USING DISCRETE-EVENT SIMULATION TO SUPPORT DECISION-MAKERS IN PRODUCTION SYSTEM DESIGN AND OPERATIONS

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ABSTRACT

It is well known that the performance of production systems in construction is strongly affected by variability, interdependence and uncertainty. For that reason, discrete-event simulation is useful for modelling the behaviour of production systems, and understanding the combined effects of those factors. This paper describes two case studies carried out in different countries on the use of discrete-event simulation models in the decision making process concerned with production system design and operations of house-building projects. In the first study, carried out in Colombia, an operations analysis of the construction of structural walls and slabs in a multiple six-floor residential building project was undertaken. Based on the simulation model, a number of recommendations for reducing the total construction time were made, enabling the production managers of the construction company to assess different scenarios, and establish an improved construction sequence in order to reduce the share on non value-adding activities. The second case study consisted of the development of a reusable simulation model for the production system design of a Brazilian construction company that constructs low-rise house building projects. This model supported the development of a new production system design for the company, in order to change from standardized to customized production of dwellings, using a mass customization strategy. The paper emphasizes the challenges of using such models in a real environment, discussing the benefits that were achieved and the difficulties faced by those companies in adopting discrete-event simulation in their decision making processes.

KEY WORDS

construction process simulation, production systems design, operations design

INTRODUCTION

Simulation models can be used in different ways, for instance, as a tool to support routine decisions or as a mean of helping people to think and understand complex aspects of a system (Pidd 2004). Simulation has been widely used

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for modelling the behaviour of production systems and it is especially useful to design new systems (Law and Kelton 2000). Shi and AbouRizk (1998) pointed out the potential of using simulation in the construction industry. However, according to those authors, there is still a need for making simulation widely used in the sector, especially by making it more user-friendly and by reducing the model development time. Another difficulty is related to the systematic lack of historical data on construction processes and operations. According to Fente et al. (1999), in order to reach a useful and valid simulation model it is necessary to use reliable statistical data which could be used to choose a correct probability distribution function (PDF).

The aim of this paper is to present and discuss two strategies for using simulation in the design of production systems and operations in the context of construction companies. Two case studies are described, carried out in different countries (Colombia and Brazil). They involved the use of discrete-event simulation as a tool for supporting decision making in residential building projects. After presenting the case studies, a discussion on the main benefits and difficulties in applying those approaches is presented, highlighting some contrasting and converging conclusions.

SIMULATION IN CONSTRUCTION MANAGEMENT

Typical construction simulation models provide information that is hard to communicate to decision-makers (Kamat 2003). Very often, they are not trained in simulation, and do not have means, time and training to validate or verify the models based only on numerical outputs (Ioannou and Martinez 1996). Thus, construction practitioners are often sceptical about simulation models and find difficult to rely on their results (Kamat 2003).

There are other causes that contribute to limit the application of simulation in construction: (a) the complexity of the construction processes and the difficulty to devise models of those processes (Oloufa et al. 1998); (b) the increase in the model's development time due to that complexity (Shi and AbouRizk 1997); (c) the lack of historical data about construction processes performance (Fente et al. 1999); and (d) frequently, a simulation model is perceived as a "black box" by the users, making it difficult to understand it and rely on it (Shi and Zhang 1999).

While production systems in the manufacturing industry are fairly stable and the time and money invested for building models tend to result in a good cost-benefit relationship, production systems in construction are temporary, and to reduce the time available for developing models is an important requirement (Oloufa et al. 1998).

Thus, two alternative solutions can be used for reducing the model development time: (a) building generic models, which are built for a particular purpose but can be used through a number of situations; (b) devise reusable models which can be used in a context different from the one that was originally intended (Robinson 2003). Developing a reusable component of a simulation model is another similar concept. In that case, part of a model is reused in a new simulation model, in a new context or for other purposes (Robinson 2003).

Reusable models are especially useful when someone is modelling systems of the same domain or sector. According to Mukkamala et al. (2003), in that case the modelling process is repetitive and the models, although similar, are slightly different. Therefore, the modelling effort can be reduced by using domain specific modules or templates which encapsulate the specific logic of that domain and hide many of the model details (Mukkamala et al 2003).

RESEARCH METHOD

FOCUS ON OPERATIONS DESIGN AT THE UDLA

The work developed at the Universidad de los Andes (UDLA) deals principally with field operations design. This means that in on-going construction projects that involve repetition of identical units (apartment towers in particular) there is an effort to obtain information in early units in order to develop the models. Tested and validated models can later be used in the decision-making process for later units. As mentioned, the objective of the research project developed in Bogotá by UDLA was to assist the decision makers during the construction phase. The research method had to be adjusted to document and provide feedback for a project in progress. The main activities involved were:

- General documentation of the constructive processes: processes were observed and documented through direct observation, photography, and video;
- Conceptual modelling: the construction processes were described using flow charts as a first approach to model them;
- Duration and productivity data collection: it was necessary to systematically observe the construction processes in order to collect data about the different activities involved in the proposed model;
- Coding of the models on the selected platform: based on the initial flowcharts, which were complemented and further detailed using the collected data, it was possible to produce preliminary models in Arena©;
- Validation of the preliminary models: the models were adjusted through a comparison between the real processes in the field and the predictions;
- Utilization of the models for decision-making: only after the models were validated they could be used to "what-if analyses", that allowed to identify improved approaches to continue with the work of future units.

Initial contacts were established with a construction company in Bogotá about two years ago to secure their interest in participating in that research effort. One of the authors worked as an engineer in that company at the time, fact that facilitated these contacts. Simulation work proceeded as described in an initial project. Once the modelling results were obtained, the construction firm established formal contact with the team of researchers to request that work be continued in other projects. This indicates that there was a growing interest, once the construction companies understand the opportunities offered by simulation.

FOCUS ON PRODUCTION SYSTEM DESIGN AT NORIE/UFRGS

Production System Design (PSD) has been a NORIE's research topic since 2003. A paper in 2004 IGLC Conference presented a model for devising the PSD of repetitive low income housing building projects (Schramm et al. 2004). That model grouped the main PSD decisions in six sequential steps and suggested that the PSD in those projects should be carried out before the construction phase began, since most project requirements and design details are usually defined in advance.

Another paper in the 2006 IGLC Conference presented an adaptation of that model to the context of complex projects (Schramm et al. 2006). In that context, one of the main conclusions was related to the necessity of including the customer's needs as an input of the process trying to increase value to it.

Since 2005 the use of simulation, particularly Visual Interactive Simulation (VIS), as a tool for helping the decision-making process in PSD phase has been investigated. In those studies, the focus has changed from the deterministic to the stochastic approach, making it possible to understand the effects of variability on the performance of production systems. Arena© is the simulation tool that has been used in those studies.

Current research at NORIE aims to investigate the role of simulation as a tool to improve the PSD process. The strategy of reusing simulation models has been tested in order to reduce the development time of simulation models. Although the unique nature of construction projects often leads to the need of starting each model from the scratch, the reuse of models for simulating projects of the same market sector seems to be feasible. In this study the design of production systems involves two main steps. The first one is a deterministic step in which the existing PSD model (Schramm et al. 2004) is used to guide the discussions. Based on the outcomes of the first step, a stochastic study is carried out in which a simulation model is built and used to improve the initial design. During the study, weekly meetings were held among the research team and the company's production management staff, including site managers, designers, and subcontractors.

CASE STUDIES

CASE STUDY 1: OPERATIONS DESIGN

The models that have been developed and are currently under development have focused on building construction projects in the city of Bogotá. The first model focused on the construction of concrete walls and slabs of 6-story buildings. The project consisted of 192 apartments, each one with an area of 72 m^2. The constructive system is based on structural walls and structural slabs, with four apartments per floor. In Figure 01 a typical building of the modelled construction project is shown.

Figure 01: Typical building of the modelled project.

The project had the necessity to reduce the duration of the construction phase. Delays in the construction process coupled with successful project sales required to increase construction pace. Because of the dominant effect on the duration of the structural walls and slabs, it was necessary to reduce the duration of the structure. However, the project had problems with: (a) the internal transportation of the formwork and scaffolding; and (b) wasted time and lack

Because of the high rental cost of the formwork, the project manager was very inclined to keep it as busy as possible. This forced the project manager to open many work fronts in different buildings simultaneously. However, he did not anticipate the delays and costs resulting from the formwork displacement from building to building.

The second point to improve the system was identified by measuring the pre-mixed concrete arrival times, transported from a near plant. The mixers arrived late frequently delaying work in structural walls and slabs.

As seen, the project had on the one hand an urgent necessity to improve productivity in order to comply with delivery times committed to clients, and on the other hand construction delays that kept accumulating. The authors thought that this was a scenario that was interesting for the application of simulation tools in order to explore alternatives for improvement.

Between the months of June and October of 2006 data was gathered to feed the simulation model. The data obtained was of two types: construction activities and their durations, and direct costs associated to those activities. The collected data showed variability in durations, therefore they were modelled as probabilistic. The main costs associated to the model were the formwork and crane lease cost, the cost of concrete, and the labour costs. In Figure 02 a general outline of the experimental model is presented. The simulation is composed of entrances that can be associated to resources (also called entities) that are displaced through the construction process: concrete, steel and formwork. A series of activities exist for the processing of the entities. Additionally, for the development of each activity there are complementary resources that can be considered stationary, such as: construction crews, and horizontal and vertical transportation equipment. Finally the finished product is obtained, represented as dwellings in the system (apartments).

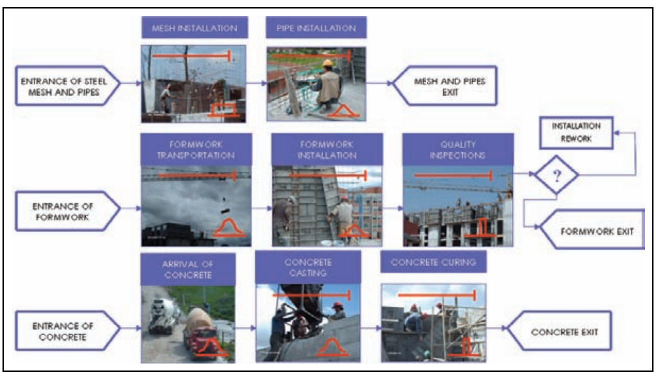

Figure 02: General outline of the experimental modelling system

The following table (Table 01) presents the comparison of the results obtained from the model and the real processes developed in the project. The model was run 35 times and the results were averaged, to compare this average with the real construction process results.

Table 01: Comparison between the predictions of the model and the real construction process

PERFORMANCE INDICATORS	RESULTS			
	Average	Minimum result	Maximum result	Observed result
Total production of concrete walls (m3)	890			890
Total production of concrete slabs	670			670
Weekly production of concrete walls (m3)	44	27	56	
Weekly production of concrete slabs (m3)	37	14	44	
Total time of simulation (days)	118			126
Percentage of time of formwork use (concrete walls)	70%			66%
Percentage of time of formwork use (concrete slabs)	75%			71%
Percentage of time of workers use (concrete walls)	78%			72%
Percentage of time of workers use (concrete slabs)	71%			78%

As can be observed, the predictions of the model are very similar to the reality of the construction process in the observed building. Given this similarity, the model was then used to develop further predictions focused on exploring different scenarios in the construction process to reduce total duration. The scenarios that were explored include: (1) minimizing formwork transportation by working in a single tower; (2) increase in manpower for structural walls and plate work; and (3) negotiate a more punctual pre-mixed concrete delivery to reduce delays. For all these scenarios, and for their superposition, the model predicted a reduction in the duration.

Unfortunately not all of the scenarios were tested in the real process. Scenario 2 was implemented, and scenario 3 was discussed with the concrete supplier, with a moderate improvement in punctuality for concrete delivery.

CASE STUDY 2: PRODUCTION SYSTEM DESIGN

This case study was carried out in a small construction company located in the Metropolitan Region of Porto Alegre, South of Brazil. That company has been involved in developing and building low-middle residential building projects. The project investigated consisted of a low-rise terraced housing project which was made up of 112 ninety square-meter two-story houses, grouped into 21 blocks of 4, 8 or 10 dwellings. The main construction techniques used were: load-bearing concrete block walls, pre-cast concrete slabs and ceramic roof tiles.

The company used to sell the dwellings after the design stage and before they were built, allowing costumers to adapt the project to some extend in order to better suit their needs. However, it had recently decided to build some dwellings to stock, in order to avoid loosing potential clients that do not want to buy a dwelling before it is built. Thus, the new production process should cope both with costumers who buy housing units before the production phase starts and those that make a decision to purchase later in the production process.

The first decision in the proposed PSD model was to establish a construction sequence for the so called base unit (in this project, the repetitive base unit is a single house). Although the company had already built three previous projects with similar house plans, construction techniques and materials, it was not possible to identify a standard construction sequence. After a number of meetings with the production management staff, an agreement on the most suitable sequence was reached. Besides the technical constraints, that sequence took into account the production and transfer batch sizes, the times for completing each process (in terms of a triangular distribution) and the resources that are necessary for each of them. Based on that discussion, a precedence diagram was produced, and pinned on the site office wall in order to explain the document and get the commitment of site managers with the standard construction sequence. That discussion involved the production manager, the foreman, the planning engineer and key subcontractors

The second step was to build the simulation model which was focused on the study of the base unit workflows, the execution strategy and the impacts of those decisions on the entire project workflows. In order to put in practice the possibility of reusing that model in other company’s projects, a generic simulation module was proposed for summarizing each production process’ production and transfer batch sizes, time to completion and the required resources. Figure 05 shows the conceptual model of the generic simulation module.

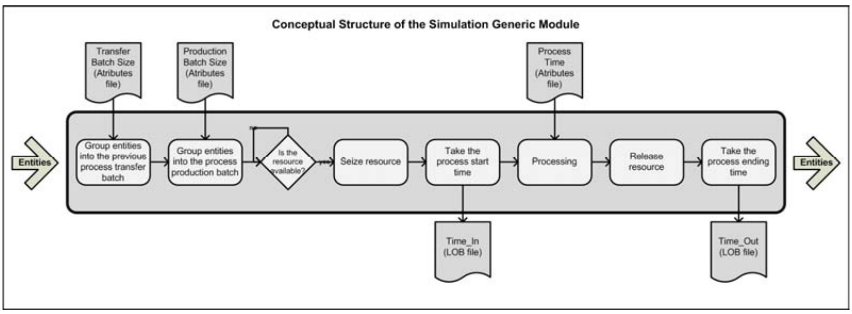

Figure 05: conceptual model of the generic simulation module

Besides simplifying and reducing the modelling time, the generic module allowed to record and write specific process data (process start and finish time, process lead time and so on) which would be used to build planning and control tools (as line of balance, production control chart and S-curves, for instance).

A simulation model was built using the generic module considering the need for model flexibility, i.e. the possibility of simulating scenarios considering different execution strategies, use of resources, for instance, and the possibility of reusing the model in other company’s projects whit similar features (mainly the same kind of base unit and production sequence). Other objective was to allow the production engineer to be able to test different scenarios through a user-friendly interface, in which he could change some parameters, run the model and check the more relevant results without having to know how to use the simulation software.

By using the generic module not only input data of the model but also the simulation outcomes could be entered and accessed through a MS-Excel® spreadsheet. Thus, besides each process time to completion and the production and transfer batch sizes, the number of house blocks in which the project was grouped into, the number of dwellings in each block and the sequence in which they would be built could be easily configured by the modeller/user.

At the other end, the simulation outcomes were designed to improve and facilitate the understanding of the user on the impacts of changes in the production system configuration. In order to facilitate the study of project's workflows, a Line of Balance could be automatically produced from the simulation outputs. That tool provided a direct and easy mean to visually assess any production system change. Moreover, that tool could be used to control the production system performance during the production phase as well. Figure 07 shows part of a Line of Balance devised from the simulation model.

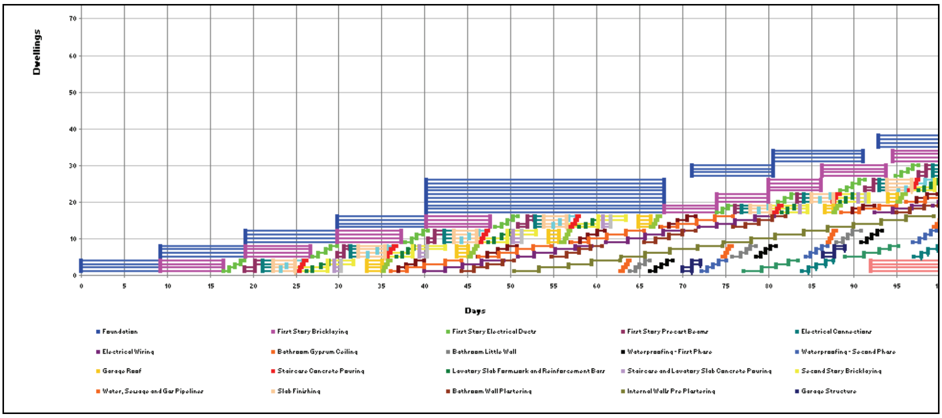

Figure 07: Line of Balance devised from the simulation model

Other tools were also devised from the model: (a) a production control chart, which allowed to the engineer to control each critical process's outcomes; and (b) an S-curve, which made possible to assess the impacts of the production system design on the cumulative costs and expected receipt.

As previously mentioned, the use of simulation helped the company decision-makers in the process of change from a standardised to a mass-customised production system design approach. Thus, a series of lean production principles and concepts were proposed and employed in the redesign of the production system, such as the reduction of production and transfer batch sizes and the reduction of uncertainty.

The simulation outcomes help managers to establish a more reliable process start time and duration. They also provided some key information for the different departments of the company involved in the customisation process. Moreover, based on the PSD produced in the simulation process, design control tools focused on the customisation process were devised, making available a unified database for the product development team, which enabled the control of some key variables:

- The last possible moment to accept client's requests for changes;

- The time to buy materials used in the customisation process;
- The amount of production resources needed for each activity during the whole project;
- The impact of changes in the production system performance.

DISCUSSION

The authors believe that the concepts involved in digital simulation, such as probability, statistics and so on are foreign to most decision makers in construction. This makes difficult the communication with decision makers in the sector and presents important challenges to convince them to explore the use of simulation tools.

Both groups have used a Visual Interactive Simulation (VIS) software to carry out their studies. That kind of technique has the potential of improving the communication between modeller and user, making easier the user's understanding on the model, which can contribute to reduce the gap between simulation and construction practitioners.

In relation to the study scope, while the use of simulation for designing operations takes place during the construction phase, helping the real time decision-making, its use for designing production systems is accomplished before the start of on-site production, in order to explore alternative system configurations and decide on the best production strategy to follow.

Although they may seem contrasting, the authors believe that those two approaches are complementary. In that sense, it would be possible to propose the use of simulation models in the design of the production system, using a less detailed model, and to use simulation to improve specific operations performance during the construction phase.

Other complementary aspect between the approaches is related to the possibility of using data collected from construction operations as inputs for devising a production system model. Also, the generic simulation module which was proposed for modelling production systems could be used to reduce the model development time of the operations models as well.

Both studies have proposed means to deal with two of the difficulties which have prevented simulation from being a widespread managerial tool in construction sector: the lack of historical data of construction processes and the long time required to develop simulation models.

Another difficulty in using simulation models is related to the necessity of a minimum level of process/operation standardization. The second case study showed the importance of establishing a sound construction sequence in order to build a model that effectively represented the project production system. This problem is not related only to reusable models but to any model of construction processes or operations. Thus, one requirement to use simulation as a decision making tool is to reach a minimum level of process/operation standardisation.

CONCLUSIONS

Two case studies have been presented which were carried out in order to assess the main benefits and difficulties of using simulation as a managerial tool for design operations and production systems, respectively.

Each study used a specific approach to deal with two of the main difficulties of making simulation a widespread tool in construction, namely the lack of historical data of construction operations and the long time required to develop a simulation model.

Although those studies may seem contrasting, it was possible to understand the complementary role between them and the possibility of improving each other by exchanging particular experiences.

Based on the findings, some requirements to make simulation a more effectively used tool in the construction sector were discussed.

Finally, despite of the potential of using simulation as a effective managerial tool, the results have showed that although very little effort from their part is required (there was no cost involved; only the effort of data collection by field personnel) only after results have been obtained in an initial project, the construction firm became inclined to pursue exploration of the tool.

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