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Reality-Based Construction Project Management: A Constraint-Based 4D Simulation Environment

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Introduction: Challenges and Innovations in Construction Management (CM) Education

Construction-related programs face a significant challenge of providing students with knowledge that works in industry. It is, therefore, not surprising that construction management (CM) programs are allocating more time in their curricula to provide students with such learning opportunities (Pierce, Gibbons, Limeges, Nowotny, Schwartzman, Scott, & Trow, 1995). As a way of meeting this need, a number of pedagogical and technological innovations were designed, tested, and implemented successfully into construction management programs. These innovations include internships, multimedia-based learning, service-learning projects, simulation, and games (Park, Chan, & Ingawale-Verma, 2003; Senior, 1998).

One of the simulation techniques, *4D virtual construction technology*, has gained recognition as an effective management tool (Schwegler, 2003). This technology allows users to present a complex construction process in an easy-to-understand format through the use of 3D graphical models in a time-lapsed or phased sequencing of events (Alianza, 2003; Haymaker & Fischer, 2001; Park & Martin, 2003). In other words, as shown in Figure 1 on next page, this technology lets users literally *grow* their buildings without physically building them on a real construction site. Since the users can see in advance what they are going to build and how they are going to build it in the 4D virtual construction environment, they can better manage and plan their construction projects.

Reported benefits of the 4D virtual construction technology include: construction schedule verification, alternative schedule generation, better trade coordination, effective temporary structure design, and active hazard anticipation and safety improvements (Brawn & Sloan, 2003; Ray & Reed, 2003). Due to its capability of presenting complex construction information in a graphically constructible format, the 4D virtual construction simulation technology provides an opportunity for CM educators to easily practice the "constructivist learning" paradigm in their education settings. Constructivist learning theory has given rise to an approach to educational practice that places the locus of initiative and control largely within the student, who typically undertakes substantial, "authentic" tasks, presented in a realistic context, that require the self-directed application of various sorts of knowledge and skills for their successful execution (Brooks & Brooks, 1993). Such activities often involve student-initiated inquiries driven at least in part by the student's own curiosity, and are designed to motivate students in a more immediate way than is typical of traditional curricula based largely on the transmission of isolated facts.

Constructivist curricula often emphasize group activities designed in part to facilitate the acquisition of collaborative skills that are typically required within contemporary work environments. Such group activities may offer students of varying ages and ability levels, and having different interests and prior experience, the opportunity to teach each other - a mode of interaction that has been found to offer significant

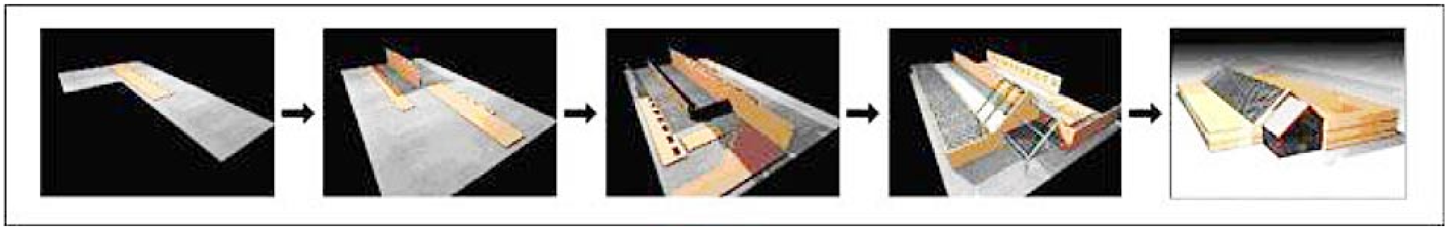


Figure 1. 4D Virtual Construction Simulation (Park & Wakefield, 2003)

benefits to all parties. Explicit attention is also given to the cultivation of knowledge about how to learn, and how to recognize and "debug" faulty mental models.

In the 4D virtual construction environment, CM educators can focus on students' critical thinking associated with the project, instead of, for example, focusing on the technicality of the CPM (Critical Path Method) schedule technique. In this simulation environment, teachers can ask questions that are designed to probe students' thinking in order to illuminate issues and problems associated with the project planning, scheduling, and execution. The responsibility of the students in this setting, therefore, is to become investigators/discoverers, team members, and/ or problem solvers.

Problems with Current 4D Virtual Construction Simulation

While 4D virtual construction simulation technology lends itself to "constructivist learning" in a large part, the current implementation of the technology has a critical drawback. The drawback is related to the fact that in the current 4D virtual simulation environment there are *no constraints* with respect to availability of resources and information. All the materials, equipment, and resources required to perform work are always readily available in the graphical environment. Students can complete work assignments without asking themselves if all the required pre-requisite work releases for the work to be performed have been granted. For example, precast concrete lifting operations are done in their 4D virtual construction site even without the essential consideration of acquiring and using a feasible set of resources such as machines, workers, and materials, and/ or without generating and reviewing a suitable set of information such as permits, inspections, purchase orders, submittals, change orders, and so on. This is because in the traditional 4D graphical virtual environment, users have no constraints on what and how they perform work.

The following description provides another example to illustrate this point. Consider two different construction projects in terms of their delivery methods: Project A is based on a typical design-bid-build process and Project B uses a design-build delivery method. If these two projects are simulated in the 4D virtual environment, is it possible for students to recognize and learn how the two different delivery methods impact the way projects are managed? Can the students learn the fact that communication requirements in the design-build project are much more complicated, as shown in Figure 2 on page 4, than the design-bid-build project? Where are the students given an opportunity to learn these communication requirements, which in turn will impact their construction projects?

The main concept behind the 4D virtual construction is to provide users with the ultimate capability of building any constructed facility so that they can explore their construction options, and optimize the construction processes. However, this unlimited and unconstrained condition in the 4D graphical virtual environment critically hampers the realism of simulated construction projects. In this learning environment, students are likely to develop their understanding based on the graphical simulation where the process interactions are not constrained. It is, therefore, likely that students are not given an opportunity to learn construction management the way it is practiced by professionals. Students need to develop an understanding and appreciation for the complexities and intricacies they will experience in real construction projects.

The purpose of this paper is to present a new construction management learning environment in which the deficiency of the current 4D virtual construction simulation is resolved. The specific development process for this new 4D virtual construction simulation learning environment is described in the following sections.

Required Knowledge/ Skills for New 4D Virtual Construction Learning Environment

In order to provide the realism of a construction project in a 4D simulation learning environment, the required knowledge and skill sets for construction management practices need to be identified. Some of the essential knowledge and skill sets in the construction management curriculum are summarized in Table 1 on page 4. For a more complete overview of the essential knowledge and skills sets required by entry-level construction professionals see the following references (AGC, 2004; LFCBD, 2004).

The majority of the tasks listed in the above table are in fact constraining pre-requisite conditions themselves for other tasks to be executed. For example, unless a contractor turns in submittals for precast concrete members that need to be approved by the architect, the contractor can not perform this job in the field. If a long-lead time item is not secured through the proper purchasing process, the related construction

Figure 2. Typical Communication Flow in a Design-Build Project

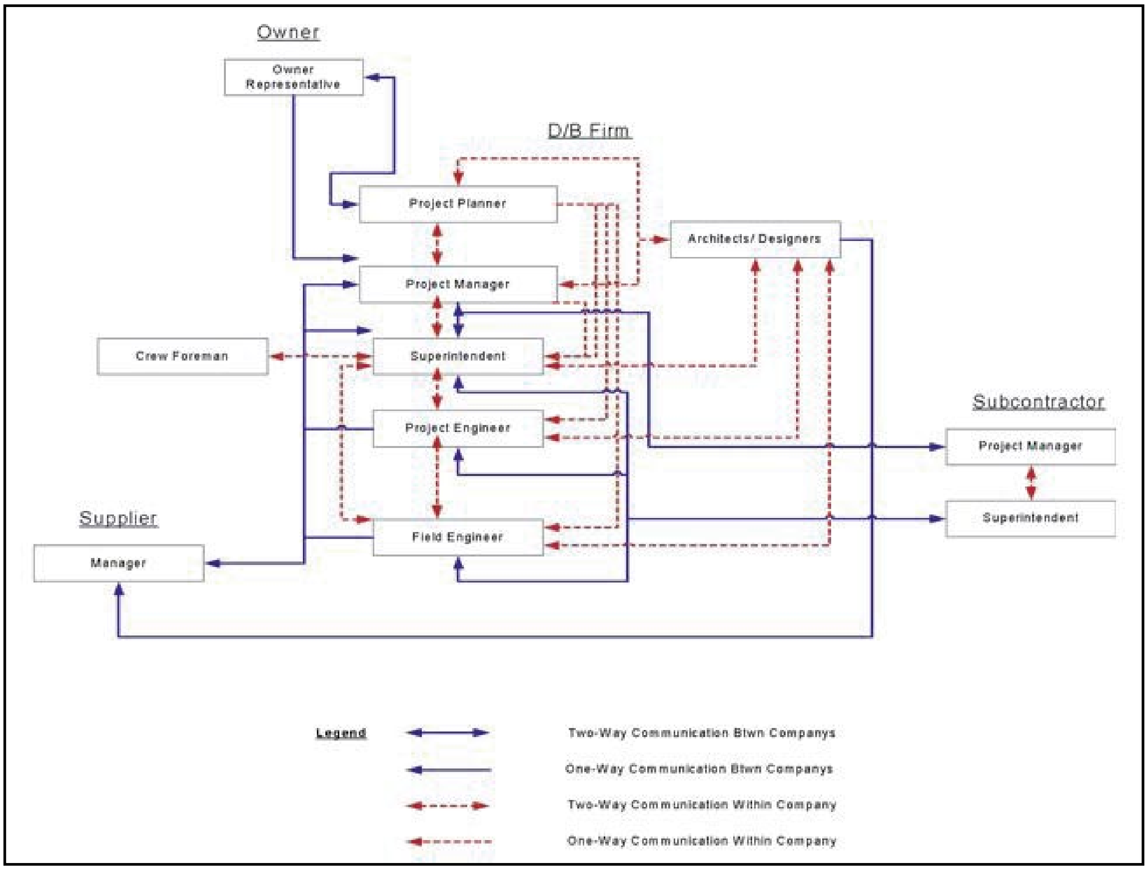


Table 1. Knowledge and Skill Sets for Construction Management Professionals

A. Project communication

❑ Organizational flow including reporting structure and communication for all key staff and any support staff in the project
❑ Information and data flow between multiple organizations
❑ Review and approval process for project documents

B. Preconstruction

❑ Purchasing schedule
- Material/equipment lead times (engineering / fabrication / delivery)
- Completeness of design
- Project construction schedule coordination

❑ Long lead items – to "red flag" any materials and/or equipment requiring additional fabrication time or early purchase due to construction sequence
- Long lead item list
- Identification of how these affect the project schedule

(continued on page 5)

Table 1. Knowledge and Skill Sets for Construction Management Professionals (continued)

- ❑ Value engineering (VE) – to decrease the project cost and/or schedule without compromising the overall quality of the end product by identifying the following:
  - Description of ve items
  - Estimated savings / additional cost
  - Schedule impact
  - Value to the project
- ❑ Cash flow analysis – to provide the owner with a projection of the cash needs for the project over the construction period in order that financing can be organized accordingly.
  - Cash flow projection coordinated with the construction schedule
  - Value for each individual month as well as a cumulative total each month

C. Engineering control

- ❑ Submittals – to manage and track all items that are required to be submitted by the subcontractor such as:
  - Shop drawings, product data, samples, mockups, test certificates, insurance certificates, schedule of values, safety programs, warranties, OM manuals, etc.
  - Submittal items list includes:
    - date required on job
    - lead time (engineering review, fabrication, delivery)
    - required submission date
  - Submittal submission and approval process
- ❑ Trade coordination – to ensure that the different trades will fit together in the proper sequence when the materials arrive on the site and are installed (for example: windows fit in the openings, ductwork fits above the ceiling)
- ❑ Change order management – to manage and properly control changes made by owners
  - Change management process
  - Time of notification and responding
  - Approval/ authorization process and parties involved
  - Authorizing documents for billing purposes
- ❑ Project control
  - Schedule control
  - Cost control
  - Quality control
    - Quality assurance / quality control measures
    - Monitoring, compliance and correction of deficiencies
    - Quality maintenance throughout field operations, safety and closeout
- ❑ Closeout – to ensure the last work completed for the owner
  - Complete list of items and any procedures for an efficient and effective closeout of the project

D. Project cost

- ❑ Estimate (budget)
  - Material, labor and equipment costs in a productivity study
  - Staff study & general conditions estimate
  - Contingency, narrative, and analysis of contingency
  - Fee/ fee proposal

(continued on page 6)

Table 1. Knowledge and Skill Sets for Construction Management Professionals (continued)

- Bid analysis – to determine the most responsive bid for this project
- Trade estimates, general conditions, fee and contingency

❑ Expenditure
- Measuring work progress
- Earned value report
- Forecasting the expenditure and update

E. Logistics & safety

❑ Logistics plan graphic & narrative – to maintain a safe, efficient jobsite for the completion of the project including sitework grading, installation of site utilities, construction of the building and the storage and marshalling of materials, and to maintain minimal disruption to the owner and the public
- Graphical site logistics plan
- Differing phases of the construction
- Written narrative defining the logic for location of the following:
  - site fence
  - construction access roads and construction gates
  - construction parking lot
  - material storage areas
  - temporary power and water
  - excavation spoils (storage / removal)
  - subcontractors trailers – size and location
  - hoisting and material access points and methods

❑ Safety plan
- Description of project specific safety issues
- Potential impact if not addressed
- Specific itemized steps to prevent a safety incident related to issues
- Company's procedure for communicating safety issues to the entire project team

(continued on page 6)

F. Schedule

❑ Detailed schedule
- Bidding and award periods
- Submittal / shop drawing / engineering activities
- Construction activities
- Milestone dates
- Punch list
- Inspections
- Payment
- Owner move-in
- Closeout

❑ Schedule narrative – to provide a narrative of the schedule identifying key dates and the logic of how you propose to construct the project
- Critical path of the project
- Explanation of the criticalities
- Risks associated with the critical path(s)
- Risk management plan

❑ Actual progress report and update

work cannot begin. Therefore, students should be equipped with the understanding of how these constraining conditions affect their success in managing construction projects. The key issue is if the current 4D simulation technology only focuses on graphical progress of the project in the 4D simulation environment, it fails to expose more delicate and complex tasks of construction projects that constrain the graphical progress. In order for this technology to be an effective reality-simulating education tool, these constraining tasks need to be simulated as well.

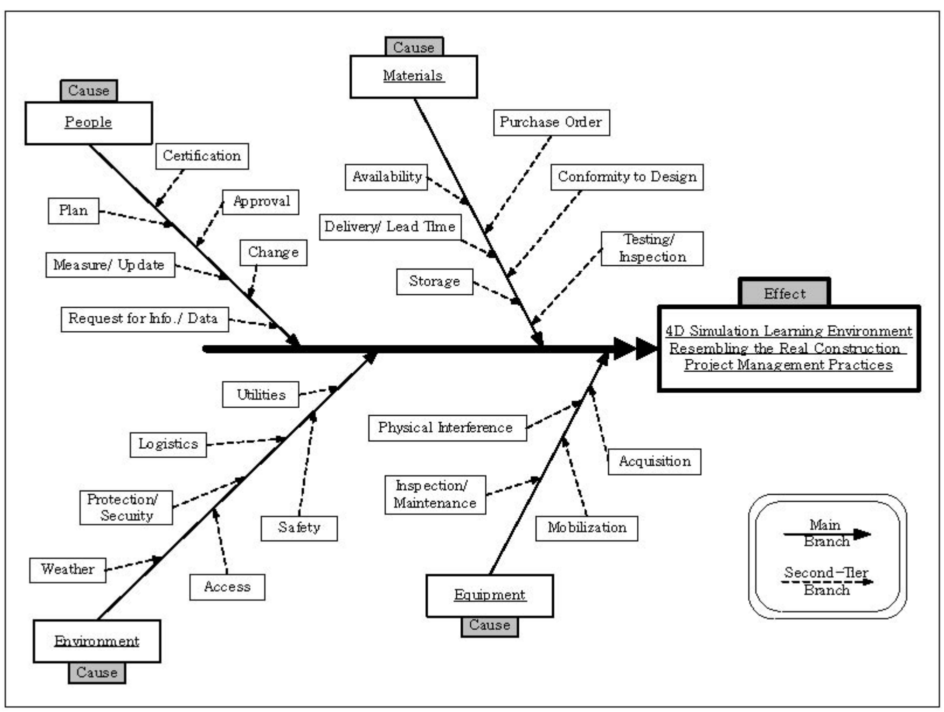
Instructional Materials Development for New 4D Virtual Learning Environment

In order to identify the specific issues and topical relationships in the Construction Management (CM) knowledge/skill sets described in the previous section, two systematic tools are utilized here to assist in the development of a new 4D simulation environment for CM education. The first tool is the cause and effect diagram, which is used to explore various resource-related issues (causes) that result in a single effect. The specific issues are arranged according to their level of importance or detail, resulting in a depiction of relationships and hierarchy. This can help search for root causes, identify areas where there may be problems, and compare the relative importance of different causes. Causes in a cause & effect diagram are frequently arranged in relation to major resource categories such as people, materials, equipment, and environment. Based on this general guideline, the cause and effect diagraph for the CM 4D simulation learning environment is developed as shown in Figure 3 so as to pinpoint specific issues to be dealt with. In the diagraph, the effect is identified by asking the following question: "How to make 4D simulations resemble real construction processes?"

In Figure 3, based on the CM knowledge/skill sets in Table 1, the specific causes are identified as second-tier branches with major resource categories represented as main branches. Each cause of these second-tier branches contributes to the impact of the main branches on the identified effect. For example, whether or not material purchase or/ and testing/ inspection tasks have been done will affect how the material resource category affects the realism of the 4D simulation learning environment. As is illustrated in this cause and effect diagram, many of the issues (causes) construction management professionals have to deal with on a daily basis are not necessarily related to physical construction itself. These physical tasks and activities such as installation and erection have been the traditional focal point or feature of 4D simulation practice. In fact, the construction project managers accomplish most of their duties by communicating and sharing information with the parties involved in the projects. It could be, for example, putting in a purchase order, expediting, inspecting, and arranging the space for storage at the site. Therefore, from the cause and effect diagram above, it can be concluded that more not-so-visible business-related operations should be incorporated into the new learning simulation setting.
As a next step in the development of the new 4D simulation learning environment, the interrelationship diagraph is developed, as shown in Figure 4, as a tool to visualize the logical patterns within the issues identified by the cause and effect diagram. The inter-relationship diagraph efficiently examines element interrelationships, helps establishes a priority ranking based on power, and illustrates potential causal patterns (Mizuno, 1979; Tague, 1995). The interrelationship diagraph reveals the impact one issue can have on other issues.

Each CM knowledge/skill set in the diagraph in Figure 4 possesses outgoing and/or incoming arrows, the former of which indicate the influence on other sets and the latter indicate the dependency on the pointing sets. For example, the success of Logistics & Safety plan of a project depends on how well project participants have maintained Project Communication and performed Preconstruction and Engineering Control functions. Therefore, the more outgoing arrows a CM knowledge/skill set has, the more influential it is on the other knowledge/skill sets, and, by the same token, the more incoming arrows a CM knowledge/skill set receives, the more its success depends on other pointing (or pre-requisite) CM knowledge/skill sets. The degree of influence

Figure 3. Cause and Effect Diagram for New 4D Simulation Learning Environments



and or dependency of each CM knowledge/skill set in Figure 4 is summarized and ranked in Table 2.

Table 2 depicts that successful construction projects are heavily dependent on how actively project participants share and communicate the project data and information, which is reflected by the high degree of influence in column (1) that Project Communication, Engineering Control and Preconstruction have on the other knowledge/skill sets of Logistics and Safety, Schedule, and Cost. Column (3) displays the importance of these knowledge/skill sets in the CM education. The reality is, however, that, as indicated in column (4), all these communication-related knowledge/skill sets are hard to implement in a typical CM curriculum. Therefore, depending on the situation of a CM education unit, some of the knowledge/skill sets with higher influence rankings can be accommodated in the simulation setting.

Simulation Steps and Framework for New 4D Virtual Construction Learning Environment

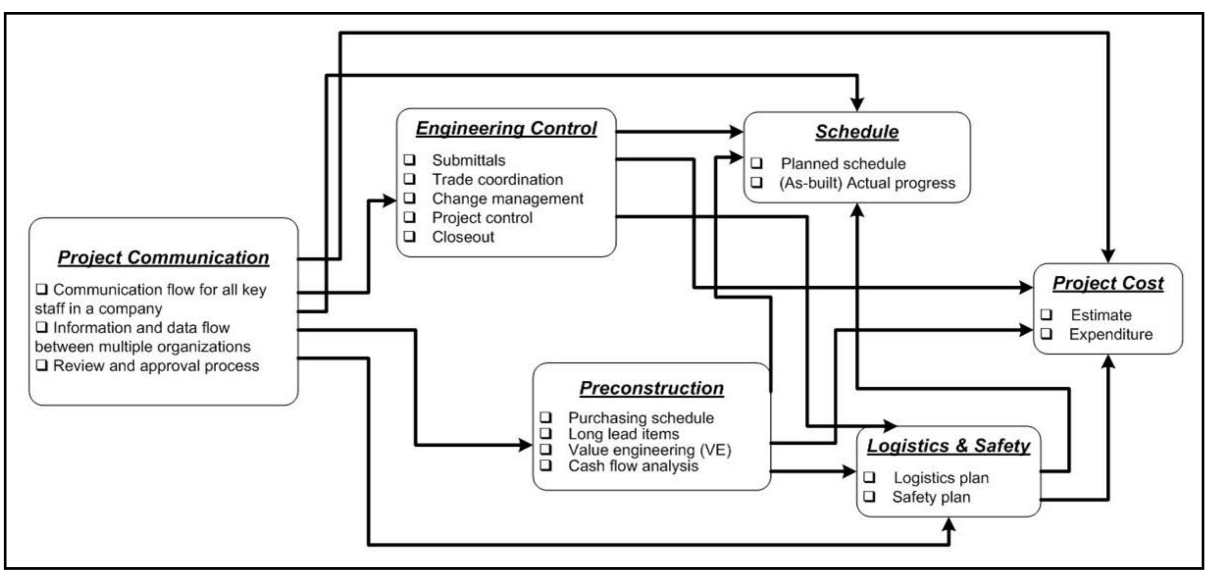
In this section the authors propose a framework for remedying the “no constraining condition” of the current 4D simulation technology as well as for promoting more emphasis on the project communication CM K/S set in the simulation-based education, all of which help provide superior reality-based CM learning environment that is based on the “constructivist learning” paradigm.

As a first step, a web-based collaboration technology is introduced and added onto the 4D virtual simulation environment in order to constrain and govern project participants and their operations in virtual construction practices. The web-based collaboration technology is well established in the construction industry and is seen as a managerial solution. It enables multiple project partners (such as owners, designers, constructors, and suppliers) to exchange construction-related information through a web project database in a real-time in order to increase communication and information sharing (Leung, Chan, & Issa, 2003).

Table 2. Priority Ranking of CM Knowledge/ Skill Sets Based on Their Impacts

Impacts / CM K/S Sets	(1) # of Outgoing Arrows (Degree of Influence)	(2) # of Incoming Arrows (Degree of Dependency)	(3) CM Education Focus (Difference = Influence - Dependency)	(4) Difficulty of Implementation (in a Typical CM Curriculum)
Project Communication	5	0	+5	Difficult
Engineering Control	3	1	+2	
Preconstruction	3	1	+2	
Logistics & Safety	2	3	-1	
Schedule	0	4	-4	
Cost	0	4	-4	Easy

Figure 4. Inter-relationship Diagraph for New 4D Simulation Learning Environments



In this new 4D virtual construction learning environment (constraint-based 4D simulation learning environment), virtual construction users (students) will have a set of constraints that control their behaviors similar to those constraints experienced by construction industry professionals. First, students need to realize that they are the source of project information and data for their work and that, at the same time, they have to rely on information and data other project participants create for making progresses in their project (Step 1 in Figure 5). Depending on their respective roles, virtual construction participants (students) need to expect and plan a set of appropriate actions that initiate the project information generation, which in turn, initiates other information transactions down the stream of project execution. The next step is that these project-specific information and data are exchanged among virtual construction participants via the web-based collaboration environment (Step 2 in Figure 5), as a way of mimicking the project reality of generating, needing and obtaining the correct information and a feasible set of resources with which to accomplish the construction work.

Once these two steps are incorporated into the virtual construction environment, the environment can function as a place where only actuality-based or constraint-conscious activities are accepted (Step 3 in Figure 5). Therefore, this environment contributes to a better communication and information exchange among project participants, not just for the visual representation of the construction processes.

The framework for this constraint-based 4D simulation learning environment is presented in Figure 6. Students perform typical virtual construction by generating the right information and by obtaining the necessary resources in the web-based collaboration environment. Students must realize the business and operational issues they will encounter as well as the planning steps and items they must handle for scheduled construction operations. Specifically, students assume roles of owners, architects/ engineers, agencies, contractors, and suppliers, and they interact with each other to simulate real construction business and operation situations along with the constraints that are part of these operations. Through a series of interactions, they generate key essential construction documents and information such as design clarification, purchase orders, equipment acquisition, change orders, permit acquisition, inspections, and so on. This information is eventually turned into constraining information, by which the activities of participants working in a virtual construction site are affected either positively or negatively depending on how they have managed the process with other inter-related project participants.

The authors also propose to include an intervention layer as depicted in the Figure 6. Classroom instructors or supervisors intervene in a series of interactions between students and the web-based collaborative virtual construction system to apply the rules of the constraints in terms of information and resources. Since all the activities made by student participants are recorded and

Figure 5. Simulation Steps in the Proposed Constraint-Based 4D Simulation Environment

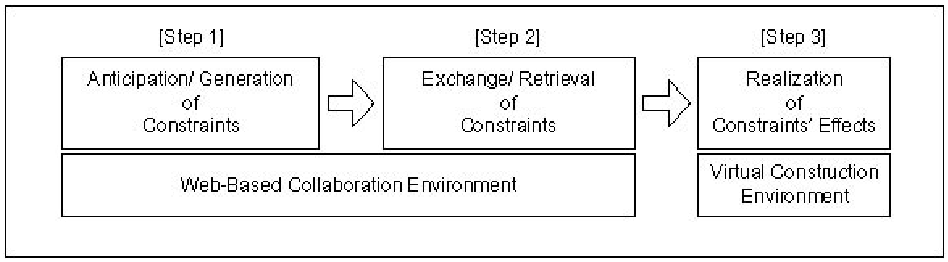
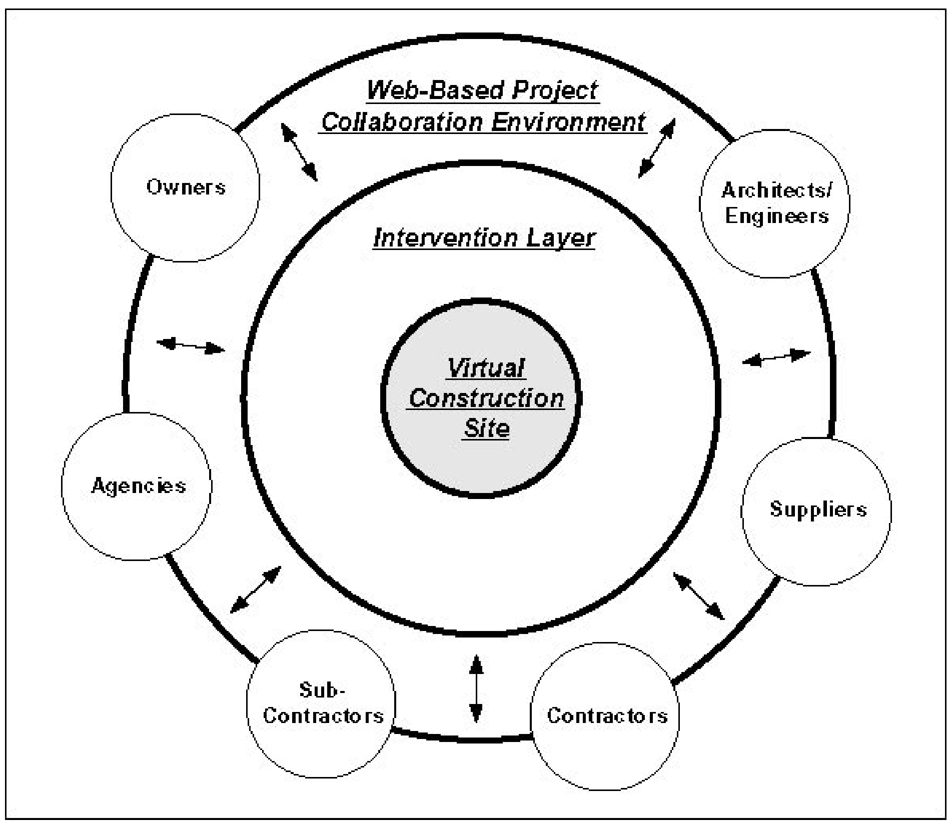


Figure 6. Framework for the Proposed Constraint 4D Virtual Simulation Environment



stored in the database of a web collaboration project site, the instructors retrieve the constraining information and justify the work that has been done on the 4D virtual site. This ensures the students have followed and abided by the constraint rules for governing their virtual construction practices. For example, if a certain activity or task has been done out of this constraining reality or there has been no sign of generation of constraining information, the related virtual construction operation loses its credibility because of the lack of reality-based construction practices. This enhances the educational experience and should result in better planning and communication.

Conclusion

To realize the benefits the constructivist learning paradigm offers, it is essential to provide students with an interactive inquiry-based learning environment where they are required to take an active role in the learning process and expected to expand and evaluate their own thinking. In the domain of construction project management, the 4D virtual construction simulation technology is in general equipped with the features of constructivism. The existing 4D virtual construction technology, however, does not allow students to realize the outcomes of their own knowledge building process because it is heavily based on graphical representations, not incorporated with the business process and communication information, the importance of which should be kept at the maximum level in the CM curriculum development to provide realism in the learning environment.

The authors' solution to remedy this problem integrates the current 4D virtual simulation environment with a web-based collaboration tool as a way of simulating construction-related processes. This new environment requires that students exchange project-specific information with others to plan required resources, to receive and apply the right information into a non-constraint virtual construction environment. The goal is to develop this "information-constrained" 4D virtual simulation learning environment where graphical construction operations are constrained realistically according to construction process information. Students get an opportunity to see how different project stakeholders (students who have different academic majors) impact their performance and how information and resource-constraints play a critical role in the success of the project. Therefore, this constrained 4D virtual construction environment becomes a true tool for learning and understanding the management process associated with the real construction projects. This innovative environment will change the way construction education is done based on the solid pedagogical paradigm, and how the construction business aspect is implanted into the existing CM curricula. The web-based project collaboration component specifically enhances other critical aspects in construction education such as facilitating synergistic collaboration between discipline-different, but yet related, all construction technology academic programs, such as construction management, civil engineering, and architecture programs.

Implications for Future Research

The results of the study have the several implications for institutions of higher learning. First, the curriculum in construction management programs should include instruction in constraint-based simulation tools. This instruction must specifically address issues that relate to construction schedule verification, generation and decision support for alternative schedules, better coordination and communications among project team members, effective temporary structure design, and improved work-site safety. Second, construction management programs need to be encouraged at the individual department level to provide specific emphasis on competencies that will address critical thinking at the specific job-site or project level. Competencies that should be given priority attention by project supervisors and managers include coaching and mentoring, effective sharing of information, thinking in new ways, seeing opportunities that others do not, using existing technologies in new ways, considering more than one alternative or solution to a problem, seeing problems as opportunities in disguise, and recognizing trends and changes.

And third, NAIT, as one of the accreditation bodies for construction management programs may need to provide descriptions of outcomes assessment models and program improvement strategies. The models and strategies can be utilized by construction management departments and programs to determine how, when, where, and why gaps exist in the skill-sets expected by employers and the skill-sets delivered by our accredited programs. As discussed earlier in this manuscript there is a tremendous need for construction management professionals who can work in a highly simulated graphical environment to solve the problems of the day. Is this need being addressed in NAIT's accreditation process? Is it being addressed in our construction management programs? If not, why?

Recommendations for Further Research

This manuscript gathered pertinent information regarding what new skill-sets construction management professionals should possess in order to carry out their daily roles and responsibilities in a highly technological work environment. This manuscript also illustrated information about how construction management professionals need to employ graphical simulations tools to solve problems and issues.

Some of these findings suggested a need for further study, therefore the following areas could be considered for further research. What are instructors' perceptions of the competencies and skill-sets required by future construction management professionals? What are construction management professionals' perceptions of the competencies and skill-sets required by future construction managers? What is the relationship between the aforementioned perceptions? What are the technological factors that hinder the development construction management professionals?

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