INTEGRATED VIRTUAL REALITY AND DISCRETE EVENT SIMULATION METHODS FOR PRODUCTION SYSTEM RESEARCH IN CONSTRUCTION

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ABSTRACT: *Researching the behavior of production systems in construction is challenging because outcomes depend not only on production system design and on control strategies, but also on the decision-making behavior of works managers, crew leaders and suppliers. People make decisions within their context, and with limited and often uncertain information. This is especially true in the case of construction projects, where production is dependent on close coordination between multiple independent subcontractors. Theoretical models of the systems are limited if they ignore the human element, or if they assume rationality in decision-making. Thus experimental setups designed to test proposed production control systems or strategies should incorporate live experiments with human subjects. Virtual reality (VR) environments linked with discrete-event simulations (DES) provide an excellent platform for this kind of experimental setup. They enable, for example, experiments to compare performance with and without proposed information systems or other tools. We review the state-of-the-art in research of production control systems in construction management, with emphasis on VR and DES. We describe the experience gained in using a hybrid 'Virtual Construction Site' (VCS) system in which construction crew leaders were immersed in a virtual reality (VR) CAVE where they worked in a DES controlled site. The VCS proved its efficacy by allowing the researchers to observe, record and analyze the decision-making behavior of human subjects in a controlled environment, with high accuracy and in relatively very short times.*

KEYWORDS: *Computer aided simulation; Construction management; Discrete-event simulation; Experimentation; Production system design; Virtual Reality.*

1. INTRODUCTION

Production systems in construction are, in general, particularly wasteful of resources due to the specific challenges of achieving smooth production flows in the complex, uncertain and variable conditions that are typical of construction projects (Koskela et al., 2012). Recognition of the potential to remove waste has led to the rise of many proposals, from practitioners in industry and from the construction management research community, for improved techniques and tools for production control. Among them, location-based management systems (LBMS) (Kenley and Seppänen, 2009) have been proposed to replace traditional tools such as the Critical Path Method (CPM), the Last Planner System™ (LPS) (Ballard, 2000) has been adopted widely for production flow control, and relatively simple kanban and CONWIP approaches have been implemented. A variety of software applications have been developed for scheduling, supply chain management, project collaboration and information sharing, and for implementing the LPS. Examples of these include the i-Booth (Ruwanpura et al., 2012), the KanBIM system (Sacks et al., 2010) and ourPLAN (Ourplan, 2013). The common goal of the systems is to improve production flow – reduce waiting times for crews, deliver materials just-in-time and in the right quantities, optimize use of equipment and reduce inventories of materials and of work in progress.

Research and development of these systems and tools requires the ability to test their efficacy. However, this is difficult for a number of reasons. Construction projects are built by complex organizations in which many independent designers, subcontractors and suppliers have different and sometimes conflicting interests. In such systems, it is very difficult to predict the effect of a proposed production control system, especially due to the often inexplicable nature of human behavior that can be irrational and strongly influenced by the context and circumstances. Yet it is essential to consider the human element when a production control system is tested.

In the following sections of this paper we first review the use of various research methods for research in the development of production control systems for construction. We then discuss the use of discrete-event simulations (DES), considering their limitations as well as their benefits. Against this background we describe a novel

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experimental approach that was sought to exploit the benefits of discrete-event simulation (DES) but nevertheless allow observation of the behavioral aspects. A hybrid 'Virtual Construction Site' (VCS) system was devised and implemented, in which construction crew leaders were immersed in a virtual reality (VR) CAVE where they worked in a DES controlled site, with and without the production control system that was the subject of the research.

2. RESEARCH OF PRODUCTION CONTROL SYSTEMS IN CONSTRUCTION

Much construction management research requires evaluation of the impact of innovative interventions on the way that work on site is planned, controlled or executed (Xue et al., 2012). In this section, we review the different methods that have been used to perform research of this kind in order to establish the background for comparison among them and for evaluation of the relative advantages and disadvantages of the methods that use VR, DES and integrated computer systems.

2.1 Field studies

The most apparently obvious approach to perform such experiments is to test the innovation directly on one or more construction sites. This requires establishment of a control baseline by measurement of key performance indicators on site, application of the innovation, and then measurement of the indicators to determine the impact.

However, experimentation on a working construction project site presents numerous challenges to the researcher. Data collection may require frequent and intensive observations of workers on site, using work study methods. The duration of measurement that is needed is often long, measured in weeks or months. Where the research requires comparative measurements of productivity, factors such as weather, absentee workers, delays in material deliveries, unexpected unavailability of working space, design errors, lack of information, are but a few of the factors that can introduce sufficient noise to render measurements inaccurate or unreliable. The inability to replicate the experiments with the same boundary conditions precludes the possibility of collecting sufficient samples to reduce the statistical significance of these anomalies. Focus groups and in-depth interviews are often used therefore instead of, or in addition to work studies.

Examples of experimentation in the field are therefore relatively rare. Ergen et al. (2007) tested a system based on radio tagging (RFID) and GPS for tracking precast concrete elements, and Teizer (2008) examined the use of various technologies for monitoring workers to improve safety in construction. Both of these focused on monitoring technologies rather than production control systems per se, and had short durations. Chen et al. (2002) provide a good example of extended measurement of an intervention on a construction site, in which the quantities of material wasted were measured over three months in both a control and an experimental building to test the impact of a bar-code material consumption control system.

2.2 Case studies

Given the difficulties listed above, case studies have become a preferred method for investigating the impacts of construction production systems. Examples abound: Khanzode et al. (2005) reported a case study exploration of the use of lean methods and virtual design and construction on a hospital project; Pheng and Hui (1999) researched the use of the just-in-time (JIT) philosophy in construction; Seppänen (2009) used three detailed case-studies to evaluate the use of location-based planning and control systems; and Walsh et al. (2004) evaluated the relationships between demand and inventory in governing the supply chains for capital projects.

By their nature, the case study research projects report the results of interventions that have been implemented in a site or company over some time, usually many months or years, with great effort. Their main drawback, however, is that they do not offer a baseline for comparison of the measures of apparent improvements. It is not possible to say by how much the performance has improved, because there is no alternative process – one cannot in general determine what the outcome would have been without the intervention. Even fairly similar construction projects cannot afford direct comparisons because of the multitude of factors that differ across construction projects. It is also not possible to test variations of the intervention.

2.3 Role—playing simulations

Role-playing simulation games can be used for experimentation. Although their use is common in management training, they are less commonly used for research. Some, such as the PTB Sandbox (Shtub, 2012), the MERIT game (MERIT, 2012), and SIM LEAN (CMB, 2010), use computer interfaces to engage players and perform background simulations. Others, such as LEAPCON and the 'Parade of Trades' were designed as 'live' simulations (without computers), although both have been modelled with discrete event simulations (Sacks et al., 2007, Tommelein et al., 1999). The primary advantage of such games is that they engage human subjects, so that unpredicted or unexpected behaviours can emerge. Naturally, the onus is on the researcher to establish that the simulation situations are sufficiently similar to the simulated reality if the results are to be considered applicable to the real world.

2.4 Discrete event simulation

Discrete event simulation (DES) is an alternative approach, offering a ‘clinical’ way to perform such experiments. A computer simulation model of the existing workflow is implemented and control measurements are made through multiple replications of the system (Martinez and Ioannou, 1999, Halpin, 1977). Next, the model is changed to reflect the new process, subject to the intervention that is being tested. Running the revised simulation through multiple replications then provides a new data set that can be compared to the control data, enabling the experimenters to draw clear cut conclusions about the difference in performance between the two scenarios.

The use of computerized DES for research in construction management began with Halpin's introduction of the CYCLONE system (Halpin, 1977). Since then, numerous systems have been built and used for a variety of applications in construction operations research. Examples include RESQUE and CIPROS, each of which extends the capabilities of CYCLONE by adding increasingly more powerful capabilities for modelling constraints related to the resources (Martinez and Ioannou, 1999), and STROBOSCOPE, which was designed for modelling complex construction operations and resolved some of the limiting assumptions of CYCLONE (Martinez, 1996).

DES has also proved to be a popular tool for research of production system design and of production control systems. (Farrar et al., 2004) described how lean production principles could be structured in a generic fashion in construction simulations, and showed how they could be used to achieve smooth flow in roadwork projects. LEAPCON (Sacks et al., 2007) was a simulation extension of Sacks and Goldin's model for lean apartment construction. Based on the airplane game, it simulated the process of construction of an 8-storey building with 32 apartments. The goal was to investigate the effect of three lean production principles (buffer size reduction, pull flow and multiskilling). The Parade of Trades (Tommelein, 1998), is another example of DES use; it shows the impact of variations in the production rates of individual work stations on the overall workflow of a production line that contains multiple stations. Brodetskaia et al.'s (2011) workflow model shows clearly and explicitly the impact of re-entrant flow of crews in a large residential project, allowing experimentation with different policy heuristics for determining crews' behaviour in terms of selecting and starting work.

The method has numerous advantages: it affords complete control of all of the experimental parameters; large numbers of experimental runs can be made in relatively short periods of time; data collection is reliable, accurate and cheap; the net impact of the innovation can be measured precisely; and the systems can be calibrated as needed. The main problem in this approach is that the behaviours of the actors in the process must be pre-programmed. The possible decisions that a ‘human’ actor can take are modelled by probability distributions that select, on the basis of random inputs, which decision will be made in any given situation. An implicit assumption behind this is that the experimenters can predetermine the range of possible individual behaviour patterns. The use of discrete event simulation also precludes the possibility of learning anything about the ergonomics of the innovation or about peoples’ attitudes to it. People’s responses to unexpected events or unstructured problems cannot be explored.

2.5 DES Systems Integrated with CAD and VR Interfaces

Many researchers have added graphic user interfaces to DES applications, using either CAD, game engines or other virtual reality tools. In one example, (AbouRizk and Mather, 2000) integrated simulation modelling with 3D CAD. Their application enabled comparison of different earthwork loading methods for a specific site represented in a CAD model by sharing information between the two distinct systems. This simplified operation of the simulation and made its results more easily accessible to its users. The VITASCOPE application (Kamat, 2003) provided a tool for visualization of the results of simulations by animating the processes in 3D virtual displays, but it was limited to post-processing – a simulation could only be reviewed once it had completed.

Rekapalli and Martinez (2009) extended that capability by integrating a discrete event simulation system with a VR animation environment that also enabled user input at runtime. In this work, they applied the ideas of 'Visual Interactive Systems' (VIS) developed in the 1970's and 1980's (Bell and O'Keefe, 1986) to the domain of discrete event simulation in construction management. Their premise was that "interaction capabilities can enhance the process of model validation and ultimately lead to achieving model credibility"; one of their primary goals was to improve the acceptability of simulations as tools for making decisions about production processes, especially for practitioners.

The Virtual Construction Site (VCS) (Sacks et al., 2012) also uses the VIS approach, but it was developed with a different purpose: to provide an experimental test-bed to test the efficacy of production control systems through experiments with human subjects. As such, it features the technological innovation of interfacing not only with the subject, but also with the prototype control system software. Thus it allows users to interact with the control software concurrently with their interaction with the VR and DES environment. The VCS setup is described in more detail in the next section.

2.6 Critical comparison of common research methods

Table summarizes the methods classified and outlined in the five groups above, listing advantages and disadvantages of each approach. Naturally, not all methods used in practice conform strictly to the groupings. The methods adopted in specific projects may exhibit overlap among them.

Table 1: Advantages and Disadvantages of various research methods

Research Method	Advantages	Disadvantages
Field tests with observations on site; focus groups and in-depth interviews with subjects	1. Direct observation of subjects' behaviour within the work environment and context. Attitudes and opinions can be explored. 2. Progress data is accurate and reliable. 3. Reasons behind behaviour and verbal responses can be clarified. 4. Use of appropriate technology can enable continuous and long-term observation/recording of data.	1. Requires extensive resources for observation. Sampling is often used instead of continuous measurement. 2. The presence of observers can influence subjects' behaviour. 3. Requires long-term observation, because events of interest occur randomly and may be infrequent. 4. Researchers have little or no control of the many external parameters affecting performance. 5. Requires intensive effort to apply the intervention in the test site. 6. Multiple periods of observation are needed for recording baseline and experimental conditions. 7. Experiments cannot be replicated with the same boundary conditions.
Case studies using interviews, questionnaires and focus groups/ workshops	1. Research is based on production-scale implementations of the intervention. 2. Data is drawn from subjects' experience and practices. 3. Cases can provide data sources from which further analysis can be made. 4. Because case studies build on actual practices and experience, they can be linked to action and their insights contribute to changing practice. 5. Results can be persuasive and accessible because the data are close to the audience's experience.	1. The very complexity of the case can make analysis difficult. Relating causes and effects can be challenging. 2. Data is often only retrospective. 3. The researcher's involvement raises questions of objectivity. 4. Variations of the intervention cannot be tested for. 5. Requires proof of generality of cases because conclusions must be generalized from specific instances. 6. Dependent on prior implementation of the intervention being studied.
Role-playing simulations	1. Relatively few resources required. 2. Multiple replications are possible. 3. Permutations of the experiment can be tested.	1. The outcomes can be highly influenced by the mentor. 2. Subjects may focus on their assigned perspective and miss the opportunity to

Research Method	Advantages	Disadvantages
	4. Allows control of the external factors influencing the behaviour. 5. Subjects can be de-briefed to learn about their motivations. 6. Element of reality is compatible with principles of constructivism. 7. Subjects responses to unexpected events or unstructured problems.	relate the simulated conditions to their work contexts. 3. Players are human – although the rules are clear, players can make independent decisions that change the results 4. The number of runs is limited by the availability and stamina of players
Discrete Event Simulation (DES)	1. Experimenter has complete control of all of the experimental parameters. 2. Large numbers of experimental runs can be made in relatively short periods of time. 3. Data collection is reliable, continuous and accurate. 4. Simulation is relatively cheap. 5. The net impact of the innovation can be measured precisely. 6. The systems can be calibrated as needed. 7. Multiple permutations of a system can be experimented with.	1. The behaviours of all of the actors in the process must be represented by snippets of software code and must be pre-programmed. 2. Assumes that the experimenters can establish, in advance, what factors influence the actors' decisions and the full range of possible behaviours and outcomes. 3. Precludes the possibility of learning about peoples' interactions with or attitudes to the innovation. 4. People's responses to unexpected events or unstructured problems cannot be explored. 5. Verification requires careful comparison with real cases, and/or subjective evaluation by domain experts.
Integrated DES and visualization with animation/ CAD/VR ***without*** **user interaction**	As above, and: 1. Verification is improved. 2. Simulations can use more complex data, including spatially-dependent data.	As above
Integrated DES and visualization with VR ***with*** **user interaction**	1. Experimenter has complete control of all of the experimental parameters. 2. Data collection is reliable, continuous and accurate. 3. The net impact of the innovation can be measured precisely. 4. The systems can be calibrated as needed. 5. Subjects can be de-briefed to learn about their motivations, their interactions with or attitudes to the intervention. 6. Subjects responses to unexpected events or unstructured problems can be explored.	1. The number of experimental runs is limited by the need to recruit and employ human subjects and the time required for each experiment. 2. Extensive resources are required for creating the virtual environments and for programming the interfaces.

3. VIRTUAL CONSTRUCTION SITE

In this section, we present a case study of a 'Virtual Construction Site' (VCS) setup, which was first designed and implemented to perform a series of laboratory experiments to test the field interfaces of the 'KanBIM' production control system for construction (Sacks et al., 2010). KanBIM is a prototype building information modeling (BIM) enabled software application designed to support Last Planner System (LPS) production planning and control. Its user-interfaces for the field provide real-time information on the construction process and enable collection of process status data from its users.

3.1 Experimental Setup

The goal for the laboratory experiments was to test the KanBIM prototype with live subjects in an environment that mimics construction site conditions with sufficient realism and freedom of action to study managerial decision making in context. Given the disadvantages of field tests outlined in Table 1, a second requirement for the setup was that it should enable the researchers to control the parameters affecting the performance sufficiently so that clear connections could be drawn between the decisions made and the operational outcomes. The solution proposed was to develop a hybrid system in which construction crew leaders could participate directly in discrete event simulation experiments, with their roles mediated using a virtual reality (VR) representation of the project, and in which they would be able to use the KanBIM system. Thus the integrated experimental system had to include direct two-way access for the KanBIM prototype to the DES in real-time.

In the experimental work scenario, the subject's goal was to build drywall partitions and to deliver maximum ready apartments in the shortest time possible. The subjects were given a set of plans defining the partitions to be built. Some of the partitions had electric conduits and piping, where the partitions had to be left with one side uncovered until the electrical and plumbing crews completed their installations. If their work was incomplete or if they had 'closed' partitions that were required to be left 'open', the plumber or electrician would not perform their work until the subject returned to the apartment and made corrections. Finally, they had to return to each apartment to close out the partitions, simulating a re-entrant workflow (Brodetskaia et al., 2011).

An important aspect of the construction context is that the actual conditions that develop on site cannot be predicted reliably by the planning function, with the result that even tasks that have been filtered for maturity in the planning process may turn out to be impossible to execute exactly as planned. For example, a crew may arrive at the work face and discover that the crew preceding them has not completed its work, or that they have not removed all of their equipment, or that the designs have changed, or the space is being used for temporary storage. The subjects made their decisions based on the information they could get from the working environment and/or from the KanBIM interface. Their actions were monitored and it is these decisions and the resulting workflows that were the focus for the data analysis.

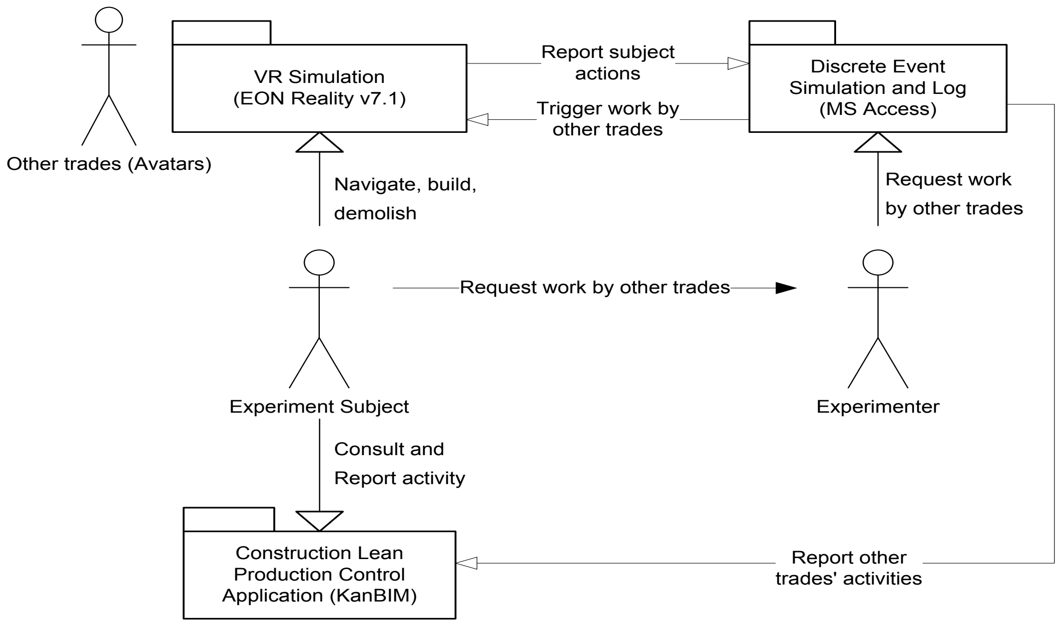

Fig. 1: UML use case diagram of the Virtual Construction Site experimental setup (Sacks et al., 2012).

The VCS was set up using a virtual reality CAVE (Cave Automated Virtual Environment). The virtual site model represented four stories of a residential building with four apartments per floor. A digital model was built using Autodesk REVIT, prepared using 3D Studio, and displayed using EON Studio in a three-sided EON Icube CAVE. The process aspect of the VCS was provided using a purpose-built discrete event simulation engine which was linked to the KanBIM application through an SQL database. Fig. 1 shows a UML use-case scenario of the experimental setup as a whole. The two human actors in the figure are the experimental subject, who fulfils the role of a single construction trade crew, and the experimenter. Workers of two other construction trades – electrical and plumbing crews – are visualized as avatars. The use case represents the experimental situation for testing the subject's behaviour while using the prototype. In the alternative baseline use case, the KanBIM production control application is removed and the subject gathers status information by navigating the building and observing the status of the work of the other trades.

In the VCS, subjects navigated the building and built the drywall partitions in each of the 16 apartments in the building. They used a remote control device to activate markings on the floor to consecutively build partition stud framework, cover one side with boards, and then cover the second side with boards, as shown in Fig. 2. Each step could also be undone to simulate demolition of work where necessary. In the course of the work subjects were required to report completion of stages of work to the supervisor (the investigator) so that other subcontractors (in this case an electrical and a plumbing crew represented by avatars) could install their system components inside the partitions. Subjects were required to return to complete the second side of each partition once the system installations are complete. Uncertainty was introduced by randomly applying obstacles to drywall installation in certain apartments, such as materials stored in an apartment that obstructs work, or scaffolding left by other trades, or introducing late design changes. The time, nature and location of the subjects' actions were recorded throughout the experimental runs.

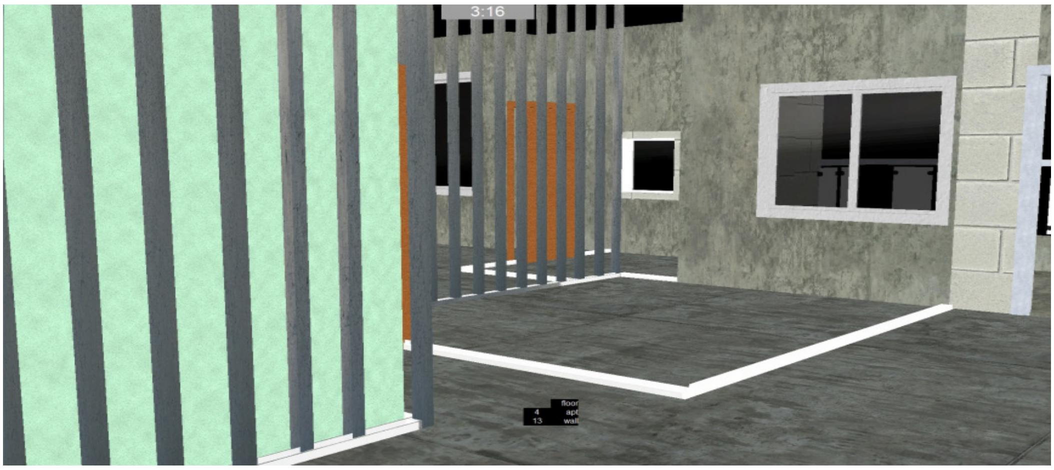

Fig. 2: Interior view of a virtual apartment, showing markings on the floor (at right), built studs (center) and studs with one side of boards built (at left).

3.2 Typical Results

The series of experiments conducted with the KanBIM prototype illustrate the nature of the results that can be achieved using the VCS setup. Each observation started with an introduction of the subject to the virtual construction project, their role in it as crew leader for the drywall team, the ways in which their work would be measured, and where necessary, the function of the KanBIM interface. Before starting the experiment itself, they were given 10-15 minutes to try the system, build partitions, and generally familiarize themselves with the environment. Each subject then worked in the VCS for one hour. All of their actions were logged and their locations were recorded every minute.

Fig. 3 shows an example of an 'as-performed' location-based progress charts for a single subject. Progress lines, such as the line marked 'a', represent where and when the subject worked. The lines marked 'b' and 'c' represent the electrical and plumbing crew avatars' work respectively. Following the lines from location to location indicates the crews' paths through the building, but viewing along a location also reveals the workflow in that location. Consider apartment #31: the subject began working in this apartment 225 work hours after the start (measured in simulation time). On completion, he informed the electrical crew, who in turn informed the plumbing crew when his work was complete. However, the plumbing crew identified an error, and notified the subject via the KanBIM interface. Only once the subject returned to the apartment and corrected the mistake (at hour 270) could the plumbing crew return to complete their work. The apartment was then unoccupied for a long period, until the subject returned to apartment #31 for the third time to close the drywalls (from 370 to 375 hours).

Despite the fact that none of the subjects had prior experience using a CAVE, in de-briefing they all reported that it represented the work environment sufficiently authentically that their behaviour was similar to what it would be on site. The following are comments written by three different subjects, describing aspects of their experience:

"I liked the idea of working on the virtual site. Although it doesn't really simulate the reality, it gives a feeling that you really work in a construction site. It can be used to investigate something very specific, but it would be very difficult to work on a virtual site if it worked exactly like a regular site."

"The construction site is a dynamic place, but not as dynamic as the virtual site. I felt that there were a lot of changes all the time."

"The experiment gave me the feeling that I'm in a construction site, although it does not really simulate the reality. In this experiment there are only two contractors, much less than in the construction site. The construction site is not as dynamic as the experiment. I worked in many apartments, did a lot of work and there where changes all the time, in the construction site the changes do not develop so fast."

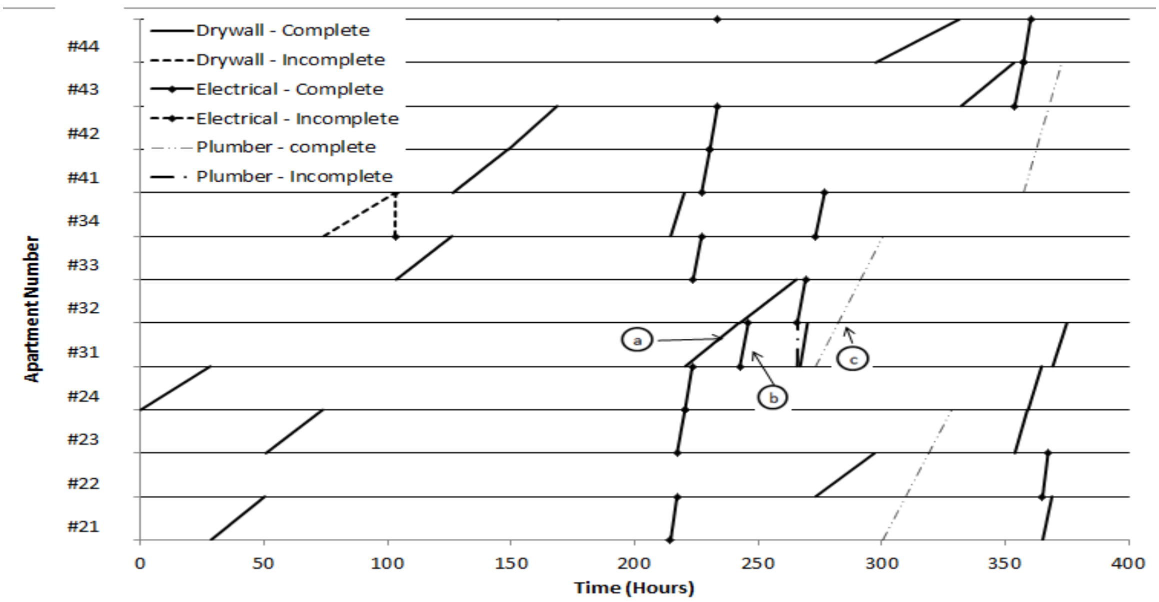

Fig. 3: Location-based progress chart for one experimental subject working without the KanBIM system

The subjects clearly felt the accelerated pace of events, which is due to the fact that actual production times (the time needed to build a partition's stud framing, for example) are collapsed in the VCS into the time of a single click of a button. The result is a sense of the intensity of decision-making in a short time. This also reflects the advantage of the VCS in that it allows researchers to observe far more decision events in a given time than they could during observations in the field.

During the first 20 minutes of each run (the first third) all subjects reported feeling curious and interested. During the second 20 minutes, those working without the KanBIM system reported feeling frustrated and confused as to what work remained to be done, while those using the system reported satisfaction, understanding and trust of the data presented. However, all subjects reported feeling impatience, irritability and fatigue during the last 20 minutes. One hour appears to be the maximum time that subjects can be asked to perform within the VCS setup, partly due to the discomfort of navigation in the 3D environment.

In addition to the location and performance data recorded in the experimental log, the integrated setup provided the opportunity to observe and feel the subject's decision making process in a live mode. The number of situations with which the subject could be confronted during one experimental hour, and hence the number of decisions that were taken and observed, was far greater than could be expected in field tests.

4. CONCLUSIONS

Various methods have been used for production system research in construction management. The most prominent methods are: field studies, case studies, and experimental methods. Experimental methods include role-playing simulations, discrete event simulations and the use of integrated systems such as DES with VR.

Field studies allow the researcher to observe subjects' behaviour directly, within the work environment. However, the intervention must be implemented, data collection may require frequent and intensive observations, and the duration of measurement needed is often long. Case studies are quite different. They report the results of the interventions that have been implemented in a project over some time (again, usually a long period), and they cannot test alternative processes. Their analysis is problematic because it is difficult to categorically associate causes with effects. Role-playing simulations have the advantage of engaging human subjects so that unpredicted or unexpected behaviours can emerge, but they are uncommon in research. The main drawbacks of this method are the influence of the researcher on the subject, the limited number of replications that can be done, and the potential for the subject to misinterpret the rules of their role. Discrete event simulations offer an entirely different method to the previous ones. It affords complete control of all of the experimental parameters and the short period of time required for each run allows many replications. The data collection is reliable, accurate and cheap and the net impact of the innovation can be measured precisely. The main problem of this method is that the behaviours of the actors in the process must be pre-programmed. Integrated systems are similar to the DES, but they are more sophisticated in that they enable experimentation with human subjects in a carefully controlled environment. They allow complete control of all the experimental parameters and offer reliable data collection. The opportunity to observe the simulation continuously allows the researcher to see how the subjects respond to unexpected events. The main drawback of this method, compared to DES, is the limited number of experimental runs that can be performed, which is due to the relatively long time needed to perform each run and to the need to employ professional subjects.

The VCS is an integrated experimental system. It extends earlier work in which human subjects interact with the virtual construction site by adding the ability to test the use of new information technology applications that communicate directly with the other actors and systems modelled in the discrete event simulation and the VR environment. The deleterious effects of 'noise' are eliminated, so that experiments can be repeated and results can be compared. The large setup cost for the VCS (modelling of the virtual environment, programming the DES, interfacing the production control system with the simulation, and programming the data collection) is offset by the quality of results that can be achieved. In the case study described in section 3 above, the VCS proved its efficacy by allowing the researchers to observe, record and analyse the decision-making behaviour of the human subjects in a controlled environment, with high accuracy and in relatively very short times.

Given the advantages and disadvantages of each method, researchers can select an appropriate method for testing production systems in accordance with the stage and scope of their project. For example, at the earliest stages of design and development of a production planning and control system, focus groups and/or in-depth interviews might be useful for collecting requirements or testing the attitudes of the target user group. Once a prototypical system has been implemented, use of an integrated DES and VR system seems appropriate. Field tests are only recommended when a more mature prototype is available. These three steps – design, analysis and testing of prototypes, and finally field trials – are common in other domains as well (such as product design). At the detailed design stage, computer environments and simulations allow the researcher to analyse, test and calibrate the systems as much as needed and with short cycle times, until it is ready for production.

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