# Interactive Situational Simulations in Construction Management

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Abstract: This research effort proposes that interactive situational simulation environments can provide platforms for better understanding the construction management domain as a closely coupled system of human and resource interactions. Situational simulations create temporally dynamic clinical exercises that expose participants to rapidly unfolding events and the pressures of decision-making. Such environments can be used for training fledgling construction managers, and as test-beds for better understanding the cognitive and meta-cognitive processes involved in the CM domain. The focus of this research effort has been to develop a general-purpose framework for situational simulations appropriate for the CM domain that can be used to develop a wide range of special purpose education scenarios. In this paper we discuss the lessons learned about the CM domain from the testing of the Virtual Coach, an implementation of such a framework, as well as, future directions in which pertinent research can be pursued.

Key Words and Phrases: situational simulations, general-purpose framework, multi-agent framework, system dynamics, cognition, and education

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## 1. INTRODUCTION

Barab et al. [1] 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 [2]. As it is the case in other fields, this duality has resulted in a disconnect between the theory and practice of construction management (CM). While 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, 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 numerous states and where logical complexities are best described in terms of the conditions required to carry out the activities [3]. 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 how knowledge in the CM domain is managed. To start with, traditional CM classroom training methods deliver concepts that are presented as fixed, well-structured, independent entities and classroom activities are disconnected from authentic context resulting in fragmentation and specialization of courses and educational experiences. This fragmentation of knowledge [4,5] 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 [6].

As experienced construction managers are retiring and fresh graduates are not being prepared appropriately for the CM industry, a void is being created that could pose problems in the future. In addition, there are few methods that allow us to analyze and study how experienced managers engage in decision-making. Given that experienced decision-making plays a critical role in the success of construction projects, studying the CM domain as an interdependent system of human and resource interactions will help in better answering 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?

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 in specific and the project being simulated in particular. In such an environment, 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.

This research effort proposes that interactive situational simulations allow us to study the construction management domain as a dynamic system, consisting of human and resource interactions. We start this paper with a brief discussion of the conceptual and formal foundations of a general-purpose framework for situational simulations and the Virtual Coach, a particular implementation of the framework. The focus of this paper however, is to analyze how situational simulations like the Virtual Coach can be applied to the CM domain. Specifically, we explore possible applications in allowing novice construction managers better recognize the systemic relationships that govern the CM domain and better understand the impact of such constraints on their decision-making skills. We also explore ways in which such environments can be used as test-beds for understanding cognitive and meta-cognitive activity in construction managers.

## 2. SITUATIONAL SIMULATION

A situational simulation is a part machine (computer software/hardware) and part human environment. The machine is responsible for simulating the CM environment using construction domain specific knowledge while being sensitive to how human participants react to it. For example, given the knowledge that labor when overworked will tend to produce lower quality work the machine would infer a ``re-work'' event when the human participant tries to crash activities by making labor work over time too often. It can also create a ``bad weather'' event that disturbs progress on outdoor activities. The human participant is expected to finish the simulated project within time and budget constraints as they would in real life. Thus, their responsibility is to constantly make challenging decisions regarding resource allocation and time-cost trade-offs. As the simulation proceeds, there are a large number of ways to complete the simulated project. The evolution of the simulated project depends on the reactions of the human participant and the scenarios generated by the machine in reaction.

### 2.1 Simulations in Construction Management

In this section we will briefly survey existing work that has already been done in the field of construction management simulations and establish the need for developing situational simulations. Simulations in construction engineering and management 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 [7], STRATEGY [6], ICMLS [8], CONSTRUCTO [9] and VIRCON [10] are all examples of simulations that deal with construction management processes, Simphony [11] and STROBOSCOPE [3] are examples of simulations that 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 [11,3]. Most simulations in the area of construction management processes are special purpose in nature. They deal with specific problems in planning [12] or bidding [7] or negotiation [13].

The third approach to classifying simulations can be based on how interactive they are. Situational simulations are interactive simulations and can be used to develop "what-if" scenarios involving construction management processes. For instance, in a situational simulation of an earth moving operation participants might be in a situation where they have to deal with finishing an operation within time and budget constraints, under the influence of bad weather and a labor strike. Participants are exposed to temporally dynamic, clinical exercises amidst rapidly unfolding events and to the pressures of quick decision-making. Most of the surveyed construction simulations have very limited user interactivity. ICMLS and STRATEGY allow user interaction and are both designed for educational purposes. However, they lack programmability and are special purpose in nature. Simulation languages like STROBOSCOPE and CYCLONE provide a general and special purpose framework for simulating construction operations and construction management processes, with absent or limited interactivity.

The dominant simulation paradigm for the reviewed simulations in construction management is based on the Activity Scanning. Such a paradigm models construction operations as a sequence of construction tasks or activities each of which has a set of defined conditions and outcomes. 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 [3]. 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 to represent the relationships between the activities, conditions, outcomes using directional arcs. The direction of the arcs goes 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 ACD paradigm would have to be modified to develop situational simulations. The primary reasons being the underlying approach to representing time. Activities in the ACD paradigm are represented as discrete time points thus making time a linear progression from activity to activity that may or may not be contiguous or even evenly spaced. In order to simulate an environment that can express multiple parallel events overlapping partly or completely on a time line without gaps such a discrete representation of time is not suitable. Moreover, situational simulations need to be able to reason about participant reactions and be able to plan the future evolution of the simulation. This requires autonomous intervention that is heavily dependent on the simulation environment being able to reason about the construction information general to the CM domain and specific to the project being simulated. The ACD representation can be extended to represent activities as intervals by defining them by initial and final variable time points, however, that would still not allow autonomous reasoning about construction information without introducing methods that allow representation and reasoning of construction knowledge mathematically.

There is no doubt that the ACD paradigm can also be used to build situational simulations, because in the end all representations are equivalent. However, we decided to instead use interval temporal logic [14] as it provides a more suitable interval representation of time and the foundations for developing expressive semantics that can be used to represent and reason about construction information.

## 2.2 A General Purpose Framework

A situational simulation of a construction project needs to have access to all relevant "As-Planned" project information including schedule, cost information and resource requirements stored in a database. The schedule information includes project activity schedules in the form of Gantt Charts outlining scheduled early start dates, durations and floats of activities and the temporal and resource dependencies between them. The cost information includes the unit cost price for each of the different types of material, labor and equipment that will be used during the project and the activities to which each of them are assigned. Besides the project information, the simulation will also have to "know" about the CM domain in general and the project in specific. General "knowledge" of the domain includes relationships between over work and productivity, the impact of weather on outdoor activities and the relationships between cost, schedule and project productivity, among other things. Specific "knowledge" about the project includes project area weather patterns, project activities that are outdoor, etc. Based on such knowledge stored in a knowledge base and the "as-planned" information provided, the situational simulation should be able to infer a loss in productivity of an outdoor activity in the case of a bad weather event and appropriately project the delays in the schedule and show comparisons between "as-planned" and "as-built" progress. The simulation would also need to be able to create a bad weather event based on its "knowledge" of the project location. Similarly the simulation can limit productivity on an activity in response to the participant crashing activities beyond given limits.

A general-purpose framework (GPF) provides a protocol that allows us to develop simulations for simulating many different projects. It can be used to encode, compute and infer with the information stored in the above-mentioned database and knowledge base. In addition, the common protocol will allow a community of developers to share, extend and build on simulations and foster collaboration in CM education. The participants of such a community can belong to academia and industry, with the common goal of training construction managers. It is a robust extensible protocol that provides the backbone to the situational simulation.

While simulating the specific construction projects, developers can augment the knowledge base with project specific information and a database that contains all project specific "as-built" information using the general-purpose framework. In the following sections we discuss the conceptual and formal foundations of such a framework and the Virtual Coach, an implementation of a hypothetical construction project using the general-purpose framework.

## 2.3 Conceptual and Formal Foundations

The conceptual foundations of the framework lie in modeling the construction management domain as a constraint satisfaction problem (CSP) during the pre-construction phase and as a planning problem during the project implementation phase. There is evidence in the literature to support the use of CSP for construction problems [15,16]. Furthermore, the constraints can be classified as either temporal constraints -relating "when" an activity may or may not happen- or resource constraints -describing "if" it is feasible for an activity to happen given the available resources. Given a set of resource constraints (availability and cost of material equipment and labor requirements bounded by a budget) and a set of temporal constraints (activity dependencies, lags and floats) the "as-planned" resource loaded schedule is a satisfiable solution for the given constraints. During the implementation phase, "events" happen when there are constraint violations and the participant is expected to make changes by allocating/reallocating resources to satisfy the constraints.

Situational simulations focus on creating interactive environments for the implementation phase of construction projects and hence need to center on detecting constraint violations as events, be sympathetic to participant input and then be able to forecast future implications of such events. This involves satisfaction of resource and precedence constraints, and reasoning processes, which govern actions and events in the construction environment. The foundations of the general-purpose framework lie at the very heart of this general understanding. Given a language to represent and reason about CM constraints such an understanding can provide the basis to simulate a diverse set of scenarios in the CM domain.

Based on the axioms of time, using First Order Logic, a formal language was developed that allowed expressive representation and reasoning of CM information [17]. Also a generic model was developed to mathematically express the relationships between cost, schedule and productivity in the CM domain [18]. The formal language when used to define a simulation environment for the CM domain, and reason within it; and used in synchrony with the mathematical model to calculate changes in productivity and schedule, results in the desired general purpose framework that can be used to implement situational simulations for a variety of construction projects.

The framework was developed using a multi-agent architecture [19]. Interactive simulation technologies in other fields have also been known to use multi-agent environments [20]. The multi-agent architecture consists of autonomous interacting agents that run the simulation by maintaining consistency of the temporal and resource constraints that capture the systemic relationships between costs, schedule and resource allocation. Thus, the human participant and the autonomous agents react to each other and together control the evolution of the simulated project, thus making it a part-human/part-machine adaptive environment.

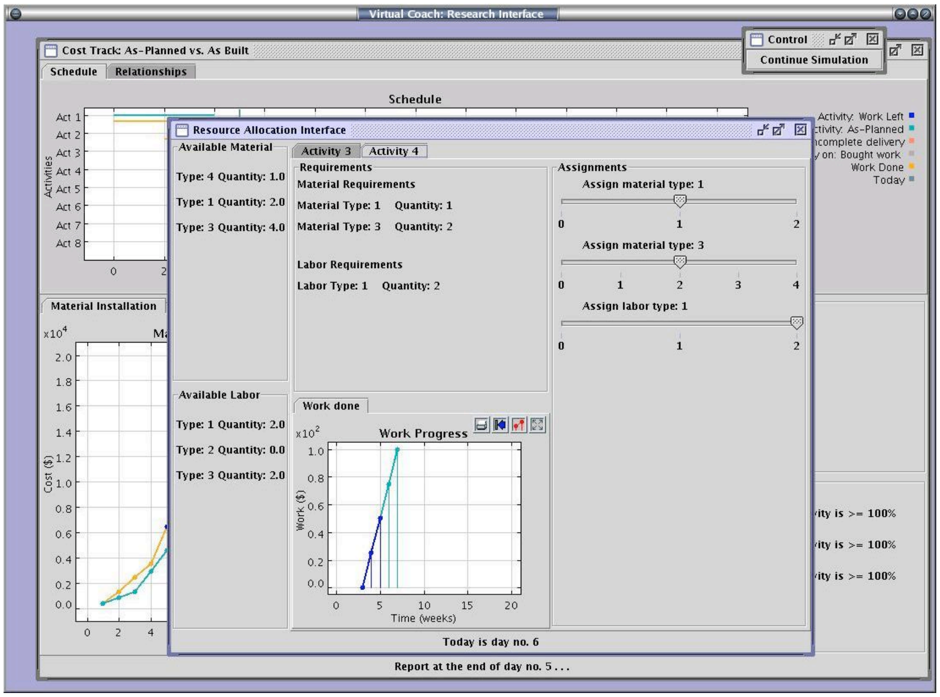


Fig1. Resource Allocation Interface

### 2.4 Implementation: The Virtual Coach

The Virtual Coach is a particular implementation of the general-purpose multi-agent framework for situational simulations. In a pilot implementation of the Virtual Coach, we simulated a twelve activity hypothetical project with realistic constraint violations and event information. In the 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

The Virtual Coach was implemented using Java 1.4.2 SDK and a PostgreSQL database server.

Participants have the ability to allocate, reallocate, or procure resources from the market place. Figures 1 and 2 provide screen shots of a preliminary deployment of the system. Figure 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.

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 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

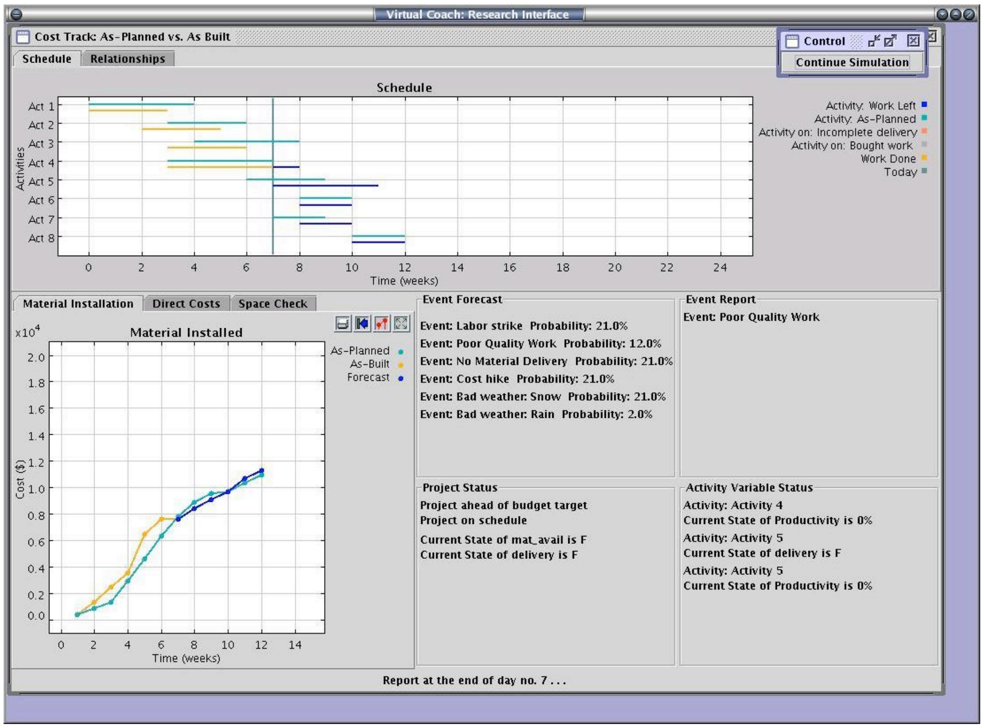


Fig 2. End-of-day Report

of the participant is to steer the project through generated scenarios and complete within budget and time constraints.

## 3. APPLYING SITUATIONAL SIMULATIONS TO CONSTRUCTION MANAGEMENT

As discussed earlier, the focus of this paper is to analyze different directions in which situational simulations like the Virtual Coach can be used in the CM domain. This leads us to explore the usage of interactive simulations in other fields, similar to the construction management domain, where skill is strongly related to experience. In the politico-military arena interactive simulation environments have been often used for developing training environments [21,22,23]. Interactive simulations using autonomous agents have also been used to train fighter pilots [20]. Such environments have been exploited effectively in natural disaster relief management [24]. There is evidence of their usage in diverse training environments such as The Virtual Gorilla Project at the Atlanta Zoo [25], The Virtual Puget Sound [26] in the field of oceanography and the Surgical Simulator [27] in the field of surgery are some noteworthy efforts that support the use of simulations for training. This supports the use of situational simulations as environments that could be used to train novice construction managers. However, it is important to explore how interactive situational simulation environments can help learning, and what we can learn about learning in the CM domain using such simulation environments. In other words what insights can we get regarding cognition and meta-cognition in the CM domain?

### 3.1 The Cognitive Science Approach and the System Dynamics Perspective

The prevalent approach to understanding how people learn has been the computational approach to human cognition. Such an approach says that knowledge about the world is represented in memory by static structures of discrete symbols, and all cognitive operations (learning and decision making) are essentially discrete, sequential and instantaneous transformations from one structure to the next. However, criticisms that cognitive activity is contextually situated [28] and is not simply a mapping of external events to an internal symbolic system [29] has led researchers to study the context and culture in which cognition occurs [30]. Recently, the 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” [31]. 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” [32].

Winn [30] 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.” 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.

Meanwhile, Port and Van Gelder [33] have also argued 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.” The authors further go on to state that decision-making problems cannot be expressed completely within the computational model of human cognition because it does not take into account changes in behavior of parameters and components over time. There is no explicit representation of time beyond it being a sequence of discrete events. It also 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 cognitive systems as dynamical systems.

This echoes Winn’s [30] 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 we cannot deny the critical role of human decision-making in it.

At this point it is important to get a brief understanding of the systems perspective and explore system dynamical approaches as applied to other areas in general the field of CM in specific. 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 we want to understand and influence the change of behavior over time [34, 35] 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 [36, 37] 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 layman’s approach to understanding the emergent behavior of complex systems, without being intimidated by the mathematical methodologies employed in analyzing system dynamics.

Richmond [36] 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. As we proceed 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 [38] 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 [39] 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 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 [39] 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 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.

## 4. EXPERIMENTATION AND RESULTS

The objective of our experimental work was to find out if situational simulations like the Virtual Coach can be used to train novice construction managers. Also, we wanted to draw conclusions about learning in the CM domain based on our observations of how, if at all, such environments can be used for understanding cognition in the CM domain.

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 students took pre and post-tests before and after they experienced the simulation. They 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. The pre-test and post-test required students to rank (on a scale of 1-10), in their opinion, the importance of a list of factors in developing a plan for a 12 week period of a 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.

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, etc.) The difference between the ratings was significantly different:

Table 1: Student Performance in Pre- and Post-Test

| | **Mean** | **Std. deviation** |
|---|---|---|
| **Pre-Test** | 21.26 | 4.92 |
| **Post-Test** | 25.31 | 4.70 |
| **T-statistic:** $t(18) = 3.32$, $p < .01$ | | |

It is interesting to note that the questions on which the students showed significant improvement dealt with resource or temporal constraint satisfaction suggesting that students learn by understanding the underlying constraints present in a project and apprehending their violations.

A qualitative analysis of the participant's '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 we got from 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 varaibles.***
>
> 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 unforseen 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 discisions affect the project. for example, it would have lice 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 likelyhood 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 decidions 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 4's 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).

## 5. DISCUSSIONS AND CONCLUSION

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 post- and pre-test results; and the high differential values of the confidence interval as illustrated in Table 1; we can conclude that an intervention using situational simulations can be useful in construction education.

From our study we also conclude 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 paper. 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 [40].

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