ATTRACTING THE NEXT GENERATION
A MULTI-DIMENSIONAL SIMULATION FRAMEWORK FOR CONSTRUCTION EDUCATION
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A Multi-dimensional Simulation Framework for Construction Education

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Introduction

The need for new instructional methods to attract students to the areas of engineering, construction, science, technology, and mathematics is well-recognized. Today’s students are well-versed in information-technology-enabled games and other virtual environments and often equate virtual reality with hands-on experience. Recent advances in information technology (IT) fields, especially in the areas of interactive simulation and gaming, have opened unique opportunities for construction educators to attract the next generation by incorporating virtual reality into mainstream instruction. “Students involved in the architecture, engineering and construction disciplines are often faced with the challenge of visualizing and understanding the complex spatial and temporal relationships involved in designing three-dimensional structures” (Nicolic, Jaruhar, and Messner 2009).

Simulation games may provide a mechanism to reduce the learning curve if the simulations are intrinsic to actual real-life projects. Students trained using real-world examples placed in computer-based simulations will further their progress toward becoming valued professionals. The FIATECH project described in this paper is a preliminary attempt at building such an IT-enabled infrastructure for construction education. The proposed infrastructure consists of a simulation-based learning game focusing on the “3Cs” (cooperation, collaboration, competition) and designed to make learning construction concepts more engaging.

Background

Smith (2000) indicates that it is “fashionable” to distinguish data, information, and knowledge. Smith further states that “data placed within some interpretive context acquires meaning and value” and that “knowledge is the collection of information into concepts meaningful to individuals or groups.” Goodhue and Thompson (1995) indicate that “for many system users, utilization is more a function of how jobs are designed than the quality or usefulness of systems, or the attitudes of
users toward using them.” Their information systems (IS) research provides insight into the linkage between information systems and individual performance, focusing on two primary objectives:

(1) To propose a comprehensive theoretical model that incorporates valuable insights from two complementary streams of research, and

(2) To empirically test the core of the model.

Goodhue and Thompson (1995) also develop a measure of task-technology fit that consists of eight factors: quality, locatability, authorization, compatibility, ease of use/training, production timeliness, systems reliability, and relationship with users. They define technologies as tools used by individuals to carry out their tasks. Tasks are broadly defined as the actions carried out by individuals in turning inputs into outputs. “Technologies must be utilized and fit the task they support to have performance impact” (Goodhue and Thompson 1995). Zigurs et al. (1998) present an analogous model operating at the group level.

“Although knowledge management (KM) is well established in the construction industry, experience management (EM) is a new concept in information systems. Knowledge management is a collection of processes governing creation, storage, reuse, maintenance, dissemination and utilization of knowledge” (Lin 2009). “Since knowledge sharing and reusing can reduce project time and cost and improve management performance, knowledge management is becoming more important than ever in the construction industry” (Hu, 2008). “However, knowledge is separated and scattered in construction projects, and each construction project is managed independently and separately. “The knowledge acquisition, and sharing across projects, becomes impossible when the employee moves from one company to another” (Hu 2008). Smith (2000), referencing Hubert and Dreyfus (1984), further categorizes knowledge as “explicit or tacit.” Nonaka (1994) defines explicit knowledge or codified knowledge as knowledge that can be easily articulated in formal language. Nonaka and Takeuchi (1995) refine this definition to include grammatical statements, mathematical expressions, specifications, and manuals. Explicit knowledge can be easily shared but is removed from direct experience. “An example of explicit construction knowledge can be object based, i.e., as patents, software code, databases, technical drawings and blueprints, chemical and mathematical formulas, business plans, and statistical reports, or rule based, i.e., expressed as rules, routines, and procedures” (Stenmark 2009). An example of how explicit knowledge can be used is found in computer-aided design (CAD), where the designer creates architectural and engineering plans by employing graphics software that “draws” from information commonly used in the industry.

Tacit knowledge is developed from direct experience and action and is often referred to as knowledge-in-practice (Smith 2000). “The importance of tacit knowledge in organizational learning and innovation has become the focus of considerable attention in the recent literature” (Lam 2000). “The construction industry increasingly employs 4D CAD models for detailed schedule reviews, but commercial applications currently used for creating these 4D models are often inadequate for construction engineering education due to their inability to concurrently create and review schedules” (Nikolic, Shrimant, and Messner 2009). Effective transfer of tacit knowledge generally
requires extensive personal contact and trust.¹ Lin (2009) concurs with these findings, suggesting that our industry’s educational strategy must encourage and reward tacit knowledge transfer from senior and experienced construction and engineering professionals “to enrich training and educational experience content.”

The IT-enabled infrastructure for construction education proposed by this paper builds on a long and rich history of earlier simulation-based learning tools, including those employed in the area of astronomy (Stickel et al. 1994), flight simulation software (Boeing, NASA 2009), and socio-technical simulators for urban infrastructure (Liu, Subramaniam, and Marathe 2003) (Lowry and Subramaniam 1998).

“During construction, project managers constantly review actual project performance and resolve any discrepancies between as-planned and as-built progress. However, it is not always easy to perform these activities since numerous individuals and parties are involved in a typical project” (Lee and Rojas 2009). Karamchedu (2005) defines this decision-making process as the “craft of thinking,” further stating, “from the execution context viewpoint, each block is no longer a mere set of tasks with inputs and outputs, but is a context unto itself. Each stage has a decision threshold. Decisions are to be made within a context that transforms it to the next context. The progression occurs when the decision threshold is crossed and thus the project moves forward.”

“It has often been said that a person really doesn’t understand something until he teaches it to someone else. Actually a person doesn’t really understand something until he can teach it to a computer, i.e., expresses it as an algorithm... the attempt to formalize things as algorithms leads to a much deeper understanding than if we simply try to understand things in the traditional way.”

—(Quoted from Knuth, 1973; in Kunz et al. 2002)

Engineering and construction design consists of many interdependent decisions (Lewis, Chen, and Schmidt 2007). “An understanding of project sequencing and value can be portrayed as a series of options and their consequences” (Jackson 2008). However, Lin (2009) finds that “...few suitable platforms have been developed to assist engineers in sharing their experiences when needed.”

“Project complexity requires that large decisions be divided into smaller ones,” but “project value often lies at the intersections of these separate and specialized knowledge disciplines” (Rechtin 1991). “State-of-the-art visual aids have been developed with advanced computer technology such as computer animation, virtual reality, and 4D CAD” (Lee and Rojas 2009). Some have proven successful. In 2002, Stanford students from the Center for Integrated Facility Engineering universally reported after graduation that their experiences provided a unique and far-reaching view of the practice and issues in the use of IT in construction engineering and research. “Students appreciate

the opportunity to develop their own practical test cases, use modern computer methods, and validate their work in industrial settings” (Kunz et al. 2002). Davis et al. (2009) describe these virtual environments as “metaverses” defined as “immersive three-dimensional virtual worlds in which people interact as avatars with each other and with software agents, using the metaphor of the real world but without its physical limitations.” Owens et al. (2009) recognize that “virtual worlds and their technology capabilities can help virtual teams find new ways to face the challenges of managing a global IT workforce.”

Nikolic, Shrimant, and Messner (2009) investigated the effectiveness of a visual construction simulator to allow students to create and review construction schedules simultaneously while interacting with a 3D model. “The next research step is to extend the functionality of the visual construction simulator and add project-based constraints that will allow students to explore possibilities and consequences of decision making, evaluate construction options, and understand how to optimize construction processes” (Nikolic, Shrimant, and Messner 2009).

The effort to develop an IT-enabled infrastructure discussed in this paper used these encapsulated fact components to scale the technology so that students can obtain hands-on experience on real problems. Experience management in construction projects promotes an integrated approach to creating, capturing, sharing, and reusing profession-based domain knowledge obtained from previous projects (Lin 2009). The approach taken by FIATECH is based on deductive synthesis (Manna and Waldinger 1992) and formulates situation-specific solutions by applying automated inference technologies on codified construction domain facts obtained from domain experts.
**Infrastructure Overview**

The architecture of the proposed IT-enabled infrastructure for construction education is shown in Figure 1.

![Diagram of the architecture](image)

**Figure 1. Architecture**

The architecture comprises three main interacting engines—a learning engine, an evaluation/guidance engine, and a consistency engine—along with a knowledge repository containing fact components and problem-solving tactics. Additionally, the architecture is Web-enabled and allows users to create their own online wikis to share experiences as well as retrieve knowledge by Web searches.

Each learning experience is modeled as a problem-solving activity where the solutions are a predetermined sequence of situations. Starting from an initial situation, users perform actions by interacting with the system to transition to the next situation. User actions in each situation are evaluated by the evaluation/guidance engine, which compares them with existing actionable solution plans to create scored situations. Scores, along with explanations, are communicated to the users.

In each problem-solving session, a solution plan is extracted from the knowledge repository by identifying the initial and final situations for each problem. Re-planning is performed whenever user actions deviate from the existing solution plan. Each extracted solution plan is communicated to the learning engine and adapted by the learning engine based on the learning modes to create
actionable solution plans. These plans are in turn given to the evaluation/guidance engine, which uses them to assign scores to user actions.

The consistency engine in the proposed system is used to consistently evolve the knowledge repository based on Web resources. The engine uses an automated reasoning tool to ensure that each additional piece of information is a conservative extension of the existing knowledge.

The proposed system is highly configurable in terms of user skill levels as well as the different learning modes. User skill levels of novice, medium, and expert are supported. These levels constrain the privileges as well as the help provided in problem solving; for instance, only system-certified experts can update the knowledge repository. Supervised, reinforced, and unsupervised learning modes are supported. The supervised learning mode creates system-prompted solutions that users must successfully replay. The reinforced learning mode is the same as the supervised mode, except that certain steps have barriers that must be replayed without system help. The unsupervised learning mode requires users to provide time-bound solutions to meet the current project constraints. Additionally, users may either play the system in a practice mode where sample competitions with the system are supported, or use a tournament mode that supports multi-user/team competitions with randomly generated situational emergencies.

On the impact on student learning…. “Wendy Newstetter, one of the founding members of the Performance Based Learning team at Georgia Tech, reports that solving problems on the frontiers of science that other experts are trying to solve at the same time, does two things: it motivates students tremendously, and has a very interesting impact on identity. A major problem with students going into the sciences and being sustained is that they don’t identify with the kind of activity they are being asked to do. Whereas, when you give them complicated multi-dimensional, interdisciplinary problems from the real world, their imagination is sparked. They begin to say ‘I can see myself doing this.’ So problem solving is about motivation and identity, about engaging students through the excitement and fantasy of trying to solve those problems.”

—(Project Kaleidoscope 2006; reported in Narum 2008)

Knowledge Repository and Problem Solving

Domain expertise is codified as facts using extended first-order logic and expert-supplied explanation tags. Each fact has a pre-situation, a post-situation, and a series of actionable steps to reach the latter from the former. Facts are combined to form fact component—compositions of facts starting and ending in situations. Facts may be composed using a variety of composition operators, including sequencers, decision-trees, and iterators. An example of the codified knowledge for residential housing is given in Figure 2.
The knowledge repository is used to create actionable steps to reach a goal solution from the given situation. Each solution is a composition of fact components whose pre-situation satisfies the given situation and whose post-situation satisfies the goal situation. Solutions are compiled into a sequence of actionable steps to form an actionable solution plan.

Each project usually has more than one possible solution and solution plan. Alternative solutions are ranked based on cost, time, and other expert-specified constraints. Structure-sharing among solution plans is used to compactly represent all alternatives. User actions are guided and evaluated based on actionable solution plans.

**Learning-Mode-Specified Solution Delivery**

Each solution plan is customized in accordance with the learning mode to achieve systematic learning. To do this, a replay capsule is created from each solution plan by annotating each actionable step in the plan with learning attributes such as explanation tags, pitfalls, and rollbacks. Explanation tags provide instructional and informative rationale for each step. Pitfalls highlight common errors, and rollbacks provide error recovery for repetitive learning.

In the supervised learning mode, the replay capsule is auto-generated for the optimal solution. Each actionable step in the capsule is played out to users with explanations, pitfalls, and rollbacks. The users replay the step and are restricted to relevant actions. The system play and user replay can be repeated as needed based on user request.
In the reinforced mode, replay capsule steps are populated with barriers that can be crossed only upon successful completion. Barrier steps are selected using domain expertise. The system also supports a single-step reinforced learning mode where a barrier is added to each step. The system provides hints/demonstrations to help cross barriers.

Unsupervised learning modes support incremental maintenance and repair of solution plans. The system is an implicit player in these modes. The system creates and maintains replay capsules up to a predefined limit. Sets of capsules become active based on observed user actions. User actions are compared with those in the active capsules and assigned scores. Unexpected user actions that block progress are repaired by rolling back the predecessor step. In this mode, emergencies are automatically created to challenge the users. An emergency is a system action that is unexpected or belongs to an inactive capsule.

**Collaboration and Competition**

Lin (2009) demonstrates the effective integration of a Web-based assistant people-based map experience management (APMEM) system into high-technology construction projects in Taiwan. Zhang and El-Diraby (2009) propose a role and ontology/taxonomy for construction product and process modeling that may evolve with the social or semantic web. In this example, collaborative learning is enabled by allowing users to share solutions that they discover in a particular problem-solving session. Unknown fact component compositions leading to a goal situation may be discovered by peers, for instance, by performing a sequence of unexpected actions. These compositions called tactics, can be added to the knowledge repositories. Tactics may also be discovered from Web resources such as mailing lists and Wikipedia® and added to the knowledge repository. These may be used to make progress from a blocked situation and/or to learn a new goal situation.

The system is Web-enabled and supports integrated peer blog forums that can be used to try unexpected actions that result in better solutions and enhance domain expertise. The information in such blogs can be in the form of either structured logs that describe starting and ending situations and actions, or annotations. Moderated informal logs (internal wikis) are also supported. Such information must be manually interpreted by experts to enhance the codified domain expertise. For instance, an expert may recommend the addition of an excavator with a jaw crusher attachment for demolition work.

Enhancing domain expertise using Web resources is a challenging problem and involves validating the new fact components and maintaining the overall consistency of all fact components. Validation is performed by consulting with domain experts and also by using reasoning tools for automatic verification whenever possible. To ensure practical consistency of the knowledge repository, new knowledge is limited to conservative extensions of the existing knowledge, i.e., new facts cannot contradict existing ones but may change their optimality.

The game-based environment with scores fosters competitive learning. The users can engage in tournaments that are customized based on the evaluation metric as well as the type of opponent.
Users may compete based on metrics such as duration or cost to complete the project. They may also set difficulty levels reflecting time required to play a step, predefined resource limits, and emergencies. The system, other users, or teams may be chosen as opponents.

Additionally, role-based competitions are supported. For instance, users may choose roles such as architect or contractor in both individual and team competitions. They may also choose opponents who play specific roles. In team tournaments, the system acts as proxy for the other roles.

Prototype Implementation

Figure 3 shows an Adobe® Flash® Player screenshot from the prototype game software. Users select learning modes via the Configuration button. This prototype is operational and has been tested on some residential housing examples provided by domain experts.

![Figure 3. A snapshot of the prototype](image)

The prototype was implemented using Adobe Flash CS3 Professional software and incorporates visual content generated by Google™ SketchUp™ sketching software. It currently supports two to four parallel activities in each project. Currently, only the supervised and unsupervised modes have been implemented; the reinforced mode will be added once it is populated with information from domain experts. The prototype supports only individual players but can be modified for group or collaborative use. The prototype has been successfully exercised on aspects of residential home construction, using domain expertise obtained via personal communications in 2009 with James Goedert and Young Cho, members of the Department of Engineering at the University of Nebraska.

Initial use of this prototype indicates that choosing the appropriate abstraction is crucial to capturing domain expertise. The current use of first-order logic, while appropriate, can be improved
by using syntactic sugar and pre-defined predicates to enable domain experts to validate the knowledge. Lessons learned about the prototype’s ease of use and gaming aspects are ongoing.

The prototype scenario starts with a sample video showing a house sample, as in Figure 3. Clicking Configuration in the menu enables one of two learning modes to be selected, namely supervised and unsupervised. This button also supports other options such as full screen and parallel activity. To start a new game, users click the Start button. Immediately, a tutorial is shown (Figure 4) that tells users what to do next. Additionally, users can go to the forum for more information. And they can see the house sample whenever they want by clicking House Sample.

![Figure 4. A snapshot of the tutorial](image)

When users exit the tutorial, they see an activity box (Figure 5). Users can select at least one, but no more than four, activities. After users confirm their selection(s) by clicking OK, they see the evaluation results with cost and duration (Figure 6). If users mouse over the Batter Board in this animation, they see the Batter Board’s educational interface (Figure 6). Following the tutorial and then clicking Next takes users back to the activity box.
For each activity, users need to select the appropriate equipment and human resources, if these are necessary. For example, an optional solution after the survey activity is the excavation activity. To successfully complete excavation, users need operators and appropriate equipment. They select these by clicking the Equipment and Human Resource buttons. Additionally, when users mouse over a piece of equipment and an operator, they see an educational interface that helps them decide whether to use the equipment and how many pieces they want. Snapshots of educational interfaces are shown in Figure 7.
After selecting equipment and personnel, users see an interface showing the total cost of their selections and the results (Figure 8).

![Figure 8. A snapshot of excavation activity with total cost](image)

If the selection results in no solution, an error message and advice from the system are shown in the message box. Users may hire a consultant for advice and to increase their learning experience. For example, in the foundation construction activity, there are several sub-activities. If users select these sub-activities in the sequence of Install Footing → Set Forms → Place Concrete → Install Rebar 1, the error message shown in the message box on the left side of the snapshots in Figure 9 is displayed. The message indicates that there is no solution based on this selection. (Note: Because the activity animation or picture is not available currently, just a single representational picture is being used temporarily. The prototype may be updated later when more animations become available.)

![Figure 9. Snapshots of error message](image)
When users need help, they can pay for a consultant's services. The consultant explains why the users failed and provides feasible solutions. Users must then replay the scenario. Snapshots of consultant services are shown in Figure 10. Users can continue to select activities step by step.

**Future Research**

The architectural, engineering, and construction (AEC) industry has made significant strides in improving jobsite productivity through the use of new IT applications referred to as virtual design and construction (VDC) tools. These tools help professionals to visualize, analyze, and evaluate project performance (Exponent 2009). The continued development of IT-enabled infrastructure for construction education across the spectrum of expertise should prove especially beneficial to students who go on to work on construction projects that use VDC systems.

Fox et al. (2008) recommend radical reductions in the time needed to communicate specific skills and offer two alternatives toward improvement. First, these authors recommend that products and processes be designed so that the specific skills they require can be communicated more easily and quickly to more people. Second, they recommend the formulation of “the communication of specific skill knowledge so it can be understood and changes the primary repository of skill information from being a person (e.g., a craftsperson) to being a digital information system (e.g., a knowledge-base).” To address shortages of qualified candidates in the construction industry, Everett and Slocum (1994) note that automation and robots offer solutions to industry-wide problems of increasing costs, declining productivity, skilled labor shortages, safety lapses, and quality control issues. “The development of a systematized approach to construction using largely dry, prefabricated components delivered just-in-time has advanced the degree of automation now possible. Automated machines are, in fact, robots. They not only carry out a complex sequence of operations, but can also control their performance Fox et al. (2008).”

Although it is still in its early days, “development of this kind is indicative of a longer-term trend” (PATH 2009). Such research is consistent with laying the foundation for more effectively employing current advances in construction automation, which is characterized by using a machine to perform physically intensive basic tasks, with operational support provided by a human craftsperson who
performs the information-intensive basic tasks. Fox et al. (2008) confirm that current practice still prevails, suggesting that “skill knowledge is typically communicated through one-to-one face-to-face human interaction between a person with relevant existing skills (e.g., a craftsperson) and a person without relevant existing skills (e.g., an apprentice).” The success of this type of system relies on encouraging the participation of, and extracting information from, construction industry experts. “Expert teachers are sensitive to those aspects of the discipline that are especially hard or easy for new students to master” (National Research Council 1999). Lin (2009) points out that senior engineers and experts will play a vital role and need to be encouraged to dedicate the resources necessary to capture their experience. “There are no recipes or formulas, no checklists or advice that describes ‘reality’. There is only what we create through engagement with others and events” (Wheatley 1992).

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