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STATE OF THE ART IN CONSTRUCTION SIMULATION

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ABSTRACT

This paper addresses the state-of-the-art in construction simulation. The major contributions to simulation literature in this area are highlighted. A brief review of the history of simulation in construction is presented and current research dealing with construction process simulation is reviewed. The paper also addresses simulation needs that are specific to construction process modeling and analysis. the apparent directions in construction simulation research and applications are also presented.

1 INTRODUCTION

Construction engineers deal with the production aspects of realizing a facility (e.g. a dam, a high rise building, or an interstate highway) much in the fashion that an industrial engineering deals with the problems inherent in manufacturing a product. In this context, construction engineers (like industrial engineers) are involved in developing and efficiently designing productive construction methods or processes. The major difference between production of a product and production of a facility is the length of the product run - the number of repetitions. In construction we normally build a unique facility which is a one-of single copy. In manufacturing, product runs vary from small batches to long runs - say of a particular model of T.V. set or lawnmower.

Possibly due to the uniqueness of constructed facilities and the perceived lack of repetition, the concept of studying work processes did not receive much attention until the late 1960s. At this time, work sampling and various graphical techniques related to bar charting were considered. It was recognized that although projects are typically unique, many construction processes are repetitive (e.g. earth hauling, tunneling, road construction, glass installation on tall buildings, etc.) and amenable to closer investigation. Due to the comparatively short "half life" of construction processes, sophisticated analytical methods were viewed as being too complex for most situations.

With the emergence of the desk top computer, application of more sophisticated methods has become more accessible. In particular, simulation of construction processes to establish anticipated levels of production and solve some of the problems related to the randomness of construction operations has become more widely accepted as a tool available for use in planning and estimating.

Random number techniques to solve stochastic problems encountered in construction have been used to establish ranges of expected cost (e.g. range estimating), evaluate project time duration (PERT simulation), and model and evaluate expected production of various construction processes. One of the earliest applications of random number methods was in a gaming context. Au, Parti and Bostleman developed a construction bidding game in the late 60s which in various configurations is still used at several universities for teaching purposes (Au et al, 1969).

Following this, the CONSTRUCTO project management game was developed at the Univ. of Illinois by Halpin to integrate the effects of weather and labor productivity into the management of projects in a network format (Halpin, 1976). A similar simulation was developed by Borcherding (1977) of the University of Texas. Recently, the concepts of the bidding game and the project management format have been integrated into an educational game by AbouRizk at the University of Alberta, Edmonton (AbouRizk, 1992).

In order to be accepted in the construction environment, simulation has to be presented in a very simple and graphical context. Contact with construction professionals indicates that formats which appear to be too theoretical or analytical tend not to be accepted or utilized. Therefore, ideally simulation systems should be pictorial or schematic emphasizing graphical input and graphical output. The early systems designed to study construction operations utilized simple bar charting concepts.

With the advent of simulation methods in construction, simple networking concepts were introduced as a modeling framework for studying construction operations. The earliest of these methods was the so-called "link node" model adapted by Teicholz (1963). After that Halpin (1973) developed the CYCLONE format at the Univ. of Illinois that has become the basis for a number of construction simulation systems. CYCLONE simplified the simulation modeling process and made it accessible to construction practitioners with limited simulation background.

2 BACKGROUND

2.1 The CYCLONE Method

Modeling a construction operation using CYCLONE requires one to focus on the resources involved and their interactions. A resource can be in one of two states, active or idle. An active state of a resource is represented by a square element while the idle state with a circle element. The resource will move between the two states and thus from one activity to the other in the model. In order to build a CYCLONE model a modelor will have to use the CYCLONE elements shown in Figure 1.

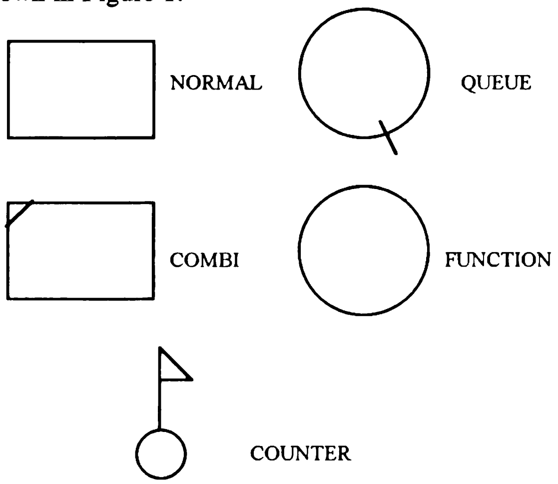

Figure 1: CYCLONE Modeling Elements

The rules for structuring CYCLONE network models using these elements are summarized in Table 2.1.

Table 1: Rules for Structuring CYCLONE Models

Element	Rule
NORMAL	A non- constraint task. It is like a serving station with an infinite number of servers.
COMBI	A task constraint by the availability of more than one type of resource. A resource arriving at a COMBI waits until all other required resources are available before it is processed.
QUEue	A waiting area for a resource. A resource arriving at a QUEue node will stay in the node until a COMBI is ready to process it.
Function	Devised so it will provide some flexibility by allowing the creation of new elements.
COUNTER	Keeps track of the number of times units pass it. It does not alter any of the resources or their properties.

CYCLONE has been adopted in a large number of construction curricula in universities across the U.S.A., Canada, Europe and Australia. It proved to be effective because of its simple structure.

2.2 Statistical properties

The statistical aspects of construction simulation follow much of the research contributions of industrial engineering. Recent research by AbouRizk (1990) showed that the duration of construction activities are best represented with flexible distributions. AbouRizk et al. (1991) provided two techniques for modeling beta distributions in a data-deficient environment and when data is available. Their work has been extended at the University of Alberta where a system providing a subjective interactive fitting environment has been developed. Touran (1992) showed that the cost of interrelated activities require the use of multivariate distributions. This work shows the effect of ignoring the correlation properties on the estimate for a project

3 STATE OF THE ART

Over the past two decades a great deal of simulation research has been carried in construction. Most of this work was motivated by the success of CYCLONE.

Riggs (1980) addressed the issue of sensitivity analysis using CYCLONE. His work showed that resource allocation can be greatly enhanced when simulation is used. Lluch and Halpin (1981) developed a microcomputer version of CYCLONE at Georgia Tech by the name of MicroCYCLONE. Work at Stanford University headed by Paulson (1987) developed the INSIGHT system which is based on the same CYCLONE elements with a more interactive interface. Touran (1981) focused on automated real time data acquisition and its integration with INSIGHT. Work at the University of Michigan under Carr led to the development of RESQUE (Chang and Carr, 1986) which is also CYCLONE based with advanced resource handling capabilities.

3.1 Simulation as a Supporting Tool for Network Scheduling

Carr (1979) developed a system entitled Model for Uncertainty Determination (MUD) which uses a coupled simulation-network scheduling methodology to provide sampling of an unbalanced estimate of activity duration, a criticality index, and an expected duration. Working with Halpin, Dabbas (1981) integrated a CPM network software system, Project I, with the CYCLONE simulation methodology to model repetitive activities. This hybrid technique was an effective planning tool for upper management which provided improved estimates for activity durations.

3.2 Process Integration and Linear Scheduling

Although intermediate statistics required to measure process production rates and stage buffer quantities are calculated by the existing MicroCYCLONE program, only final statistics are retained for the user. Under the direction of Halpin, Lutz (1990) developed process cycle and stage buffer monitoring enhancements for use with MicroCYCLONE. The enhancements consisted of the coding of several subroutines to foster the collection and recording of initial, intermediate, and final process and stage buffer statistics.

A statistics collection mechanism consisting of a generic FUNCTION element followed by a SINK element was developed by Lutz (1990) to collect initial, intermediate, and final statistics between processes. The developed statistics collection mechanism provides two new features to the existing MicroCYCLONE program; it allows the use of multiple counters in a single model and tracks the number of partially completed production units in queue as a function of time for SINK elements. The existing program only allowed the use of one counter in a single model. The SINK element performs the same function as a QUEue element and has typically been used at the end of the model to collect completed production units. However, multiple SINK elements can now be used in the place of QUEue elements in a single model to collect additional statistics.

One application for the statistics mechanism is to foster the collection of statistics for individual processes during the simulation of a multiple-process linear construction model. This can be accomplished by inserting statistics collection mechanism after each distinct process in the model. Additional statistics (i.e., element label, cycle number, and simulation time) are collected in a file on the specified data disk entitled "filename.FUN" for non-CON and non-COU FUNCTION elements. Additional statistics (i.e., element label, quantity in buffer, and simulation time) are collected in a file on the specified data disk entitled "Filename.QUE" for SINK elements. These elements are specified in the Network Input statements as discussed in the MicroCYCLONE User's Manual (Halpin 1990).

After a simulation has been completed, the statistics collection files (i.e., "filename.FUN" and "filename.QUE") are imported into a spreadsheet program for data manipulation as required. This data is used to generate system constrained process production or flow line curves (i.e. curves representing the realistic production behavior of individual processes in a multiple-process model as constrained by the system during simulation) and to generate stage buffer charts. These graphical plots can be used to easily determine what is wrong with an operation, to locate bottlenecks in the system, and to develop alternatives for improving the performance of the system.

3.3 Graphical Object Oriented Simulation for Process Modeling

COOPS (Construction Object-Oriented Process Simulation System), a new discrete-event simulation system with an object-oriented design, was recently developed by Liu and Ioannou (1992). With the object-oriented design, COOPS has the capabilities to track resources, to construct a simulation model using user interactive graphics, capture resources, to define different resource requirements, and to link with other planning systems. COOPS simulation models are presented in a graphical format similar to those used by CYCLONE and consist of three kinds of objects (e.g., nodes, links, and attachments) and four kinds of nodes (e.g., activity, queue, consolidation, and router) in a precedence network.

The knowledge representation of the object-oriented simulation design closely matches that of frame-based expert systems. The modeling objects can be directly queried by other planning systems at the system level during runtime. The program code has been implemented by defining classes and adding methods and instance variables according to object behavior analysis. The user interface involves a combination of three window objects providing a main menu, tool box, and a drawing area. The latest version of COOPS was developed using Actor 3.0, an object-oriented programming language from the Whitewater Group, and runs under Microsoft Windows 3.0.

3.4 Knowledge-Based Simulation of Construction Plans

CIPROS, an object-oriented, interactive system for constructing discrete-event simulation networks and simulating construction plans, has been recently developed by Tommelein at the University of Michigan (Odeh, Tommelein, and Carr, 1992). The system allows the user to relate project specifications and design drawings to a construction plan.

Drawing and plan data are related to construction resources and processes by means of a library of construction methods represented as elemental simulation networks and class hierarchies. Simulation of the construction plan aids in assessing its quality and feasibility and identifying areas for improvement.

Variate generation, control of experiment and output analysis remains totally dependent on research carried in other industrial engineering areas.

4 APPLICATIONS OF SIMULATION IN CONSTRUCTION

Although it is difficult to represent a construction project for simulation purposes, a number of successful simulation applications have been recorded. One of the prime applications of simulation is on the process level as stated earlier in the paper. In this regard the focus is lowered to the process level where a project is envisioned as a collection of processes.

4.1 Process modeling and simulation

Construction process modeling has matured over the years with numerous examples given in Halpin (1990), and Halpin and Riggs (1992). These include earth moving, pavement construction, concrete placement on high-rise buildings, cladding, tunneling and underground pipe-jacking, and a wealth of others. The objectives of process simulation ranges from productivity measurement and risk analysis to resource allocation and site planning. With an accurate representation of the activities constituting the process, the modelor can estimate the production of the process and probabilities of meeting a given schedule. As resources in construction include heavy and expensive equipment, various allocations can be examined and the most suitable ones adopted. Works by Halpin et. al (1989) addressed this issue.

4.2 Claims analysis and dispute resolution

Simulation has been found to be an attractive tool in mitigating construction disputes. The most common cases which can benefit from simulation analysis in this regard include productivity loss due to weather, interruptions due to changes, owner or trade-contractor interferences, or unexpected conditions. The contractor often seeks compensation based on loss of productivity or change impact for non-recoverable costs or delays due to conditions beyond his control. Simulation models have been successfully used to provide an accurate representation of the original condition as expected at time of bid and the condition that would have been encountered after the new facts arise. Since productivity loss is derived from factors such as weather, labor skill, and site conditions, the simulator can build the simulation model and introduce the new facts to study and analyze their impact on the productivity, cost or time of the project. A recent example of this was reported by AbouRizk and Dozzi (1992). In their work the authors developed a simulation model for the jacking operation of a bridge as part of a mediation between the public owner and a steel contractor. The original anticipated condition based on drawings provided by the owner reflected lower and less complex jacking operations. The design was proven non-workable and the parties agreed to mediate a settlement for the total compensation and time extension. The CYCLONE model built for the process accurately predicted the total number of man-hours lost due to the added levels of complexity which when combined with the new required quantities of steel provided the total added cost.

4.3 Project planning and control

Most of the work in project planning and control dealing with simulation has been of a hybrid nature. In general, CPM based methods are used and a form of Monte-Carlo simulation allows evaluation of the network. Dedicated systems have been in use and are available from commercial software vendors.

The major problem with simulating a construction project is its size and complexity. This, in general, does not provide a positive return on the effort invested in building a simulation model. It is not uncommon to have a project with over 2000 activities in a construction project. Much research is still needed to provide a simple, efficient, workable, and accurate method for construction project simulation. CPM-network techniques are still the leading control method used at the project level. This, however, does not provide the analyzer with all benefits of simulation and is therefore of limited use to practitioners.

5 FUTURE DIRECTIONS IN SIMULATION RESEARCH AND APPLICATIONS

Construction simulation is moving in two parallel directions. In one direction construction-specific simulation methods are being developed to facilitate handling of huge amounts of data in a structured way. On the other, more work is being carried to find more application areas of simulation in the construction discipline.

5.1 Directions in Project Modeling

The basic problem can be defined as developing a system that is capable of representing huge amounts of data while the representation process is structured and simplified from a user's perspective.

Object oriented simulation systems are promising tools for project representation. These mainly use the CYCLONE constructs but provide more flexibility in resource representation and process integration. A sample of such a system is presented by Ioaunu in this session. Other promising ways of handling project simulation draw on the successful implementation of the gaming environment CONSTRUCTO. Work currently in progress at the University of Alberta is addressing the issue of project representation and modeling following the general framework of CONSTRUCTO.

5.2 Directions in other applications

The problem of applying simulation in construction is two-fold. On the one hand, it involves developing user friendly interfaces for building simulation models or networks since construction simulators are normally non-sophisticated and tend to stay away from methods requiring difficult modeling constructs. Works by Riggs at Georgia Tech. are aimed at providing such tools. Expert systems have been also developed to query the user in simple language and then build the simulation network (see Touran (1992), for example).

Simple Monte-Carlo experimentation with costing in the form of range estimating has picked up considerably. The commercial software market is starting to introduce spread-sheet add-ons which are being received very well in construction. Along the same lines are bidding assistant programs which are game-based with heuristics imbedded for decision making purposes. Most of the ones in the market have simulation elements in them. These areas are considered representative of the few simulation methods that are infiltrating the construction industry. The main reason is their sophisticated user interface and the ease by which simulation is handled.

The other aspect of the problem is convincing practitioners of the benefits of simulation. This has proven a difficult matter with the few exceptions outlined previously and in areas such as construction claims. Construction contractors normally will spend money only when they have to and not before the fact. The introduction of CYCLONE-based simulation in a large number of construction curricula will provide a core of practitioners that will facilitate simulation adoption in the future. Meanwhile, more work is required to convince the industry that this tool is valid and appropriate.

6 CONCLUSIONS AND RECOMMENDATIONS

Simulation as a tool for construction engineering and management applications is very promising. The successes in the industrial and commercial sectors present a basic framework for implementing simulation in construction. The research, applications and multitude of developed software products in industrial engineering gives researchers in construction the necessary foundation to tackle a more complex and less defined problems. More research will be required before simulation gets adopted in the area of project planning and control, however.

CYCLONE-based methods have proved to be effective and simple to use, two key elements for the successful implementation of quantitative methods in construction. More work is also required in the area of hybrid systems which seems to be the most promising area of construction simulation. This includes expert systems for model specification and development, heuristic support within simulation modeling, CPM and Line of balance integration as well as other operations research tools.

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