Modeling the Construction Management Process to Support Situational Simulations

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Abstract: Construction managers are decision makers who administer nontrivial processes. The replacement of highly experienced construction managers and other construction professionals is a laborious process for the industry. This paper introduces a conceptual framework for the construction management practice that serves as the foundation for the development of situational simulations. Situational simulations are temporally dynamic clinical exercises with the objective of exposing participants to rapidly unfolding events and the pressure of decision making. The application of situational simulations provides construction managers and other decision makers the opportunity of experiencing and responding to risky events without endangering the success of real projects, further enhancing their decision-making skills. The construction management conceptual framework includes a process, a product, and an information model. The analysis of a basic mathematical representation of the process model is the focus of this paper.

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Introduction

Knowledge workers are essential for the success of construction projects. Unfortunately, experienced construction knowledge workers are retiring and taking their decision-making skills with them, generating gaps of knowledge in the construction industry. The replacement of highly experienced project managers and other construction professionals is a laborious process for the industry, because decision-making skills are acquired slowly over many years and sometimes through the execution of costly mistakes. In addition, construction engineering and management curricula are not very helpful, as decision-making skills are difficult to teach in a traditional academic setting. The analysis of historical case studies is often used, but this approach is limited by what has already happened. Thus, a case study approach does not allow the exploration of ‘‘what if’’ scenarios or doing so in the context of dynamic conditions.

The aviation and medical industries face a similar dilemma of how to expose their professionals to realistic situations for acquiring and developing decision-making skills without endangering the life of passengers or patients, respectively. Both industries are solving this problem by taking advantage of situational simulations in virtual environments. As an illustration, flight simulators allow pilots to virtually execute and study different alternatives, while computer-aided surgery allows doctors to perform virtual operations. A similar approach can be applied in the construction industry by developing situational simulations to provide construction managers and other decision makers the opportunity of experiencing and responding to risky events without endangering the success of real projects.

This paper introduces a model of the construction management process that represents one of the building blocks of the Virtual Coach, a visualization-based decision-making environment for the execution of situational simulations.

The Virtual Coach platform (Fig. 1) takes advantage of both client-server and peer-to-peer protocols to generate a Web-centric virtual environment where educators can focus on the development of simulation exercises rather than on the associated technological issues. The Virtual Coach technological platform supports the integration of modeling, simulation, visualization, and computational software into a virtual environment on the World Wide Web. This virtual environment responds to participants' manipulations, challenging them to use their knowledge and skills to experiment and solve problems in a dynamic setting where conditions constantly change in response to their actions. The Virtual Coach platform supports the following objectives:

- Dissemination of knowledge: Broadening learner, industry, and public awareness of and access to the expertise found at different institutions of higher education through dissemination of on-line situational simulation exercises.
- Building of partnerships: Partnering among institutions of higher education and between the academic community and the industry to leverage resources and expertise in order to generate a richer educational environment for the learner.
- Encouragement of education-oriented simulations: Establishing formal certification of simulations as ‘‘educational exercises.’’
- Encouragement of postexercise activities: Developing such resources as group analyses and debriefing sessions. In these activities, learners review and examine simulation exercises. They describe the events that occurred, account for their actions, and discuss alternative strategies to solve the problems encountered.

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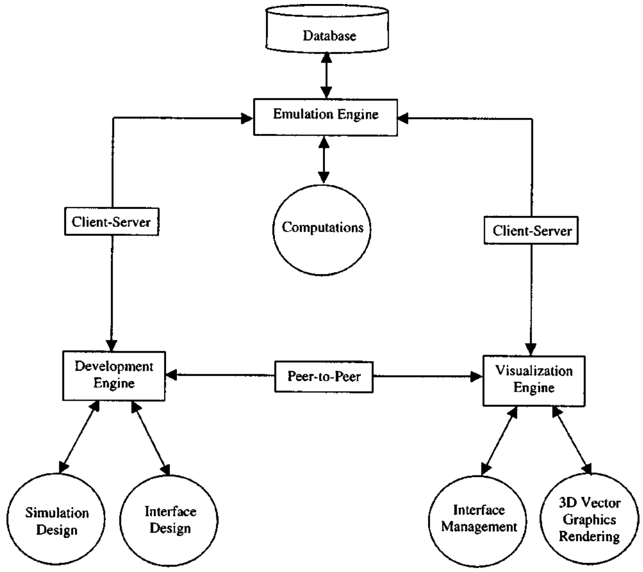

Fig. 1. Virtual coach technological platform

- Building of repositories: Building the capacity to document, collect, and store information about student reactions and results during simulation exercises that can be later used to support research efforts. For example, in the Virtual Coach these repositories could be studied through data mining techniques to extract knowledge about the decision-making process of learners.

The Virtual Coach environment is made up of three applications: (1) the visualization engine; (2) the emulation engine; and (3) the development engine. The visualization engine manages the user's interface, the emulation engine performs all computations necessary to implement the simulated environment, and the development engine provides a visual development environment for authors who wish to create simulation exercises. Fig. 1 illustrates the interactions among these engines. This infrastructure facilitates collaboration, as developers are able to generate, modify, upgrade, and store their simulations in their own personal computers. There is no need to post the simulations to a Web server, as the system is built to take advantage of the peer-to-peer protocol.

Situational Simulations

The Virtual Coach implements temporally dynamic clinical exercises with the objective of exposing participants to rapidly unfolding events and the pressure of quick decision making. Such exercises usually require the evaluation and interpretation of relevant data to "solve the crisis/problem." Situational simulations are also known as strategic, role-playing, and crisis-management simulations.

Barab et al. (2001) argue that the core of cognitive science and resultant pedagogical models is based on the Cartesian philosophy of mind-matter dualism. This has created a separation between the learner and the learning context. Students can recall concepts when they are explicitly required to do so but are not able to apply them spontaneously to situations even when they are relevant. On the other hand, learning through situational activity does not disembody concepts from their context. Learning environments that use situational simulations present concepts while clearly illustrating their relations to the environment. Barab et al. (2001) also studied student-resource and student-technology interactions in technology-rich, collaborative participatory environments. Some of their findings suggest that gaining in-depth knowledge and skill with respect to a particular practice or concept is directly related to the availability of resources and the contextual demands. In a field such as construction engineering and management, where context-specific knowledge and awareness is imperative, situational simulations would be able to challenge the students' capabilities and thereby improve their understanding of the concepts and their interrelations.

An example of situational environments is the Virtual Gorilla Project (Allison et al. 1997) at Georgia Tech, which has been developed to explore techniques for using virtual reality to present information experimentally to users that would otherwise be difficult for them to learn. Using real-life data regarding gorilla behavior from the Zoo Atlanta gorilla exhibit, an environment was modeled where the user could explore areas that are normally beyond limits to the casual visitor. The environment extends the educational experiences provided in the traditional zoo by encouraging users to personally experience what it is like to join a gorilla family group and "test behaviors and elicit appropriate responses" from other members of the gorilla family. This project is also being used to expose a graduate-level class from the School of Architecture at Georgia Tech to zoo design principles by allowing them to immersively experience the main gorilla habitat at Zoo Atlanta. They can also gather information regarding habitat design principles; create, delete, or modify design elements; and experiment with different visitor viewpoints.

The Virtual Puget Sound Project at the University of Washington (Windschitl and Winn 2000) represents another illustration of a situational simulation. It uses an oceanographic model of the Puget Sound to create an artificial environment that simulates physical features such as salinity and tidal currents. The hypothesis of their research is that "immersive and nonimmersive interfaces to simulations support different aspects and different degrees of constructivist pedagogy that are difficult to implement in science classrooms without technology, but which are known to improve the understanding of difficult scientific concepts and principles." Their studies have proved that learning occurs when people adapt to their environment. Hence, in order to understand adaptation, educationists will need to think of the learner as embedded in the learning environment and physically active in it. This indicates that an interactive situational simulation using virtual environments can be effectively used to create a teaching environment where students can individually construct context-specific concepts on their own rather than receive symbolic messages that they can only remember and recall.

Finally, there are other indicators suggesting that situational simulations are of great help in developing training environments for skills that are developed through experience. The Army and Marine Corps have used situational simulations to improve command training in large-scale exercises (GAO/NSIAD 1991). In fact, the most extensive use of situational simulations is found in the politico-military areas (Goldhammer and Speier 1959; Bloomfield and Whaley 1965; Allen 1987). However, examples can also be found in other areas such as relief operations management after natural disasters (Ritchie 1985).

Construction Simulations and the Virtual Coach

Traditional construction process simulations are usually applied at the planning stage to optimize resource allocation. Some examples include simulation-based scheduling (Sawhney and AbouRizk 1995; Senior 1995; Chehayeb and AbouRizk 1998), construction methods simulation (Gonzalez-Quevedo et al. 1993; Vanegas et al. 1993; Ioannou and Martinez 1996; AbouRizk and Wales 1997; Senior and Halpin 1998), earthmoving simulation (Farid and Koning 1994; Smith et al. 1995), and repetitive construction simulation (AbouRizk and Halpin 1990; Lutz et al. 1994). A common characteristic of these simulations is that they are event driven. By contrast, situational simulations are cycle-based driven.

In discrete event models, discrete items change state as events occur in the simulation. The state of the model changes only when those events occur and the passing of time has no direct consequences. Therefore, simulated time advances from one event to the next and it is uncommon for the time between events to be equal. In cycle-based models, the values of variables change based directly on changes in time, and time changes in equal increments. These values reflect the state of the modeled system at any particular time, and simulated time advances evenly from one time step to the next.

An example of a situational simulation developed for the construction management domain is AROUSAL (Ndekugri and Lansley 1992). AROUSAL (A Real Organizational Unit Simulated As Life) is a business simulation system designed to assist contractors and other construction industry firms in developing their managers and in evaluating the potential costs and benefits of different business and organizational strategies. AROUSAL simulates the management process in the construction industry. It generates information that would normally be available to management staff and enables teams of students to deal with this information and related issues as they would in real life. Business settings in AROUSAL are presented through audio-visual and written case study materials.

The major difference between AROUSAL and the proposed system in the Virtual Coach is that, while the former focuses on the management process of a construction firm, the latter simulates the management process of a construction project. AROUSAL does not simulate any technical situations related to construction engineering issues. Conversely, the Virtual Coach uses an event manager that randomly throws in events (managerial and/or technical), as is expected during the course of a real-life project. The participant is not forced to take a specific set of decisions in a specific situation, but is challenged to decide on the relative urgency of various parameters and come up with the best decision. Unlike the case study approach used in AROUSAL, the participant using this system is provided not only with information specific to a crisis, but also with information that is specific to the simulated environment. Giving the participant an opportunity to construct the situation from the provided information and to identify a particular crisis is the goal of the Virtual Coach.

Another example of one of the earliest project-centered situational simulations developed for the construction management area is the game CONSTRUCTO, created more than thirty years ago by Halpin and Woodhead (1970). This game included the basic components of a situational simulation. CONSTRUCTO was based on a process model only and did not include any information or product models or the visualization of the simulated environment. Instead, the model introduced in this paper is polymorphic and supports a multiplicity of scenarios backed by process, product, and information models. Furthermore, the process model in CONSTRUCTO and the one defined in the Virtual Coach are significantly different. CONSTRUCTO does not support nomological constraints, which in turn, isolates the participant from the surrounding environment. In addition, it only supports one type of dependency given by the project schedule as defined in the network diagram. No dependencies for materials or other resources are included in the model. CONSTRUCTO also limits the ‘‘situations’’ in the model to weather-related events. The Virtual Coach model, on the other hand, supports any technical and/or managerial event for which cause/effect relationships can be defined between the event and the underlying mathematical equations that define the process model.

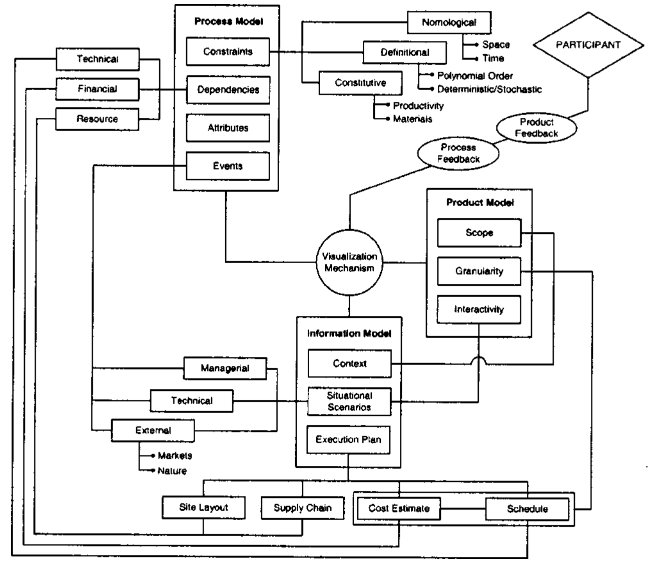

Fig. 2. Virtual coach conceptual framework

Conceptual Framework

Construction management is a nontrivial process which encompasses a series of complexities that must be represented in any model. The conceptual framework introduced in this section is a representation of the construction management process, which serves as the foundation for the development of situational simulations. The components of this framework are shown in Fig. 2. There are three major models: (1) the process model; (2) the product model; and (3) the information model. The process model is a representation of the building process, the product model is a representation of the physical facility, and the information model is a representation of the data environment. In addition, this conceptual framework also includes a visualization mechanism to provide process and product feedback to the participant. Even though this paper focuses on the process model, a brief description of all models is included in this section to provide a comprehensive view of the entire framework.

Process Model

As depicted in Fig. 2, the process model is defined by constraints, dependencies, attributes, and events. Constraints are limitations to the process given by nomological, definitional, or constitutive principles. Nomological constraints are nonnegotiable limitations that must be satisfied because they are dictated by natural law. Two instances are space and time. For example, in the process model, two materials cannot occupy the same space at the same time, nor can the total amount of materials stored at the site exceed the available space. Definitional constraints are limitations imposed by mathematical relationships. Two instances are the polynomial order of the equations and the deterministic/stochastic nature of the variables. All equations in the process model are first-order polynomials, which simplifies numerical calculations as linear relationships are used to extrapolate and interpolate data. In addition, all variables in the process model are deterministic, further reducing computation requirements. Finally, constitutive constraints are limitations imposed on the process model by choice. Two instances are productivity and materials. Productivity is represented in the process model as dollars per unit of time, rather than squared feet, cubic yards, or any other production metrics per unit of time. This limitation was imposed to provide a single unit to measure the variable and thus facilitate the application of events that impact the productivity of a variety of activities. Materials is another variable for which a limitation was specified. The number of different materials in a typical construction project could run into the thousands. In order to reduce the data storage requirements of the process models, materials were classified into two categories: driving and nondriving. An activity-based material tracking system for driving materials is implemented in the process model. Driving materials are defined as the biggest cost drivers in an activity. This self-imposed limitation on the process model significantly reduces that number of materials to be tracked, as it is often the case that only a handful of materials comprise most of the material costs of an activity, even if several dozens are required. Nondriving materials are bundled into one variable and are immune to changes in prices.

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

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

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

Product Model

The product model is a representation of the physical facility and is defined by its scope, granularity, and interactivity. The scope relates to the percentage of the actual facility that needs to be represented by the product model. This decision is dependent on the information and process model needs. For example, some situational simulations may focus only on a few activities rather than on an entire project. When this is the case, there is no need to model the entire physical facility, as a model of the physical structure associated with the preceding activities and those required by the simulation exercise should suffice. In addition, the scope of the product model can also be limited by proper restriction of the interactivity of the model. There is no need to model those aspects of the physical structure that are not going to be experienced by the participant. In essence, the same principles that apply to the design of movie sets also apply to the definition of the product model: build/model only those items that the viewer/participant is going to be exposed.

Granularity is related to the level of detail on the model of the physical facility. The granularity of a product model is intrinsically associated to the project schedule in order to support 4D visualizations of the process. However, granularity is also linked to the situational scenarios, as different scenarios may require different levels of detail in the product model. For example, a situational simulation could be developed to expose participants to the 1981 Kansas City Hyatt Regency Hotel disaster (Sweet 1999). This simulation should include fully developed details of the steel connections for the second and fourth floor walkways according to both the original design and the proposed modification. This level of detail would be of the essence for the success of such a simulation. However, if a similar facility is modeled for simulations without events related to the steel connections, then the product model does not have to provide such level of detail and details about the connections of steel members could be omitted altogether from the model.

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

Information Model

The information model is made up of the context, the situational scenarios, and the execution plan. The context provides the participant with information related to the construction project, including scope definition and business plan. It also provides data about the site in which the project will be erected, including information such as local availability of resources (labor, materials, equipment) and local regulations. This context information offers the participant a general understanding of the project goals and restraints.

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

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

Visualization Mechanism

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

Mathematical Representation of the Process Model

The mathematical model is the cornerstone of the process model. The equations described hereafter have been inspired by the ‘‘Activity Based Costing’’ model developed by Cokins (2002). All project costs have been resolved into summations over the ‘‘Activity-Time Element’’ cost objects, which in turn are summations of associated items. The Activity-Time Element is simply a time interval snap of a particular activity during the duration of the project. Hence, if a project consisting of activities $(i_1, i_2, \ldots i_n)$ is divided up into a finite number of time intervals $(t_1, t_2, \ldots t_n)$, then the processes in a particular activity i spanning over a particular time interval t, represented by the unique ordered pair of (i,t) is defined as an Activity-Time Element object. The summation of the costs involved with each of these objects will provide the cost of the whole project. The cost associated with each Activity-Time Element is in turn a summation over all its labor, material, and equipment requirements.

The equations are used to manipulate Activity-Time Element specific information, which is stored in a database. The database (Rojas and Mukherjee 2002) is also built on an identical activity based schema. As Cokins (2002) mentions, activity based cost management can be used as a mission critical managerial information system. It allows systematic accessing of cost data from the database. The equations are then used to dynamically calculate direct costs, indirect costs, productivity, remaining duration, and other metrics of the project as the simulation proceeds, in order to create indicators to the participant’s performance. This also provides a technique to report costs of a project using multiple breakdown structures (Milinusic 1999). Hence, at any particular point of time during the simulation, participants can get snapshots of the cost pertinent to the situation at hand. The equations are applied to the activity-specific cost data for this purpose. For example, if a situation so arises, when the participant needs to know the status of equipment-related expenditures, the system would query and sum equipment-related costs across all Activity-Time Elements till that point of time.

The equations are built based on the constraints and dependencies of the process model. Equations related to the schedule are omitted from this section, as they are based on the well-known traditional critical-path method algorithm. These equations are used essentially to calculate direct costs, indirect costs, remaining activity durations, productivities, and percentages of completion at any instant of time. The first equation of the model is given by

$$\mathrm{TC}_t = \mathrm{TDC}_t + \mathrm{TIC}_t \tag{1}$$

where TC_t = total cost in time t; TDC_t = total direct cost in time t; TIC_t = total indirect cost in time t.

Total indirect cost in time t (TIC_t) is defined as the sum of field and home office overhead as follows:

$$\mathrm{TIC}_t = \frac{(\mathrm{TDC}^P)(\mathrm{OH}) - \Sigma_{t=1}^{t-1}\mathrm{TIC}_t}{\mathrm{RD}_t} + \mathrm{TSC} \tag{2}$$

where TDC^P = total direct cost as planned; OH = overhead percentage; RD_t = remaining duration in time t; and TSC = time sensitive cost.

The first term of Eq. (2) represents the determination of home office overhead to be applied as indirect cost for period t. Home office overhead is modeled as a percentage of total budgeted direct costs. This is a common methodology used by construction companies. The percentage to apply is computed by dividing home office expenses by a contractor’s annual construction volume. For the simulations, the overhead is treated as a predefined data item, which will remain constant during the life of the project. Therefore, this term is time independent in the model. The second term in Eq. (2), the time sensitive costs, represents the field overhead. Field overhead is modeled as a given lump sum per period of time, and it is time dependent. Field overhead covers the costs of items such as project manager’s salary, field engineer salary, utilities, and rentals, among others.

Total direct cost in time t (TDC_t) is defined as the sum of the direct costs for all activities in the project:

$$\mathrm{TDC}_t = \sum_{i=1}^{a} C_{i,t} \tag{3}$$

where $C_{i,t}$ = direct cost of activity i in time t; and a = total number of activities in the project.

The direct cost ($C_{i,t}$) of activity i in time t is defined as the sum of the cost of materials; labor, and equipment:

$$C_{i,t} = M_{i,t} + \sum_{j=1}^{m} (Q_{i,j,t})(P_{j,t-\lambda}) + \sum_{k=1}^{n} (N_{i,k,t})(w_{k,t})(1+\mu_{k,t}) + \sum_{l=1}^{p} (U_{i,l,t})(E_{l,i,t}) \tag{4}$$

where $M_{i,t}$ = cost of nondriving materials for activity i in time t; $Q_{i,j,t}$ = quantity of driving material j for activity i in time t; $P_{j,t-\lambda}$ = price of driving material j in time $t-\lambda$; λ = material procurement time lag; m = number of driving materials for activity i; $N_{i,k,t}$ = number of workers in category k for activity i in time t; n = number of worker categories for activity i; $w_{k,t}$ = basic wage of workers in category k in time t; $\mu_{k,t}$ = mark-up on labor for workers in category k at time t; $U_{i,l,t}$ = number of units of equipment l for activity i in time t; $E_{l,i,t}$ = cost of equipment l for activity i in time t; and p = number of equipment types for activity i.

The first element in Eq. (4) is the cost of nondriving materials. This cost is defined as

$$M_{i,t} = \frac{\Sigma_{t=S}^{F} M_{i,t} - \Sigma_{t=S}^{t-1} M_{i,t}}{\mathrm{RD}_{i,t}} \tag{5}$$

where $\mathrm{RD}_{i,t}$ = remaining duration of activity i in time t; S = start; and F = finish.

Eq. (5) states that the remaining cost of nondriving materials is computed as the total cost of nondriving materials for the project from start to finish minus the cost of nondriving materials already recovered. This cost is then divided by the remaining duration to uniformly distribute the cost through time. The cost of nondriving materials from start to finish is defined as

$$\sum_{t=S}^{F} M_{i,t} = M_i^P + M_i^R \tag{6}$$

where M_i^P = cost of nondriving materials according to the original plan; and M_i^R = Cost of nondriving materials because of rework.

In order to solve Eqs. (2) and (5), the remaining duration (RD) must be calculated. RD represents the amount of time that still needs to be invested on an activity to complete it. Mathematically, RD is represented by the following two equations:

$$\mathrm{RD}_{i,t=S} = \mathrm{OD} \tag{7}$$

$$\mathrm{RD}_{i,t>S} = \left[\frac{Q_{i,1}^P + Q_{i,1}^R - \Sigma_{t=S}^t Q_{i,1,t}}{\Sigma_{t=S}^t Q_{i,1,t}}\right]\left[\frac{\Sigma_{t=S}^t C_{i,t}^P}{(\gamma_{i,t})(PR_{i,t})}\right] \tag{8}$$

where OD = original duration; $\gamma_{i,t}$ = event driven factor to alter the productivity of activity i in time t; and $PR_{i,t}$ = productivity of activity i in time t.

Eq. (7) states that, at the beginning of the simulation, the remaining duration of an activity is equal to its original duration. Eq. (8) indicates that the remaining duration of an activity for any other time period involves a more complex calculation. First, the first driving material is used to calculate a ratio of the quantity of the material not yet installed to the quantity of the material already installed. For example, if an activity involves the pour of concrete columns and 1/3 of the columns have already been poured, then the factor would have a value of 2, as the ratio is calculated by dividing the remaining quantity of material still to be installed (2/3) by the quantity of material already installed (1/3). Second, this factor is used to estimate the remaining direct cost of the activity according to the original estimate. Finally, the remaining direct cost is divided by the productivity value to provide the remaining duration. This remaining direct cost is calculated based on the original estimate rather than on actual expenditures to avoid problems related to the operational definition of productivity used by this model. For example, if material costs or labor wages were to increase, the use of actual costs would overestimate the remaining duration because productivity values are calculated as dollars by unit of time according to the original estimate and are not adjusted because of increases in input prices.

Eq. (8) also includes a gamma factor (γ), which has a default value of 1 and can only be changed by an external event. As an illustration, the decline in labor productivity due to a severe winter storm event would be reflected by a reduction in the gamma factor. The value of the gamma factor will always be less than or equal to unity. When there is no decline in productivity, due to an external event, gamma takes a value of 1. In case of an event, the value falls below unity and, being inversely proportional to RD, it increases the remaining duration of the activity. In case of an event the decrease in the value of the gamma factor is proportional to the intensity of the crisis. Eq. (8) introduced a new variable: productivity. Productivity is calculated through two equations:

$$PR_{i,t=S} = \frac{C_i^P}{\mathrm{OD}_i} \tag{9}$$

$$PR_{i,t>S} = (PR_{i,t=S})(\tau_{i,t})\left[\frac{\Sigma_{k=1}^n (N_{i,k,t})(\varepsilon_k)}{\Sigma_{k=1}^n N_{i,k}^P}\right] \tag{10}$$

where C_i^P = direct cost of activity i as originally planned; $\tau_{i,t}$ = overtime factor to alter the productivity of activity i in time t; and ε_k = efficiency factor of worker category k.

Eq. (9) states that, at the beginning of the simulation, productivity is equal to the direct cost of activity i as originally planned, divided by the original duration of the activity. Eq. (10) indicates that productivity of an activity for any other time period involves a more complex calculation. First, the productivity of activity i in time t is defined as directly proportional to estimated productivity at the beginning of the project. This assumption is valid, as productivity values are not expected to change dramatically from one time period to the next unless special external events occur. Second, an overtime factor *tau* has been included to consider the effect of overtime work on labor productivity. The calculation of *tau* will require supplemental algorithms, which are in the process of development. The algorithms will be based on the theory that overtime leads to higher production but lower productivity. Finally, productivity values can also change because of deviations from the original plan. The last parenthesis of Eq. (9) takes into consideration these eventualities. For example, if an activity has a crew of five workers and the project manager decides to increase it to 10 to compress the activity duration, then the model should reflect higher productivity values, as expected. In addition, not all skilled workers posses the same level of "skills." Therefore, if because of market conditions a project manager is forced to hire workers with an inferior skill set, the model should also reflect lower productivity values, as expected.

In order to completely define Eq. (4), the quantity of the driving material j for activity i in time t must be determined by

$$Q_{i,j,t} = \frac{\Sigma_{t=S}^F Q_{i,j,t} - \Sigma_{t=S}^t Q_{i,j,t}}{\mathrm{RD}_{i,t}} \tag{11}$$

Therefore, the quantity of a driving material is determined as the total amount of the material that remains to be installed divided by the remaining duration. The total amount of the material is estimated by

$$\sum_{t=S}^{F} Q_{i,j,t} = Q_{i,j}^P + Q_{i,j}^R \tag{12}$$

where $Q_{i,j}^P$ = quantity of driving materials according to the original plan; and $Q_{i,j}^R$ = quantity of driving materials because of rework.

Finally, percentage of completion ($PC_{i,t}$) for activity i in time t is defined in the model as

$$PC_{i,t} = \frac{\Sigma_{t=S}^t Q_{i,l,t}}{Q_{i,l}^P + Q_{i,l}^R} \tag{13}$$

where $Q_{i,1}^P$ = quantity of the first driving materials according to the original plan; and $Q_{i,1}^R$ = quantity of first driving materials because of rework.

A simulation may have "Inspection Events" that will inform the participant, from time to time, about the quality of work performed. When quality on certain activities is not met, the participant will need to go back and redo the activity. The quantities of driving materials associated with the activities that will need to be reworked will sum up to give Q^R.

An illustration of some of the constraints imposed on the model follows:

$$\sum_{i=1}^{q} Q_{i,j,t} \leqslant Q_{j,t} \quad \forall j \tag{14}$$

$$\sum_{i=1}^{q}\sum_{j=1}^{m} S_{i,j,t} \leqslant S_t \quad (15)$$

$$\sum_{i=1}^{q} N_{i,k,t} \leqslant N_{k,t} \quad \forall k \quad (16)$$

$$\sum_{i=1}^{q} U_{i,l,t} \leqslant U_{l,t} \quad \forall l \quad (17)$$

where $S_{i,j,t}$ = storage space occupied by driving material j of activity i in time t; and S_t = total storage space available at the site in time t.

Eq. (14) is a material availability constraint which establishes that the total quantity for each driving material to be installed at time t throughout all activities in the project cannot exceed the quantity available at the site. Eq. (15) governs the availability of material storage space at the site by stating that the storage space consumed by every material in every activity in time t cannot exceed the total storage space obtainable. Eq. (16) is a labor constraint which establishes that the total number of workers in each category cannot surpass the number of available workers. Finally, Eq. (17) is analogous to Eq. (16) with respect to the availability of the different pieces of equipment to be used on site.

Limitations of the Process Model

The equations and constraints introduced herein define the basic structure of the process model. Some limitations were imposed on the model in order to reduce computational requirements, simplify mathematical complexities, and decrease data storage needs. The rest of this section describes the limitations that were chosen to reduce computational requirements. Therefore, the model presented in this paper should be considered the first step toward the development of a more comprehensive and realistic representation of the construction management process that will be enriched by overcoming the limitations explained in this section.

First, all variables in the model are deterministic. The introduction of stochastic variables would improve the model, as it would allow the inclusion of ''noise'' and ''risk.'' The current representation of the model creates an as-built process that is identical to the as-planned process until an external event occurs or the manager reallocates resources. The inclusion of ''noise'' would create small variances in the process to make sure that, even when external events and/or management decisions are not present, the process still generates an as-built environment slightly different from the as-planned one. The inclusion of ''risk'' through probability trees or Monte Carlo simulations would also improve the degree of realism by supporting decisions that may not have unique outcomes.

Second, all equations in the model are first-degree polynomials. An alternative representation of some of the equations may improve the accuracy of the model by taking into account those relationships that are best modeled with nonlinear equations. For example, the rate at which some activities consume labor resources may be better represented by a higher-order polynomial to account for lower consumption rates at the beginning and the end of the activity or any other proper pattern.

Third, all decisions in the model are made by only one participant. In essence, the participant plays the role of a project manager for a contractor who is self-performing the entire project. Therefore, the model can be improved by allowing multiparticipant simulations where different people would play different roles as representatives of the general contractor, trade contractors, the owner, and the city, among others. Multiparticipant simulations would add another layer of complexity in the model, as each participant would have the ability to control and make decisions only about a portion of the activities.

Finally, multiple versions of this model could be executed concurrently by different participants and linked to generate a multidimensional environment where another participant playing the role of a construction company executive oversees the different projects and provides feedback to each individual project manager in order to optimize the administration of the company as a whole rather than the administration of an individual project.

Conclusions

The development of situational simulations of construction engineering and management issues in virtual environments has the potential of transforming the current educational paradigm of both current and future construction professionals. Situational simulations, via interactive and graphically appealing environments, encourage the study of ''what if'' scenarios and the acquisition of decision-making skills through analytical rather than heuristic processes. The development of conceptual and mathematical models to represent the construction management process, such as those introduced in this paper, is the first step toward the development of truly interactive situational simulations of the construction environment.

The aim of this research is to create a learning environment for construction managers and provide them with situational simulations which they can use to construct concepts that are relevant to the environment of the construction process. Data regarding participant responses will be mined and will in the long run help in understanding trends in the decision-making processes of fledgling construction managers. Also, using data generated from the participation of experienced construction managers, this research will help in developing cognitive models of decision making in construction management.

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