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

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Abstract

Situational simulation environments are temporally dynamic clinical exercises with the objective of exposing participants to rapidly unfolding events and the pressures of decision making, typical to the implementation phase of construction projects. The need for contextually rich education environments in construction suggests the development of a general purpose situational simulation, which can be used by independent developers to build effective training environments. However, the absence of an existing simulation paradigm to effectively develop such training environments indicates that there is scope for research in the area of developing a new framework that can support general purpose situational simulations in construction. This thesis proposes that a multi-agent framework can be used to create a general purpose situational simulation environment for the construction domain. Design and implementation of a situational simulation involves an understanding of the reasoning processes. The reasoning processes can be isolated using a conceptual classification of problems in the construction management domain into constraint satisfaction and planning. This provides the conceptual foundation for a formalism which can be used to represent and reason about activities, events and situations in the construction domain. Based on this representation, I propose to develop a multi-agent framework which can be used to implement a general purpose situational simulation environment for training construction managers.

1 Introduction

Traditional classroom curriculum does not allow fledgling construction managers to experiment and explore different ways of dealing with situations that unfold during the implementation phase of multi-faceted construction projects. McGabe et. al. (2000) argue that current civil engineering coursework teaches only the theories of construction management and that students may encounter difficulties in applying theoretical principles when exposed to real world situations upon employment. Sawhney et. al. (2001) state that civil and construction engineering curricula does not allow the inclusion of issues of importance to construction, or the significance of hands-on experience and interaction with practitioners. AbouRizk and Sawhney (1994) also recognize the deficiency of traditional teaching methods in providing students with the skills necessary for solving real world problems.

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). Traditional construction education follows the Cartesian view of mind-matter dualism where the learner and the learning context are detached. As a result concepts are presented as fixed, well structured, independent entities and classroom activities are disconnected to authentic context resulting in fragmentation and specialization of courses and educational experiences. This fragmentation of knowledge has been identified in the construction domain (Chinowsky and Vanegas 1996, Fruchter 1997) and is partially responsible for the polarization of the learner and learning context.

In a field like construction management where problems present multi-faceted situations dependent on context, a traditional approach to learning is not fulfilling. This understanding has led researchers to explore 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). These efforts provide a stepping stone towards creating participatory, contextually rich educational environments. However, most of these simulations can be classified as special purpose simulations in context to construction educational environments because they deal with the simulation of specific construction operations and not necessarily the whole construction process.

Situational simulations can exploit the richness of virtual learning environments by providing an 'embodiment' within the context of situations specific to the construction management domain. They provide temporally dynamic clinical exercises which expose participants to rapidly unfolding events and to the pressures of quick decision making. When implemented through virtual environments, situational simulations can provide participatory and contextually rich educational environments. Extensive use of situational simulations has been seen in the politico military arena (GAO/NSIAD 1991, Allen 1987, Bloomfield and Whaley 1965, Goldhammer and Speier 1959) and in natural disaster relief management (Ritchie 1985). General purpose situational simulations can be used by independent developers to program a very wide variety of training environments for construction management. The apparent crisis in construction education suggests the development of such a general purpose situational simulation environment.

Situational simulations involving construction scenarios are fundamentally different from simulations of construction processes. In their simplest form, construction simulations use a set of initial conditions and parameters, and a well defined model to project outcomes regarding the simulated operation. Hence given information regarding the availability of trucks and loaders, unit cost and the amount earth to be moved a simulation would be able to project the total time and cost for an excavation operation. Situational simulations also have a defined model and a set of initial conditions, but as the simulation proceeds the system generates random events and expects the user to react to such events. Where the simulation finally ends up is completely dependent on the model used, the way the events are generated and the user interaction. For instance in a situational simulation of an earth moving operation participants might be in a situation where they have to deal with finishing the operation within time and budget constraints, under the influence of bad weather and a labor strike. The participant has the ability to access and reallocate resources, however, the challenge lies in how and they deal with such situations. Situational simulations run in quasi-real time i.e., the net time taken by the real project under simulation is some multiple of the simulated time. This brings in a temporal and interactive dimension to situational simulations which construction simulations don't have.

Simulation languages like STROBOSCOPE and CYCLONE have for a long time provided a general purpose framework for simulating construction operations based on Activity Scanning simulation paradigm for discrete event simulation. Such paradigms are not very well suited for situational simulation environments. They treat activities and events as time points, thereby making the representation of overlapping intervals of time difficult. SLAM II is a general purpose simulation environment that can be used across multiple domains for discrete event and continuous simulations using a Process Interaction simulation paradigm. However, it is also better suited for simulations rather than situational simulations. Also, because of its broad scope it would be difficult to introduce reasoning algorithms specific to the construction domain. The general impression is that the existing general purpose simulation paradigms and languages may not be appropriate for developing situational simulations.

The need for contextually rich education environments in construction suggests the development of general purpose situational simulation environments, which can be used by independent developers to build effective training environments. However, the absence of an existing simulation paradigm to effectively develop general purpose situational simulation environments for the construction domain indicates that there is scope for research in the area of developing a framework for a general purpose situational simulation environment.

1.1 Hypothesis and Objectives

The hypothesis of this thesis is: *This thesis proposes that a multi-agent framework can be used to create a general purpose situational simulation environment for the construction domain.*

The objectives can be listed as:

- Conceptualize problems in the construction management domain by classifying them into defined classes of problems (like CSP or planning problems)
- Develop a conceptual framework for situational simulations based on product, process and information models
- Develop a "language" 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 which captures the concepts of equilibrium during the implementation of a construction project
- Based on the mathematical model of the construction domain suggest a functional semantics which can be used by an agent to reason about the sensitivities of the simulated system to the changes in the different aspects in the environment.
- Develop a multi-agent framework which can be used to create general purpose situational simulations
- Develop the semantics for a language that can be used in future to develop a programming language for a general purpose situational simulation
- Implement the system within the proposed multi-agent framework
- Develop a specific situational simulation for the construction of a major base ball league stadium
- Experimentation and interaction with expert and novice construction managers

Please find a time schedule of completion of listed objectives in Appendix A.

1.2 Potential Contributions

The contributions of this research (classified by area of research) can be listed as:

1. Construction Engineering and Management
    - Development of an environment which can be used by independent developers to build situational simulations that suit their educational requirements
    - The conceptualization of problems in the construction management domain in terms of constraint satisfaction and planning can lead to a theory of construction which does not borrow from the fields of manufacturing or the management sciences
    - The formalism developed as part of this research provides an expressive language to represent and reason about construction knowledge
    - Such a general purpose environment may be a very useful collaborative tool for educators in construction faculties across different universities
    - Participant performances studied over time can potentially reflect trends in learning patterns amongst students and thereby help educators in identifying strengths and weaknesses of their curriculum

- Investigates a system dynamics approach to understanding equilibrium during the implementation of a construction project
- Results from experimental study regarding learning patterns amongst construction managers might suggest knowledge organization patterns amongst construction managers

2. Simulation Technologies
    - This thesis introduces a multi-agent framework for *situational* simulations. The formalism used to define the framework can represent simultaneous events overlapping in time without using Distributed Interactive Simulation (DIS) technology. Also, the simulation time changes *during* events as opposed to traditional discrete event simulations where simulation time changes in *between* events.
3. Intelligent Environments
    - Investigates the use of intelligent agents to reason about and control the evolution of situational simulation environments in a complex real world domain like construction. The multi-agent approach is different from the widely used SOAR architecture.
4. Cognitive Sciences
    - Results from experimental study regarding learning patterns amongst construction managers may provide interesting insight into the cognitive processes of construction mangers

2 Background and Literature Review

In order to support the hypothesis that a multi-agent framework can be used to create a general purpose situational simulation environment for the construction domain and that such a contribution is indeed going to be an unique contribution to more than one field it is necessary to survey state of the art trends in research in some of the following fields.

2.1 Simulation Systems 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. In this section we 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 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. (ref to webpage).

Finally, the Event Scheduling (ES) systems use event graphs which comprise of 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).

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.

Situational simulation environments simulate the reality of the construction process. In real life, events and activities take time to occur. Events are unpredictable, can occur simultaneously, have deterministic outcomes, are causal in nature and are motivated by a logic specific to the simulated domain. 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. The system is interactive and as time passes it evolves based on participant interaction and the events simulated within the environment. Hence, 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 it is also best to have a distributed model for the different simulation tasks. None of the surveyed methods completely suit the requirements to provide a framework for situational simulations.

2.2 Survey of Existing Gaming Environments

The Construction Management Game and CONSTRUCTO are the earliest efforts at using simulation games in construction. 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.

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.

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. 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.

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 qued linearly and chained by dependency of input of each trade on the output of a previous trade.

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. It also uses MSBN, a probabilistic expert system to provide intelligent guidance to the automation of stochastic functions within the program.

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.

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 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. Bourgault, et. al., (2002), successfully tested the use of Video-conferencing and IT-based educational tools in a one day seminar across different geographical locations to illustrate real-time interactive simulation of engineering projects.

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.

The simulation systems discussed in this section are discrete event simulations, which can be classified under the PI simulation paradigm (ICMLS, Sawhney, et. al. 2001) or the ACD simulation paradigm (STRATEGY, McCabe, et. al. 2000).

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 our quest for an abstraction of processes in the construction management domain, we 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 paper 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 and software environments. However, as Tambe et. al. (1995) explains, though closely related the concept of using agents for synthetic environments differs from both 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). We investigate the SOAR architecture 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 choosen, 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 Puzzle problem amongst other problems.

The reason why the SOAR architecture is of great interest to us is because, Tambe et. al.(1995) have successfuly 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 aircrafts, across a network of workstations. The aircrafts 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 also running multiple FSMs. The proposed framework runs multiple finite state machines (for each activity context) within a single simulation model. This has been explained in detail in (Mukherjee and Rojas 2003).

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 a $d = (\Delta, \rho)$ where Δ is a base set of formula in some logical language and ρ 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 $\varphi | \Delta \vdash_{\rho} \varphi$ 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 autonomously 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 a 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 Cognitive Sciences

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 System Dynamics

The situational simulation environment emulates the construction management domain and therefore must be based on an appropriate representation for the domain. Later sections in this paper describe a representation using a formal axiomatic system that allows us to express the semantics of the construction environment and provide a language to reason about its evolution. However, it must be understood that while such a computational representation may be useful for developing virtual environments, it may not necessarily be the best mental model for the students to perceive. After all, the real world isn't really perceived as a formal axiomatic system, even though it may be conceptually modeled as one. The ultimate fulfillment of a learning environment lies in how well students perceive what they are supposed to learn. Such a demand calls for an approach which captures the nature of the construction domain. The quest for an appropriate model which can be best used to define the perception of the environment takes us to the cognitive sciences.

Van Gelder and Port (1995) argue that the problem with the computational approach to cognition is that it fails to recognize that "cognitive processes and their contexts unfold continuously and simultaneously in real time." In the computational model time is a sequence of discrete states. The authors further go on to state that decision making problems cannot be expressed completely within the computational model of human cognition. Such problems usually use a symbolic representation for a range of possible choices, their outcomes and associated utility values. Then, in a sequence of symbolic manipulations, the outcome with the highest "utility" is chosen. The authors argue that such a model, by leaving out time from the picture cannot predict how a particular choice can be more or less attractive at different points of time. Also, it does not take into account the effect of the time spent in the deliberation process on the decision itself. They finally conclude that an alternative approach to understanding cognitive processes is by treating natural cognitive systems as dynamical systems.

A system is a set of self contained aspects of the world, which interact and evolve over time. In a dynamical system all future behavior is defined by some rule on the current status of the world. Natural systems are best described as dynamical systems, as such an approach focuses on the behavior of different aspects in the system over time and how such behavior affects its evolution. Cognitive processes are best described by the systems dynamics approach, because they are also part of the natural world (van Gelder and Port 1995). Such an understanding has lead educators to look at learning as perception within a dynamical system. Given that *conceptually* both cognitive processes and natural systems can be modeled as dynamical systems, it is reasonable to assume that education environments, which aim at developing students' cognitive facilities by allowing them to construct concepts from their experience in the environment, be presented to them as dynamical systems. This will facilitate and aid the process of learning and create a better mapping between the students' cognitive processes and the system at hand, than a perception grounded in the computational approach would.

The question is, can the construction management domain indeed be modeled as a dynamic system? Sterman (1992) describes the use of system dynamics modeling for the management of construction projects. He describes the construction management domain as a "tightly coupled" system, and goes on to state that "system dynamics can capture such interdependencies so that the causal impact of changes can be traced throughout the system." He further states that the system dynamics approach can be used to deal with "dynamic complexity" arising from interdependencies in large scale projects.

2.6 Discussion

The fact that there have been various attempts at developing a number of simulation gaming environments can lead us to the conclusion that there is a need for contextualized training environments for construction managers. Situational simulations provide a great medium to provide such training environments. This is supported by evidence from the cognitive sciences, which suggest that the most appropriate environment would be one that embodies the context of the construction domain and embeds the learner into it, and through the combined evolution of the environment and the participant, supports the learning process. A survey of existing simulation paradigms and general purpose simulation languages in construction appear to be inappropriate to best represent and reason about situational simulations of the construction process. However, existing agent architectures and theories indicate that the situational simulation environment can be effectively built using a multi-agent framework. Finally, for the educational promise of the environment to be realized, it is important to develop an interface which will allow the participant to perceive the system dynamics of the construction environment. The uniqueness of this proposal is that it suggests a general purpose multi-agent framework for situational simulations and implements it using a system dynamic interface.

3 Methodology

3.1 Conceptualization of the Construction Domain

Simulations are based on theoretical models of the real life processes they emulate. Our understanding of complex real life problems at the highest level starts with an abstraction. An abstraction can be theoretically derived by dissociating detail from the underlying thread of reasoning. An understanding of the bare bone reasoning framework, provides us with a model, which provides a stepping stone to investigate the domain in greater detail. The conceptualization process consists of discovering the underlying threads of reasoning which support the construction domain. There are two approaches to conceptualizing the problem.

The first approach investigates the nature of the problems that relate to the pre-construction and construction phase of projects in an attempt to classify them as constraint satisfaction problems. Research reported in the literature suggests a CSP formulation for the construction planning phase (Succur and Grobler 1996, Hammond et. al 2000, Choo et al 1999). Further, an investigation is made into establishing conceptual relationships between constraint violations and the occurrence of events during the implementation phase of a construction project. Some examples of events are: a bout of bad weather, a delayed resource delivery, a technical problem relating to a specific construction operation like earth moving and a labor strike. Events often tend to be triggered by conditions and always have repercussions on concurrent and future activities. This hints at the causal nature of events in the construction environment. According to Suchman (1967), causality can be applied when one input appears to imply the occurrence of an output, and a causal relationship can be inferred by analyzing how input and output are related or associated. Soibelman (2002), claims that Suchman's model can be applied to events in construction projects. This investigation will help in providing a conceptual foundation that can be used to formally model the causal nature of events and their relationships to constraint violations within the construction environment.

The second approach creates a model that will serve as the basis for general purpose situational simulations. The framework is based on a conceptual framework of a process model, a product model and an information model. The framework has been discussed by Rojas and Mukherjee (2003). The product model of the simulation represents the constructs which make up the interface and the physical embodiment of the simulated environment. The information model encompasses information about the project that is being simulated. The information is coded into databases and knowledge bases. While the database has information about the 'As-Planned' execution of the project, the knowledge base has knowledge about actions and events, and related logical inference rules specific to the context of the construction management domain. The process model comprises of systemic descriptions of the processes being simulated. It is the very heart of the simulation.

3.2 Developing a Formalism for an Agent Framework

Design and implementation of a situational simulation involves an understanding of the reasoning processes. The reasoning processes can be isolated using a conceptual classification of problems in the construction management domain into constraint satisfaction and planning. Representation of information based on such a conceptual understanding of real life construction processes is the first step in creating situational simulation environments. Such environments should also have the capacity to reason about inter-relationships and abstract rules pertinent to construction processes, besides being responsive to participant interaction and design. This will allow the simulations to create consistent situations and evolve with the progress of time. It is useful to develop a formalism, which can represent precedence and resource constraints, and the causal relationships between events. The semantics of the formalism can be used by an agent to reason about constraint violations in the present and possible futures of the environment.

The objective here is to develop a formalism which uses the syntax of First Order Logic and semantics based on a deduction model of belief (Konolige 1986) 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 with individual identities and properties. Knowledge representation and reasoning is widely studied using first order logic (Russell and Norvig, 2002). To start with, the situational simulation environment is formally defined and characterized. The representation has to be based on an aspect of the environment which is non-variant in behavior across all possible simulations. Such an aspect should also be able to effectively express information about the environment. Time is such an aspect. No matter what the context of the simulation, the behavior of time is always consistent. This leads to an investigation of an interval representation of time as proposed by Allen and Ferguson (1994). Based on definitions of the environment and axioms of time, actions and events can be defined. Temporal logic can be used to expressively represent and reason about constraint satisfaction and the causal nature of actions, events and situations. Such a representation allows the creation of an axiomatic semantics which can be used for logical reasoning.

Rojas and Mukherjee, (2003) explains the mathematical model which defines the relationships between direct cost, indirect cost, remaining duration and production rate during the construction process. Each of these inter-related aspects of the environment are expressed as time dependent equations. In the simulation environment each of the equations are computed by programs. By denoting each program by a function we can develop a set of compositional relationships that will allow an agent to reason about the sensitivities of the simulated environment to its component aspects from a systemic perspective. This reasoning will provide the participant with a system dynamic approach to dealing with the problem and will also provide the necessary information for the interface.

Based on the formal axiomatic representation of the system and the defined reasoning methods, a multi-agent framework can be developed for the situational simulation environment. The framework is based on agent operations, which are defined within the formalism, which is in turn based on a general conceptual model of the construction domain. This general approach to building the multi-agent framework makes it suitable for developing a general purpose situational simulation paradigm. The framework can be used to develop a programming language with well defined syntax and semantics, that can be used to program a general purpose situational simulation. The implementation of the programming language is beyond the scope of this thesis.

3.3 System Implementation

A prototypical general purpose situational simulation for the construction management domain, the Virtual Coach will be developed as an implement ion for the proposed multi-agent framework. The system will be implemented over a web-based distributed client-server architecture. The goal of making situational simulations available to participants across distributed locations provides the motivation for such an architecture. This phase will include the development of an user interface which will provide the participant a perception of the dynamics of the simulated construction project. Implementation involving the information semantics in situational simulations (Rojas and Mukherjee 2003a), the information model (Rojas and Mukherjee 2002) and data mangement across the distributed architecture (Rojas and Mukherjee 2003b)has already been completed.

3.4 Situational Simulation Development

Once the Virtual Coach implementation is complete, it will be used to develop a specific situational simulation regarding the construction of a major league baseball stadium. This will involve acquiring AutoCAD drawings, 3D graphics, movie files, visual aids and information about an 'As-Planned' execution of the project. The whole process will also involve the development of situations that will be used in the simulation. This will indicate the success of using a multi-agent framework for a general purpose situational simulation.

3.5 Experimentation

This will include two different studies. The first study will conduct an investigation into how construction managers approach problem solving in the real world. The goal of this study will be to investigate if at all there exist patterns of knowledge organization amongst construction managers and if so to investigate the theoretical nature of such a pattern. Studies of experts and novices (Chi et.al. 1982) have shown that experts notice features and meaningful patterns of information, which cannot be reduced to set of isolated facts and propositions but is instead 'conditionalized' to sets of circumstances (Bransford et.al.,2000). The following steps will be used while conducting this study:

- Develop situations typical to construction projects. This will involve interaction with experts.
- Develop hypothetical event centric concept maps to reflect the interplay of the aspects involved in the situation.
- Develop a questionnaire, which will elicit the opinions of participants regarding their belief about how the aspects involved in the situation interact.
- Collect responses from construction managers with varying levels of industry experience.
- Use *ConProFac* (Concepts Propositions and Facets), a software developed by Prof.Bill Winn at the University of Washington, to study association patterns in the responses. *ConProFac* is based on the theory of parallel distributed processing (Rummelhart and McClelland 1988). Based on the information collected from the participants *ConProFac* simulates the connection patterns between different conceptual units that reflect how the participant associates the concepts with each other.
- Investigate if there is any significant statistical correlation between the experience of construction managers and the generated association patterns.

This study is completely open ended. However, if objective relationships can be discovered between the way construction managers tackle problems and the length of time spent by them in the industry, then this could be a starting point for further investigation in the area. The method could also be potentially used in future to investigate the effectiveness of situational simulation environments in construction. However, the effectiveness of this method is contingent to its success.

The second study will be conducted after the completion of an implementation of the Virtual Coach. This will involve a subjective testing of the environment. It will involve the voluntary participation of expert and novice construction managers in the environment, and elicit their reactions to the environment. An objective testing of the effectiveness of the developed environment cannot be conducted due to limitations of time.

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