a better understanding of the inter-relationships and causal loops. Based on the enthusiastic feedback we received from the students and our analysis of their reactions, we strongly encourage further development of adaptive and dynamical learning environments, such as the Virtual Coach, as useful tools in CM education. Furthermore, given the body of literature in the SD/ST and the cognitive science community, which support the usefulness of such learning methods, we strongly encourage the adoption of such environments into the CM curriculum. This does not mean that we abandon traditional classroom teaching methods. Instead, we should harness the power of such environments and the SD/ST approach to enhance understanding. It is not an either or and indeed it would be unfortunate if we lost the joy of listening to the leaves rustle in our quest for better understanding the forest.

Finally, how does this understanding stand to influence the CM domain beyond education? The answer lies in our understanding of the meta-cognition involved in CM. What do we learn about the domain from our knowledge of how we learn in it? This is not an easy question to answer conclusively within the scope of this work. However, we would like to suggest that the use of situational simulations may help us better research this question and develop a theoretical understanding of construction without assuming it to be akin to other industries like manufacturing (Koskela and Vrijhoef 2001).

Chapter 9

CONCLUSIONS

Learning is a very important cognitive activity. It is a journey that construction managers take from being novices in school to experts after many years of experience. How do novice construction managers learn? How do they build expertise through experience? Most importantly, what tools are available that will allow us to educate novice construction managers and provide instructors with guidance in answering these questions? These are some of the critical questions that this dissertation raises and provides pointers to possible answers. In doing so it sets the stage for better understanding human cognitive and decision-making processes in construction and integrating it with existing construction theories to develop a systemic perspective of the complexities in the CM domain.

A better understanding of complexity in the practice of construction management and its incorporation into the academic curriculum and research is a first step towards bridging the disconnect between theory and practice: the original motivation for this research.

Specifically, I proposed a general purpose multi-agent framework that can be used to create a wide variety of situational simulations for the CM domain and developed the Virtual Coach, an implementation of the framework. Further I used the Virtual Coach as an experimental setup to better understand cognitive and meta-cognitive processes in construction management and evaluate its effectiveness as a training environment. I also introduced a method that can be used to understand expertise among construction managers by exploring their mental models - a first step towards better understanding knowledge organization among expert construction managers.

In conclusion, it is important to summarize the contributions of this work and provide pointers to future directions.

9.1 Summary

Situational simulations emulate the CM domain as an interdependent system of human and resource interactions. They are dynamic, interactive, context-sensitive, adaptive environments powered by autonomous reasoning agents that can simulate future project scenarios. In such an environment participants are exposed to diverse project management situations rapidly unfolding in time. Situational simulations can be used for exploring “what-if” scenarios, useful in training construction managers, in crisis management, as test-beds for understanding cognitive processes and in building decision-making support systems. Given the diverse applications of situational simulations and the requirement for construction domain specific reasoning processes, it is necessary to develop a general purpose framework that can be used to create situational simulations for a variety of CM projects.

The focus of my Ph.D. research was to develop a general purpose multi-agent framework for the CM domain. I also developed the Virtual Coach, a specific implementation of this framework and tested its usefulness as a contextualized training environment and for exploring cognitive and meta-cognitive processes in CM.

The prevalent paradigm in construction simulations, Activity Scanning (AS), represents activities as discrete time points and simulates time as a progression from one activity to the next often across unequal temporal distances. This approach has been useful in developing special purpose simulations of construction operations. However, using the AS paradigm in simulating CM processes, that involve multiple inter-related activities in an interactive, dynamically evolving environment, may not be suitable, as it makes the representation of partly overlapping parallel activities/events and reasoning about constraints difficult.

To solve this problem, I developed a “language” based in the semantics of interval temporal logic that allows formal expression of construction information and reasoning about temporal and resource constraints governing the simulation. The reasoning in the simulation environment is rooted in the axioms of time and on the conceptual understanding that problems in the CM domain can be expressed as constraint satisfaction problems (CSP). The temporal semantics backed by a knowledge base allows autonomous agents to communicate and reason about the evolution of the simulation, while being sympathetic to

user interaction (Mukherjee, A. & Rojas, E. 2003). The simulation also uses a deductive mathematical model of construction management processes, (Rojas, E. and Mukherjee, A. 2003) for the calculation of cost, productivity and remaining duration of the simulated project.

The multi-agent framework is a series/parallel combination of agent operations (reasoning processes). It provides a grammar for autonomous agents to use for their interactions. Using this grammar, agents can communicate and reason about the evolution of the simulation, while being sympathetic to user interaction (Mukherjee, A. et al. 2004). It also forms the basis of an API for developers to create project specific situational simulations.

The Virtual Coach, an implementation of the proposed framework, was tested using a class of senior level CM students (Mukherjee, A. et al. 2004), as part of a Project Management class. The students were made to take a pre-test and post-test before and after they ran the simulation respectively. A quantitative comparison in their test performance before and after shows a statistically significant improvement in test questions pertaining to resource and temporal constraint satisfaction. Based on a qualitative and quantitative analysis (Mukherjee, A et al. 2005b) of student reactions and performance showed that cognitive activity in the CM domain is strongly dependent on the ability to apprehend constraint violations and is aided by a systemic view of the domain and a better understanding of the reciprocal causal relationships between availability of resources, cost, schedule and human decisions.

The development of the multi-agent framework and the introduction of a semantics based on constraint satisfaction and interval temporal logic is a first step toward developing a general formalism to represent and reason about activities, events and situations in the construction domain. The proposed framework also provides developers with an extensible platform that can be used to program situational simulations for a diverse set of construction projects. Also, developers can augment the system by programming additional reasoning agents into the simulation. This introduces a simulation paradigm in CM that can be used to simulate and study human decision making and resource interactions as a coupled system.

9.2 *Future Research*

This research effort is at the root of a broader research agenda that aims to better understand human-resource interactions and human decision making in the construction management domain. It is recommended that in doing so the following research questions be explored.

- Can situational simulations be used to better prepare construction managers across diverse CM scenarios in both academic and industrial settings while effectively gathering information about their reactions to the simulated scenarios?
- What methods can be used to analyze the gathered data?
- How to formally investigate the manner in which construction managers with varying levels of experience organize their knowledge?
- How to use the results of our analysis in advancing theory and practice in CM?

Broadly speaking the main objective of future research will be to gather and analyze data using situational simulations of diverse CM scenarios while evaluating their impact in the development of better decision-making skills. The general-purpose multi-agent framework developed in this research effort will provide a critical tool in conducting this research.

The following steps are recommended in conducting this research effort:

- Deploy the general purpose framework across the Internet among a community of academic institutions and construction firms.
- Share and develop diverse situational simulations that can be used to train students and fledgling construction managers.
- Implement case studies of real construction projects and compare simulation evolution with project performance histories.

- Log all simulation interactions so that a wealth of diverse and significant human interaction data that can be collected and analyzed using state of the art machine learning techniques
- Develop a System Dynamics framework describing human resource interactions in the CM domain.
- Identify the principles that guide expert decision-making.
- Integrate results from the analyzed data to develop a theoretical framework that can be introduced in construction education and for planning and optimization in practice.

Based on our understanding of mental models of expert construction managers and common practices and approaches of novice construction managers that are modified as they move towards expert cognition, I propose to lay the foundations of a theory for better comprehending decision-making in the construction management domain. Such an effort will be based on an approach that seeks to formalize problems in construction management as a combination of human and resource interactions and will provide a systemic approach to understanding the impact of human decision making on resource interaction in terms of feedbacks that are often counter-intuitive and delocalized in time and space.

At the same time, the implementation of the framework itself and situational simulations like the Virtual Coach will need more development so that it can be successfully used to explore the above research problems.

Further investigation has to be conducted in future, into the usability and scalability of the framework for simulating diverse construction management scenarios by developers in academia and industry. The community of academic researchers and construction managers from the industry will be involved in testing the ease of use of the framework and the reusability and interoperability of simulation components.

Future work will also need to test the deployment and development of situational simulations using the general-purpose framework across a national peer-to-peer network. All the interaction information will be stored in Internet databases and made securely accessible to

researchers. The success of the peer-to-peer national network for information sharing will be critical in successfully building and fostering a community of developers and researchers.

The general-purpose multi-agent framework will also need to be further modified to provide an intuitive interface for representing budget, schedule and performance information effectively to provide the participants an appropriate picture of how their decision making is impacting the progress of the project from a systemic perspective. This will involve human interface and graphical data representation research followed by human subject testing of the interface for appropriateness.

The proposed research intends to use the state of the art techniques in visualizing information from construction operation simulations. Currently such techniques involve post-simulation information visualization and are very useful for visualizing information from non-interactive simulation runs. The authors believe that such visualization languages that are currently under development can be interfaced with the existing general-purpose multi-agent framework, but will need modifications to take into account the dynamic and interactive nature of situational simulations.

Finally, in conclusion I would like to point out the interdisciplinary nature of this research effort and underscore the importance of such an approach. While the research focuses on decision making in the construction management domain, it is dependent on the application of artificial intelligence technologies and at the same time is influenced by theories from the cognitive sciences. The implementation requires a command over information technology and a good understanding of issues in human-computer interaction besides a background in civil engineering and construction management. In my interactions with faculty and students at the Human Interface Technology Laboratory, the Department of Computer Science and the College of Education at the University of Washington, besides my home department, I have developed a perspective that will greatly benefit future research efforts.

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Appendix A

PRE AND POST TEST

This section lists the following:

- The test that was administered to the students before and after they experienced the Virtual Coach situational simulation.
- The survey that was provided to the students to provide feedback during the debriefing session after the posttest.

A.1 Pre and Post Test

The test involves a construction management crisis scenario and a list of factors that influence decision making in the situation.

You are looking at the following scenario, (schedule shown in following Figure (A.1)

The red connecting lines indicate dependencies. Activity B cannot start till Activity A is 75% complete. Activity C cannot start till Activity A is complete and Activity D cannot start till Activity B and Activity C are both complete.

You are on week 1 of a twelve week period of a construction project. The schedule is shown in the diagram. You have the following information:

- Activity B cannot start till Activity A is 75% complete
- Activity C is critical
- There is about a 55% chance of a labor strike occurring in week 3 or week 4, which could result in reducing your productivity by 50%.

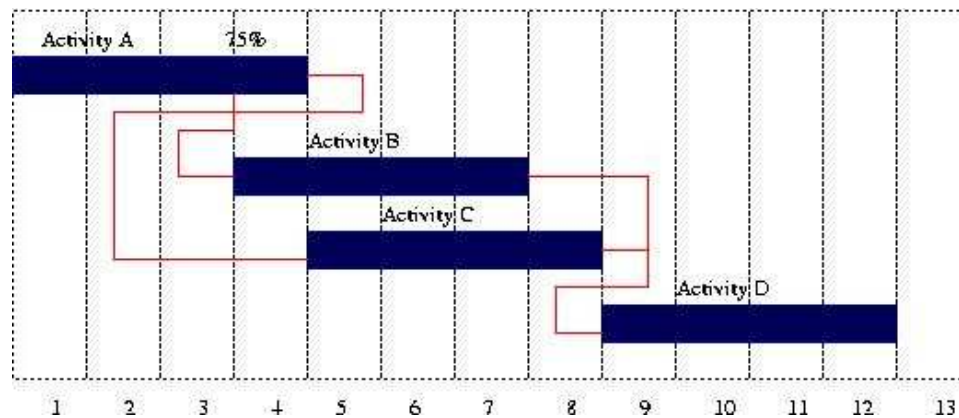


Figure A.1: Activity Schedule

- Your work site has a space constraint, so you can only accept material delivery for Activity B or Activity C on week 3. However, if there is available space on your work site, you may be able to accomodate both the deliveries.
- Delivery for Activity D is scheduled for week 7. The delivery may not be possible unless the Activity B has been completed.
- You can free space on your site by using your existing materials at a faster pace.
- Typically you can push your labor force to be about 1.5 times as productive.
- You may be allowed to buy new material or hire more labor in case of an emergency at a premium cost.

Based on your understanding of the situation at hand you are required to develop a plan for the future. Following is a list of possible strategic decisions that you might need to take in the course of the twelve week period. Please indicate:

- On a 0-10 scale prioritize each of the following to reflect how importantly you would consider the implications of these decisions while developing your plan

- When you would most probably take the following decisions during the twelve week period
- The reasons which would lead you to take thses decisions

Please fill in the user-id provided to you.

User id:

First factor: Accelerate Activity A

Priority Rating:

Time point of action (week number)

Your reasons:

Second factor: Accept Delivery for Activity C

Priority Rating:

Time point of action (week number)

Your reasons:

Third factor: Accept Delivery for Activity B

Priority Rating:

Time point of action (week number)

Your reasons:

Forth factor: Delay Activity B by a week

Priority Rating:

Time point of action (week number)

Your reasons:

Fifth factor: Start Activity C on time

Priority Rating:

Time point of action (week number)

Your reasons:

Sixth factor: Schedule less work for week 3 and week 4

Priority Rating:

Time point of action (week number)

Your reasons:

Seventh factor: Make no changes: carry on working as planned

Priority Rating:

Time point of action (week number)

Your reasons:

Eighth factor: Accelerate Activity D

Priority Rating:

Time point of action (week number)

Your reasons:

Ninth factor: Acquire premium labor for week 4

Priority Rating:

Time point of action (week number)

Your reasons:

Tenth factor: Accept any unforeseen delay: make up later on

Priority Rating:

Time point of action (week number)

Your reasons:

A.2 The Debriefing Survey

The participants were required to answer all the questions. For the *other* option and in question 10, they were free to input their own responses.

Question 1. What is your opinion of the way construction management is taught in the classroom?

- It is inadequate and completely disconnected from the industry
- It is adequate but it does not completely prepare students for the industry
- It is excellent and completely in synch with the needs of the industry
- Other

Question 2. Do you think there exists a gap between the construction curricula and what the industry expects of graduating students?

- Yes
- No
- Other

Question 3. Do you think simulation technologies, like the Virtual Coach, can be harnessed to create a curriculum that allows students to explore various construction scenarios and thereby gain "virtual experience"?

- Yes
- No
- Other

Question 4. Instead of having 3 or 4 different courses dealing with isolated topics like estimation or scheduling or project management, would you rather prefer a single simulation environment that provides an understanding of all the topics at the same time?

- Yes
- No
- Other

Question 5. Do you think the construction curriculum helps students develop decision making skills?

- Yes
- No
- Other

Question 6. Do you think that interactive simulations, like the Virtual Coach can help students develop better decision making skills?

- Yes
- No
- Other

Question 7. Do you think it is important to provide students with an understanding of the "bigger picture"? For example, an better understanding of the dependencies between cost and schedule and resource availability.

- Yes
- No

- Other

Question 8. Do you think simulation technologies like the Virtual Coach can help students get a better idea of the "bigger picture"?

- Yes
- No
- Other

Question 9. Do you think simulations like the Virtual Coach can train novice construction managers in better understanding how unexpected events can affect progress on a construction project?

- Yes
- No
- Other

Question 10. Briefly tell us what you liked about the Virtual Coach and what you feel needs improvement.

Appendix B

MENTAL MODELS EXPLORATION SCENARIO

This appendix lists the construction management problem scenario that was provided to the 7 participating construction managers and the survey that was used to elicit their responses. The first section consists of the information provided to respondents, the second section lists the scenario and the third section is a listing of the questions they were required to respond to.

B.1 Information Provided

This study is being conducted to explore and compare trends in decision making patterns amongst novice and expert construction managers. You are requested to read the following scenario and then follow the link at the bottom of the page to a new browser window, where your responses will be electronically collected using a questionnaire.

You may notice that the information provided in the scenario is incomplete and probably insufficient to answer all the questions in the questionnaire. However, please understand that this ambiguity has been deliberately designed to accomplish the objectives of this study. We expect you to fill in the questionnaire based on what you intuitively feel about the situation at hand. You are free to make any assumptions you want and draw your conclusions based on them. Please do mention all your assumptions in the space provided in the questionnaire. The objective of this study is to compare and contrast discernable trends and patterns in the ways experienced managers make assumptions and take decisions compared to their fledgling counterparts.

This is a preliminary study and we are strictly speaking, exploring uncharted territory. If you have any suggestions, feel free to contact Amlan Mukherjee at the Human Interface Technology Lab., at the University of Washington. We appreciate your participation in this study.

All information collected will be protected, and be used specifically for this study. Your identity is not being noted anywhere in this survey, and cannot be co-related with your responses. This way your privacy is being maintained. Thank you for your participation.

B.2 A Construction Management Scenario

B.2.1 Project Particulars

Type of Project: Construction of a state-of-the art library facility

Size of Contract: \$104 million

Project duration: 24 months

Project start date: August of 2001

Expected end date: August of 2003

B.2.2 Project Description

This new centralized library facility has 11 floors. Five floors are designated for primary library functions, while the other six floors will include spaces for public usage such as spaces for children and socially interactive "living rooms". The building will also have a 275-seat auditorium, which will be located in the center of the building. There will be elevators and escalators on either sides of the central auditorium.

The exterior of the building will have a curtain wall, which will be made from tinted glass. It will also be surrounded by steel tubing, which will act like diagonal braces that provide lateral support to handle earthquakes and wind loads. The total square footage of the building is roughly 355,000 square feet.

The library is being built in a very busy part of downtown Seattle. Space available on the construction site is limited. All material delivery happens just-in-time for installation.

B.2.3 Project Participants

Owner: City of Seattle

GC/CM 'At-risk' contractor: First Construction Co. First has previously successfully bid and worked on many public works projects with the city. They have a reputation few construction companies in the area can beat. Their special construction expertise is in building curtain walls. They can provide tinted glass in customized colors. In this particular project they intend to deliver curtain walls with a light blue tinge, at the owner's specification because studies have shown that it allows greater energy efficiency.

Design Architect: First Architects Inc.

Sub-Contractors: First Construction sub-contracts out all of the work excepting for the construction of the steel tubing structure and the installation of the curtain walls. The glazed glass for the curtain walls is manufactured off site and delivered just in time for installation by Best Glass Co.

B.2.4 The Scenario

It is late January of 2003. There was a bout of very bad weather early in December, which completely paralyzed the project site, and delayed progress by a month. The owner decided that bad weather is an "act-of-God" and gave First an extension of 15 days on the final completion date. However, they did not agree to additional payment. This was indeed helpful for First because the contract terms included liquidated damages per day of \$15,000. At present, project completion is close to 60% compared to 67%, scheduled to have been completed.

In order to finish by the new deadline First will need to complete installation of curtain walls by June of 2003, enabling the interior decoration sub to complete on time.

The curtain wall installation is supposed to start this week, but you have just discovered that the first installment (20% of complete delivery) of the curtain wall glass is defective because it does not meet the tint specifications. This is critical, because the success of the project depends on how well the curtain wall is installed. Further investigation shows that there was a clerical error while ordering the tinted glass on part of First Construction.

The curtain walls are now occupying almost all the available storage space. There are other electrical and HVAC subs working on the project who need storage space. If there is

no place for storage they cannot take delivery and that will delay progress on their project.

The workforce who had been employed to work on the curtain walls are now on site with nothing to do. They are skilled laborers and are in demand for other projects across the city. By loosing them at this time, First might face a severe labor shortage when the right glass ultimately arrives. Needless to say, there is no certainty about when that will happen.

B.3 The Survey

Please analyze the information that has been provided and devise the best possible plan of action subject to the situational constraints. Based on your decision please answer the following questions. We have identified four distinct areas of concern: Space Management, Schedule Management, Labor Management and Materials Management. For each of them please indicate, briefly your plan of action, using available information. For example you might decide to hire skilled laborers (a plan of action) in order to manage labor, or crash activity X (a plan of action) in order to manage schedule.”

Question 1. Area of Concern: Space Management

Question 2. Area of Concern: Schedule Management

Question 3. Area of Concern: Labor Management

Question 4. Area of Concern: Materials Management

After you have decided on your plan of action, assign a number from 1 to 10 to evaluate how you believe your plan of action will affect the project schedule, project cost and the reputation of the company, for each of the areas of concern. A value less than 5 would indicate an adverse impact, while a value higher than 5 would indicate a positive impact. A value of 5 would indicate maintaining the as-planned schedule.

In questions 5, 6, 7 and 8 please indicate how you believe your ”plan of action” will affect the project schedule:

Question 5. Area of Concern: Space Management (a number between 1 and 10)

Question 6. Area of Concern: Schedule Management (a number between 1 and 10)

Question 7. Area of Concern: Labor Management (a number between 1 and 10)

Question 8. Area of Concern: Materials Management (a number between 1 and 10)

In questions 9, 10, 11 and 12 please indicate how you believe your "plan of action" will affect the project cost:

Question 9. Area of Concern: Space Management (a number between 1 and 10)

Question 10. Area of Concern: Schedule Management (a number between 1 and 10)

Question 11. Area of Concern: Labor Management (a number between 1 and 10)

Question 12. Area of Concern: Materials Management (a number between 1 and 10)

In questions 13, 14, 15 and 16 please indicate how you believe your "plan of action" will affect the reputation of your First Construction:

Question 13. Area of Concern: Space Management (a number between 1 and 10)

Question 14. Area of Concern: Schedule Management (a number between 1 and 10)

Question 15. Area of Concern: Labor Management (a number between 1 and 10)

Question 16. Area of Concern: Materials Management (a number between 1 and 10)

Question 17. Please indicate the number of years of experience you have in the construction industry. (Please include time spent in any kind of construction related employment).

VITA

Amlan Mukherjee was born in Guwahati, in the north-east Indian state of Assam. He grew up in Calcutta and got a B.E. degree in Civil Engineering from Birla Institute of Technology and Science, Pilani, India, in 2000 an MS in Civil Engineering at the State University of New York at Buffalo in 2001 and a Ph.D. from the University of Washington, Seattle in 2005. In August 2005 he will be an assistant professor in the Civil and Environmental Engineering department at the Michigan Technological University.