SIMULATION IN THE CONSTRUCTION INDUSTRY - A CASE-STUDY REVIEW

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Despite its similarities to manufacturing, construction has not embraced many best practices used in manufacturing. One such best practice, computer simulation has been used extensively in manufacturing to model many different types of process and scenario. Recognising the benefits of the transfer of manufacturing technologies to construction much research is being undertaken under the IMI initiative, Construction as a Manufacturing Process. This paper describes ongoing research funded by the IMI into the feasibility of using computer simulation to model construction processes.

Keywords: Construction planning, Simulation.

INTRODUCTION

Research indicates that current planning in the construction industry suffers from an inability of the existing tools to cope with the complex and dynamic conditions which exist on a construction site. However, computer simulation, because of its inherent capability of modelling dynamic conditions has found widespread use as a decision-support tool in the planning of manufacturing processes. Yet, despite the similarities which exist between manufacturing and construction, simulation has found a low utilisation in the construction industry.

A study of secondary sources of simulation in the construction industry was undertaken to elicit knowledge in areas such as the type of activities which have been modelled, the benefits and problems encountered, typical software methodologies, and the reasons given for using simulation. This paper sets out to discuss the research methodology and findings from the case study into the use of simulation in the construction industry.

STUDY OBJECTIVES

The objectives of analysing the case studies was to establish features both beneficial and possibly detrimental to the potential implementation of simulation in construction. The types of case attributes included the following:

Current planning techniques used in construction; types of process which has been modelled in construction; identification of the typical construction simulation project characteristics; Identification of simulation tools’ software characteristics used in construction.
STUDY METHODOLOGY

Knowledge of discrete-event simulation in the construction industry is almost non-existent (Aouad et al. 1994). Consequently, a study of current construction projects involving simulation or the interviewing of construction personnel with relevant experience was not feasible. Mintzberg (1973: 229) stated that where suitable personnel are inaccessible or observation techniques are impractical secondary sources, such as documentation, provide good reference data, particularly because secondary sources allow the data to be analysed repeatedly; the data covers a broad time span; and it draws on the analyses of others. As with many research techniques there are drawbacks. Gill and Johnson (1991) identified that when analysing secondary sources the context in which they were written must be appreciated, stating that “There is a need to make allowance for the audience for whom the secondary sources were originally intended and the possible motives the author might have in saying what they said.” However, a qualitative study of the documented cases was undertaken in the pursuit of a greater knowledge of simulation in construction.

The first stage of the study was to select the individual case studies. Glaser et al. (1967) stated that when building theory from case studies, sampling can be carried out for theoretical, rather than statistical, reasons. Thus as the sample size was not affected by factors such as standard error or accuracy, twenty papers were selected, based upon each paper’s richness of data. The methodology used for carrying out the case studies is shown below in figure 1. (Source: Yin, 1994: 80).

Each case study was analysed independently and the data recorded in an individual case attribute grid. Figure 2 below illustrates two of the tables used in the analysis of each case-study. Eisenhardt (1989) advocates the use of analysing each case on a case by case basis when she states that “Overlapping data analysis with data collection not only gives the researcher a head start in analysis but, more importantly, allows researchers to take advantage of flexible data collection.” When qualitative rather than quantitative data is collected, it is advantageous to have reflexive collection methods, so as to include any previously overlooked data (Stake, 1995). Thus, the case attribute grid evolved throughout the study as and when useful information emerged from each case (the dashed line in figure 1 indicates this feedback loop to attribute grid design). After all the cases had been examined, a cross-case grid was developed so as to evaluate the emergent hypotheses. Finally, a written case report was produced detailing the data which was collected and the subsequent analyses.
STUDY RESULTS

CURRENT CONSTRUCTION PLANNING

There is a high level risk associated with managing a construction project, due to its complex and uncertain nature, which is why typically thirty-three percent of a construction manager’s time is spent on planning and co-ordinating activities (Mustapha and Langford, 1990). However, Simon (1957) identified the limitations of the human planner when he stated that “Although decision makers aspire to make good decisions, the capacity of the human mind for formulating and solving complex problems is very small compared with the size of the problem whose solution is required for objectively rational behaviour in the real world.” Consequently, a variety of decision support tools to help managers plan more effectively have been developed, and a survey carried out by Aouad and Price (1994) identified the planning techniques most commonly used in the construction industry to be bar-charts and network methods such as CPM (Critical Path Method) and, to a lesser extent PERT (Project Evaluation and Review Technique). Bar-charts and CPM are the most widely used because of their simplicity, ease of use and the readiness with which they are understood by all concerned, but they tend not to reflect any uncertainty in activity duration, due to the fact that they assume resources have infinite capacity and are always available (Kavanaugh, 1985). Such limitations are caused by their inability to model accurately the dynamic transient conditions often present in construction operations. The result is that buffer times are often incorporated into plans to account for unpredictability, and lead to a reduced accuracy of project plans. Simulation offers the potential to plan for the unpredictable with greater confidence, hence reducing the need for costly buffer times.

JUSTIFICATION FOR USING SIMULATION

Most authors justified the use of simulation by citing the gains which have occurred in other disciplines such as manufacturing, where the benefits have been found to include:

Aiding synthesis of different planning members; greater understanding of system characteristics; increased production efficiency; improved resource management; increased productivity; reduced work in progress; reduced inventory; increased accuracy when forecasting lead times; reduced production costs; reduced production lead times.

Pidd (1992) compared simulation to other modelling techniques such as direct experimentation and mathematical modelling and concluded that simulation’s relative advantages included low cost; the ability to model wide time frames quickly; the ability to replicate results; the ability to model activities other than those in steady-
state; and the ability to sample from non-standard probability distributions. Further advantages of using simulation are that it fosters creative attitudes; promotes total solutions; encourages cognitive process; and enables effective communication of good ideas (Robinson 1994). Halpin (1992) indicated that particular one reason for using simulation in construction was because of the limitations of current planning tools, stating that “because of the complexity of interactions among units on the job site and in the construction environment, queuing models can be applied to only a limited number of special cases.” Thus simulation, through its ability to model the dynamic characteristics of operations as evident in manufacturing, offers the potential to be an improved planning technique over existing tools.

SIMULATION IN CONSTRUCTION

The research which has been undertaken has been predominantly carried out in N. America. This can be partly explained by the ‘champion’ of construction simulation being Daniel W. Halpin, an academic based in the United States who, over the past twenty years, has published several books and many papers both on construction management and simulation. The case study database also reinforced the preliminary evidence that there was little industrial involvement with simulation, indicating either a lack of interest or low awareness of simulation by the construction industry.

Applications of simulation in construction, though limited, have included the following:

pipe-laying; dam construction; earth-moving; location planning of mixing plant; bridge-building; tunnelling; and high-rise construction. Although these applications are diverse, the actual processes modelled are similar. Modelling of soil excavation, concrete pouring, crane operations and material transportation were common to eighty percent of the cases. In contrast, only thirty five percent of the cases modelled any process other than those named above. Obviously earth and concrete related processes are a necessity for nearly all construction projects, hence they have been modelled extensively, but there are many other processes which could have been modelled when considering these construction operations. However, the two processes primarily modelled were either crane loading/unloading and the transportation of material. Modelling these processes are particularly suitable because:

The processes are repetitive; the processes are characterised by the use of expensive capital equipment (i.e. trucks and cranes), hence it is more critical to utilise this equipment efficiently; resources such as truck and crane movement are better controlled and more predictable than processes which involve humans.

Light-weight construction activities typified by mainly manual labour (electricians, plumbers, etc.) were modelled in only two of the cases. Although the electrical wiring of a high-rise building is repetitive, it involves many complex human interactions, consequently making it less suitable for computer modelling.

STAGE OF PLANNING THAT SIMULATION IS USED

For the purposes of the study, a construction project was classified by the following criteria: pre-construction planning; construction scheduling; and post-construction.

Ninety percent of the sample utilised simulation at the pre-construction stage. Planning objectives at this stage are typified by budgeting, which entails optimising resource configurations to meet the specified objectives.
Twenty percent of the sample used simulation at the scheduling stage. The planning focus at this stage is on the management of the actual construction operations and processes, i.e. when they occur, who carries them out, what is required etc. Likewise in manufacturing, simulation tends to be used less frequently for the day to day scheduling of operations. Reasons which make it unfeasible for use in a real-time situation, include the length of time it takes to design, build, run, validate and evaluate a model.

AbouRizk & Dozzi (1993) utilised simulation during the post-construction phase of a project to arbitrate between the client and the contractor. This case was particularly interesting because it was industry-led, and the documented results indicate that that simulation project was extremely useful in reaching a mutually satisfying conclusion.

The best time to build a simulation model is after the actual event has occurred because of the wealth of data available, hence simulation is perhaps most suited to this stage of a construction project, in contrast to typical simulation projects (either in manufacturing or construction) in which data is frequently unavailable.

**REASONS FOR LACK OF CONSTRUCTION INTEREST IN SIMULATION**

Although it has been established through much research that simulation is a valuable tool in manufacturing, and that it even overcomes certain limitations of current construction process planning tools, simulation has remained primarily in the academic community. Therefore it was felt that there must be mitigating circumstances for simulation being overlooked by industry. Many of the case-authors did suggest reasons as to why simulation was not used more. Excessive modelling time, unrepresentative models and inaccurate results were commonly identified as main reasons for simulation’s lack of success. However, these can be thought more of as the visible symptoms of poor simulation projects rather than the main causes. The major causes which emerged against using simulation in the construction industry were lack of data; current simulation software; poor skills; nature of construction; and lack of methodology (all expanded upon below).

**Data collection**

Data collection, which encompasses gathering and validating data, is typically a major activity in any simulation project, occupying up to forty percent of the total duration in a manufacturing simulation project (Trybula, 1994). Typical pitfalls when collecting data include:

- System complexity leads the modeller to collect data in ad hoc manner; difficult to identify the available data sources; poor quality of data available.

These factors are equally applicable when collecting construction data which has resulted in implementations of simulation not representing many of the relevant characteristics of project components or construction resources (Tommelein 1994).
Skills and awareness
The computer as a tool has been under-utilised in on-site planning of construction processes. This differs from manufacturing, which has embraced techniques such as computer-aided manufacture. Consequently there has been a lack of awareness about process simulation in construction, leading to few construction managers with the necessary skills or awareness to be simulationists. Those skills include the ability to translate an operational logic into a form which the computer understands, to be a competent statistician, and have the ability to draw valid conclusions and make recommendations based upon simulation experiments. Unskilled simulationists can lead to the actual simulation projects over-running in duration, and models being incorrect.

Current simulation software
Inadequacies of previous simulation systems were cited as reasons why simulation has not been adopted by the construction industry. Recognised industry standard simulation packages such as ARENA and Witness tend not to have been used in construction because of the fundamental differences between construction and manufacturing. For example, a main assumption with commercial simulation software (developed primarily for modelling manufacturing activities) is that an entity flows in and eventually out of the system. In construction however, the entities remain in the system, in the form of the end product itself (e.g. the bricks that form a house). The software used in the sample cases had been mainly developed by academics, nearly all of which were extensions to the CYCLONE modelling methodology, itself a derivation of activity-cycle diagrams. These less extensive packages, developed primarily for construction, have been more widely accepted, mainly because they are easy to implement, and cost less. However, the amount of detail which can be modelled using these simpler packages is limited, which can lead to unrepresentative models.

Lack of Methodology
Two cases cited that the lack of a recognised methodology caused problems for inexperienced modellers when simulating. Simulation research in manufacturing has identified that very often simulation practitioners are instructed on the fundamentals of using and getting the most from an individual simulation package. However, ‘good’ modelling techniques and methods were left to the practitioner to develop intuitively. With no framework to follow, inexperienced simulationists took too long to build models, and modelled critical factors incorrectly, thus invalidating the model.

Nature of Construction
The construction site is a highly dynamic system, involving many interactions between different resources and activities, and is also far less controllable than its manufacturing equivalent, i.e. the factory floor. The factory floor is static (i.e. it does not alter significantly over time) which is in contrast to the construction site which alters daily as the building is constructed, foundations are laid, etc. Likewise, environmental factors such as weather may have to be incorporated into the model to make it representative of the system, adding complications to the modelling process. These complex factors make it difficult to model certain construction activities using present software.
HIERARCHICAL LEVEL OF CONSTRUCTION INFORMATION MODELLLED

A construction project can be broken down into various levels, including Activity, Operation, Process, and Work Task (Halpin 1992). All of the sample modelled process/work task type operations, but only twenty-five percent of the sample modelled detail up to operation/activity level, the primary reason being that simulation is most suitable where repetition is high. When considering the hierarchy of construction, repetition is low at the project level (for example, the building of a unique bridge) but is high at the work task level (for example, the truck movement for earth removal of bridge foundations).

Modelling at both process/task and operation level increases the demand on both the computer hardware and software, but it does however lead to the following benefits:

- Increased model detail; improved ease of modelling (through the use of libraries etc.);
- Reduction in modelling time.

CLASSIFICATION OF SIMULATION TYPE

A method of classifying models relates to the manner in which the model represents changes of state within the system being modelled. Models can be said to be either discrete-event or continuous: a model describing changes in the status of the system as occurring only at isolated points in time is known as discrete-event, whereas continuous models usually consist of sets of algebraic, differential, or difference equations (Pegden et al. 1990).

Ninety-five percent of the sample simulation packages monitored change in state by discrete-events rather than continuously. One reason for this is when modelling activities such as ‘build a wall’, it is sufficient to know only the start and finish times, and not what occurs in between. A second reason is that construction sites, due to their complexity, are very difficult to model accurately. Using only mathematical equations, many assumptions have to be made, hence making the results unreliable. For these reasons, continuous simulation is less suitable for the modelling of most construction processes. Harris (1992) did attempt to model the flow of material around a construction site using simulation, but this was an isolated case and met with limited success.

TYPE OF DISCRETE-EVENT SIMULATION STRATEGY USED

Simulation languages can be based upon several different approaches including Process Interaction (PI) and Activity Scanning (AS), and the particular approach of the simulation tool is considered to affect the type and ease of scenario which can be modelled. PI modelling focuses upon the entity as it flows through a system. The entity, as it moves, ‘requests’ and ‘releases’ resources dependent upon its own requirements. The PI approach is suitable for modelling systems where entities have many attributes and the resources have few states, or attributes and resource interaction is low. These characteristics are particularly applicable to the manufacturing industry, hence its widespread use. In contrast, AS modelling focuses upon the activities that can take place and the order in which they happen. Resources and entities are treated in a similar way, in that an activity either requires them or not.
Figure 4 shows that the majority of discrete-event simulation systems used the activity scanning approach rather than process interaction (a common technique in manufacturing). This is probably due to the complex resource interactions in construction. Construction resources tend to switch between many states both physically and spatially, hence the suitability of an AS based approach to the simulation of construction operations.

**WHAT TYPES OF SOFTWARE HAVE BEEN USED**

Discrete event simulations can be performed on a computer through the use of general purpose programming languages, or through programming languages or tools designed specifically for simulation (Martinez, 1996).

Only one of the case studies used a general purpose programming language, in this instance ‘C’. Advantages of using languages such as ‘C’ are the almost limitless numbers of scenarios which can be modelled. However, drawbacks include: knowledge of programming language required; little re-usability of models; model communication difficult for ‘non-programmers’.

The other nineteen case studies used simulation models written with simulation specific languages. There are a variety of methods used for classifying simulation software, such as Law and Kelton’s (1991) classification of simulation tools as either simulation languages or simulators. Pidd (1992) divided simulation software into seven categories:

<table>
<thead>
<tr>
<th>General purpose programming languages</th>
<th>‘C’</th>
</tr>
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<tbody>
<tr>
<td>Pre-written libraries</td>
<td></td>
</tr>
<tr>
<td>Simulation programming languages</td>
<td>SIMSCRIPT II; SLAMSYSTEM</td>
</tr>
<tr>
<td>Flow diagram systems</td>
<td>BPA; CIPROS; COOPS; DISCO; GPSS; HSM; INSIGHT; Micro-CYCLONE; SIREN; STEPS</td>
</tr>
<tr>
<td>Program generators</td>
<td></td>
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<tr>
<td>Visual interactive simulation systems</td>
<td></td>
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<tr>
<td>Visual interactive modelling systems</td>
<td>REACT/RESPOND</td>
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The most common classification of simulators are those using a flow diagram approach. This is largely because most of the systems are an extension of the CYCLONE (CYClic Operations NETwork) modelling methodology originally developed by D.W. Halpin in 1973. The table also indicates that the packages predominantly used in construction are not those typically used in the manufacturing sector (Simulation Study Group, 1992), such as WITNESS or ARENA.

**ANIMATION**

Animation is the visual representation of the simulation model (Carson, 1990). Manufacturing simulation software typically includes the use of animation modules of varying realism. These modules work from either a 2D perspective, a 2½D perspective, or in some cases even a 3D perspective. Benefits from a model being represented through animation include:

- Eases model debugging; eases model comprehension; eases model communication; eases model development.

Animation was almost non-existent in the case studies. Some systems, for example DISCO, used a primitive form of animation, in which the model icon changed colour when the program processed a particular activity. However, none of the samples used anything approaching even 2D animation.
Although an animation module is both time consuming and complex when included in a process simulation package, the benefits of including one are an increase in interest and understanding of models by non-simulationists.

SIMULATION OBJECTIVES
Shannon divided typical simulation objectives into the following criteria: Sensitivity Analysis, Scheduling, Prediction, Optimisation, Functional Relations, Evaluation, Comparison and Bottleneck Analysis. Objectives from the case studies included: optimising resource configurations (Sensitivity Analysis); determining construction completion times (Prediction); feasibility study prior to purchasing a piece of concrete machinery (Evaluation); arbitration over costs involved with design changes (Comparison); planning of the operations in house construction (Scheduling). Similarities in problems and objectives therefore do exist between manufacturing and construction, and simulation is also capable of being used as a decision support tool when planning in construction.

EXPERIMENTATION
Having described the typical objectives from the sample simulation projects, this section details how those objectives were measured, and also the typical factors modelled in individual projects. Productivity and completion time were the most preferred performance criteria, which is understandable in that most activities or resources are measured by their rate of work or how long it takes to finish an activity. Simulation also offers the facility to model factors such as resource utilisation and queuing length. These are factors which are often easily incorporated into a simulation model and offer a more complete portrayal of the system. Costing was favoured less as a criteria, probably due to it being a factor which fluctuates regularly thus making it an unstable reference criteria.

Simulation allows various attributes within a model to be investigated during the experimentation stage of a project. Typical attributes which were varied included the following: activity duration; machinery breakdown; material quantities; operating methods; weather; resource configurations. Each of these appeared with differing degrees of regularity throughout the sample. However, by far the most common factor investigated was varying the number of resources (in practice ‘to determine the effect of increasing the number of excavation trucks on an earth-removal operation’).

The investigations carried out on the sample models, coupled with the results, indicate that simulation can model construction processes and that the results, if applied to real situations, would lead to conclusions benefiting the planning process.

CONCLUSIONS
The objective of this study was to determine why there has been only limited use of simulation in the modelling of construction processes, and also to determine common factors between the different cases which have a strong influence on the success or failure of a simulation project.

The consensus from the study was that simulation is a feasible tool for modelling construction processes. However, as seventy-five percent of the papers were from academics presenting their own system or modelling technique (and hence may be biased), this conclusion will be treated with some scepticism. Yet in situations where
simulation had been used for modelling ‘real industrial applications’, it was found to be a successful tool.

Although it does appear that simulation is suitable for modelling in most construction domains, for example bridge building, tunnelling, or the building of skyscrapers, certain processes are more suited to being modelled than others. Processes which had been repeatedly modelled throughout the survey were mainly those which involved relatively simple resource interactions, for example, material transportation involving the use of heavy machinery.

Factors such as the software interface, modelling expertise, and data collection methods need to be addressed before simulation is suitable for widespread industrial applications. However, simulation is a tool which potentially could be used for improving the planning of construction projects.

REFERENCES


