PROTOTYPING CONTRIBUTIONS FOR PRODUCTION MANAGEMENT IN CONSTRUCTION

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ABSTRACT

The uncertain nature of construction requires the use of tools that generate useful information and support decision making in each phase of the product development process (PDP). Experimentation techniques have been adopted by other industrial sectors with the aim of supporting product development, especially due to the existing uncertainty and risk. However, those techniques have been poorly used in construction, especially in the study of production processes at building sites.

This paper describes three studies that were carried out in construction companies with the aim of investigating the role of two experimentation techniques, FRS and on-line learning, and also the requirements for their implementation.

The results suggest that these techniques can be used to understand work methods and to establish standard operation elements. The production constraints did not allow the standard work to be fully adopted and interrupted the continuity of the cycle observation–reflection–action that could create in-depth knowledge on work methods. The paper discusses the requirements for establishing an appropriate environment in order to increase the prototyping contributions for creating an in-depth knowledge on work-methods.

KEY WORDS

Prototyping, first run study, standard-operation

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INTRODUCTION

Experimentation techniques have been adopted by other industrial sectors with the aim of supporting product development in a wide range of situations, such as product validation, designing production operations, and performance evaluation. Those techniques play an important role when there is much uncertainty in production process.

The uncertain nature of construction requires the use of tools that generate useful information and support decision making in each phase of the product development process (PDP). In fact, although the Last Planner‰ system seeks to improve the production flow reliability, assuring the beginning of tasks only under favourable conditions, Howell and Ballard (1999) admit that the lack of a better knowledge of work methods is an important source of uncertainty in the production process. Aiming at increasing plan reliability, those authors suggest the use of experimentation techniques such as First Run Studies (FRS).

A 'First Run Study' (FRS) consists of a detailed plan elaborated by a multifunctional team composed of representatives of those who will perform the activity. This plan is put into practice in the first run and followed by methodological study, redesign of the operation and retrial until a standard is met or beaten (Ballard, 2000). FRS is a way of experimenting[7] with new work methods, similar to that used on prototyping in industrial sectors.

However, FRS and other prototyping techniques have been poorly used in construction for designing operations and defining work standards. For instance, according to Kondo (1991), work standards usually include three elements: objective of the work, constraints on carrying out the work, and methods (means) to be employed in performing the work. It is not clearly discussed in the literature on construction management how prototyping techniques contribute to the knowledge of these elements and what is the detail level of the work standard established.

The aim of this paper is to discuss the role of prototyping techniques and how to implement them for operations design in building projects. This research work was based on three empirical studies, carried out in two different construction companies from the South of Brazil. The first study explored the contributions and requirements of on-line learning in construction sites, while the other two studies investigated the implementation of FRS in two different project environments.

FRS AND PROTOTYPING

Chew et al. (1991) suggest four methods to deal with uncertainty due to new technology development and its implementation: (a) learning from others experience; (b) simulation; (c) prototyping; and (d) on-line learning. Prototyping implies actually building and operating the new technology on a small scale in a controlled environment. On line-learning consists of examining the actual, full-scale technology while it is operating.

Clark et al. (1992) recognize that, even in the automobile manufacturing industry, uncertainty persists at the production phase, as a result not only of the lack of knowledge on work methods, but also of the large number of elements that interact unexpectedly. Those authors suggest that experimentation techniques should be extended to the production phase. For instance, a pilot run is a full-scale rehearsal of the commercial production system that is conducted first on separate pilot lines and later on production assembly lines. A successful pilot run is followed by ramp-up, the start-up of commercial production, which begins slowly and gradually accelerates to full production. A pilot run is equivalent to what Chew et al. (1991) calls prototyping and also to FRS proposed by Howell & Ballard (1999). On-line learning is equivalent to ramp-up.

In this paper, prototyping is used in a broader sense, i.e. as a general methodology to approximate the product under investigation, reducing uncertainty irrespective of its development phase.

Other authors (Rosenthal & Tatikonda, 1992; Brown & Eisenhardt, 1995; Reinertsen, 1997; Patterson, 1999 and Ulrich & Eppinger, 2000) suggest an early combined use of prototyping resources. Virtual and rapid prototyping (RP) have been largely adopted to reduce cost and duration of experimentation in the early phase of product design. Grimm (2004) describes RP as a collection of technologies driven by computer-aided design (CAD) data that produce physical models and parts through an additive process.

In construction it is not common to build prototypes, but, rather, the actual building is a kind of prototype (Koskela, 2000). This means that the production stage is often used for eliminating errors generated in the design or production planning processes. This peculiarity of construction increases the importance of researching how prototyping techniques can anticipate such errors and problems and what are the requirements for its successful adoption.

RESEARCH METHOD

Figure 1 summarizes the research design adopted in this research work, including research questions, sources of evidence, and variables.

Three empirical studies were developed, over a period of six months. The first two were carried out in Company A, involved in highly complex construction projects – typically industrial, commercial and hospital projects in which the client facilities must operate normally. The third study was carried out in Company B, in a much less complex environment compared to the previous studies. That company was involved in the development and construction of repetitive residential high-rise buildings. In the first two studies, action-research empirical studies were carried out in the same building site, for introducing prototyping techniques in Company A. In Company B, a descriptive case study was undertaken in one of its projects, since prototyping techniques have been in use there for several years.

In the first study, the use of on-line learning was investigated in the assembly of a reinforced concrete precast stair-case. The high daily cost of the crane hired to assemble the prefabricated structure did not allow stoppages and attempts to study different work methods. Chew et al. (1991) argues that the worse scenario happens when it is not possible to explore the other three learning methods previously or simultaneously.

In the second and third empirical studies the possible contributions and the necessary requirements for carrying out FRS were investigated. In both situations there was enough time for building a prototype for a well defined repetitive unit.

The variables used in the analysis are related to the components of a standard (objectives, constraints and work method). In this research work, method means a specific way of doing a task, which comprises the work content (what operations are necessary), the method design, the resources employed, the duration of the operations (production capacity) and the work in progress (WIP). This definition is based on the necessary information for establishing work specifications suggested by Currie (1977), and on the work-standard elements proposed by Imai (1997), Monden (1998) and Liker (2004).

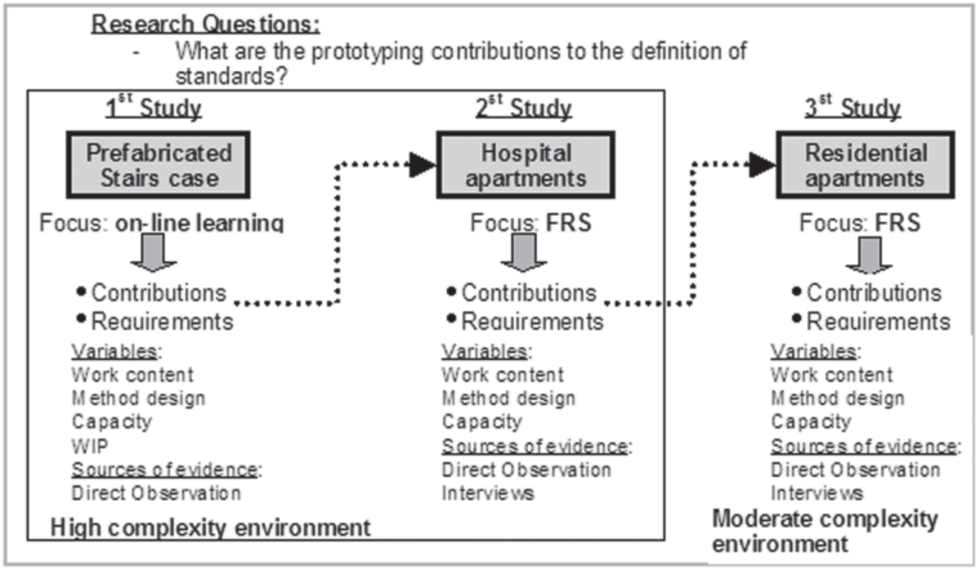

Figure 1 – Research design

RESULTS AND DISCUSSION

First Study

Prior to the start of the activity, a fairly simple 3D model of the prefabricated staircase (Figure 2) was developed by one of the researchers. This model was used as a resource for discussing the production process with the foreman who was in charge of the assembly process. At each cycle of the on-line learning some additional data were collected and represented graphically using operations design tools, such Standard Operation Sheets[8] and Resource Balanced Charts.

The aim of the on-line learning experiment was to reduce the cycle time, due to the high crane daily costs, and also to improve the safety conditions. Moreover, the need for reducing work-in-progress was analyzed.

Despite the information available, discussing the production process was not easy, mostly due to the fact that the foreman found it difficult to make his tacit knowledge explicit.

The exercise of virtually trying different method designs[9] was fruitful because discussions and externalisation of foreman knowledge were limited by real world problems. This detailed plan was helpful to promote discussions regarding work methods and to improve knowledge on how to do the job, even though it has not been followed in practice due to real world constraints. It is important to highlight that these real world constraints were not concerned with the work method, but to broader project management issues, such as contracts, prefabricated plant operations, etc.

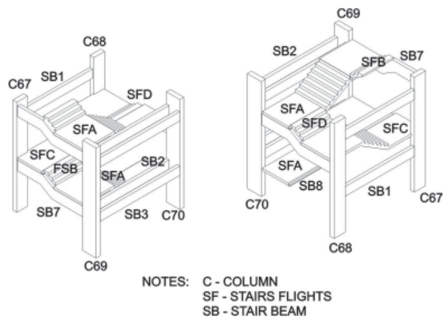

Figure 2 – 3D model of the precast staircase

Apart from these problems, on-line learning made it possible to understand the work content, to identify work method constraints and to define basic directives to be followed. For example, managers had not realized that the column-beam joint involved grouting after welding. The foreman knew this requirement but was not aware that it was necessary to cure the grout for 12 hours before assembling stair flights. This information resulted in a basic directive: grouting of SB7 and SB8 (only these two beams received the weight of the flights- see Figure 2) should be done by the end of the day in order to allow curing overnight.

Due to adjustments that had to be made in SB8 at the prefabrication plant, there were sometimes delays in the delivery of that beam, causing changes in the assembly sequence on site. Although the standard was not followed, some improvement opportunities were identified, such as changes in set up operations and in the design of methods (e.g. some operations could be carried out simultaneously). It was also possible to reduce the cycle time (2 days for each floor instead of 3 days – the initial prediction of the foreman). The foreman accepted this new target (Figure 3), because there was an expectation that problems were solved. However, there was a lack of involvement of production in the full implementation of the proposed improvements. For that reason, some of them were not fully applied.

The positive results of this intervention stimulated the researchers to investigate the use of FRS in the same building site, but in a different type of process. There idea was to develop an earlier understanding of the work method and the sequence of operations by using FRS. It was expected that FRS was a more adequate experimentation environment, by decreasing production pressures and getting production managers' commitment.

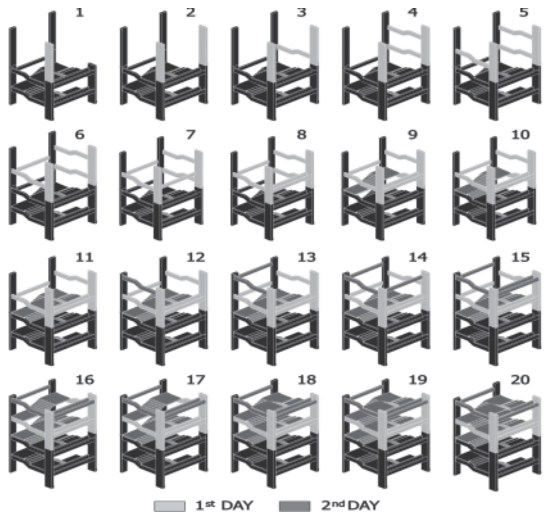

Figure 3 – Two days cycle time

SECOND STUDY

The FRS was carried out in the construction of a repetitive unit, which consisted of two hospital apartments. There were 62 of these units in the building. FRS activities were scheduled well in advance of the remaining sixty apartments. Each of those units involved the construction of brickwalls and dry-walls, installation of building services, and finishings.

Although only two units were built, it was possible to: (a) identify activities that had not been previously planned; (b) establish a new sequence of operations from the discussion of alternative work methods; and (c) establish the production capacity for activities that were well defined[10]. FRS clearly contributed for developing a more in-depth knowledge of work methods for these activities (work content, method design and production capacity). As the schedule of the remaining sixty units was very tight, the prototyping exercise proposed the elimination of some operations and the reduction of durations for others. Most proposed improvements were successfully applied, but the standardized sequence defined in the FRS was not fully adopted due to the lack of production constraint removal.

Two main factors increased the duration of the FRS, causing an overlap with the installation process: (a) there were many design errors and problems that had not properly dealt with (e.g. lack of space to fit the pipes in), and (b) delays in the delivery of materials. Such an overlap caused much rework, since some design problems were only detected at the production of the first apartment units.

Moreover, the development of the FRS caused a work overload for production managers and its benefits could not be fully perceived by them. As a result, they could not get fully involved in the decision-making process that should happen in a prototyping exercise. This problem was partly caused by the fact that FRS activities were not included in the look-ahead planning, nor in the short-term trouble-shooting list of activities, which could have helped managers to perform tasks associated to FRS.

THIRD STUDY

The third study was carried out in a company that had been using successfully prototyping techniques for improving production processes in a much less complex environment. This company used FRS for producing one apartment unit well in advance in relation to the production process. This prototype typically consisted of the construction of dry-wall, and installation of building services.

Four main factors contributed to the success of FRS. First, the company had systematically used prototyping in all projects. Second, the company kept a long term relationship with most subcontractors, which made it easier to standardize the same managerial procedures involved in FRS. Furthermore, partnerships were established with material suppliers who provided the necessary resources for carrying out the FRS. Third, most design and production problems had been solved either in the design process or in previous projects. Lastly, the quality control at the initial construction phases (structure and external walls) was very effective, limiting to a great extent possible deviations in the main dimensions of the apartments. For that reason, prototyping was focused on the validation and fine adjustment of the product, using a detail design and existing work standards as references. For instance, one of the FRS main objectives was to define solutions for solving tolerance problems in wet areas (i.e. bathroom, kitchen, laundry), making sure that the connections between finishing elements (for example, wall tiling, sink and WC basin installation) are properly done.

Therefore, compared to previous studies, prototyping in this environment was a much simpler and more focussed activity. This type of prototyping fits Ulrich & Eppinger's (2000) definition: "any entity exhibiting at least one aspect of the product that is of interest of the development team can be viewed as a prototype". In fact, Patterson (1999) stresses that prototype construction should focus on areas where outcomes are uncertain. In this study, this means that if the dimensions of wet areas were correct, most probably all succeeding finishing activities would be straightforward as they would exactly follow what was designed.

The presence of the production manager was demanded only when a major problem was faced. Besides that, there was a self-organizing cellular like team which avoided the inclusion of FRS activities in the lookahead planning. FRS activities were conducted autonomously, apart from the hierarchical site chain of command.

This third study highlighted a successful application of FRS which yielded the necessary information in connection to product design validation. It might be argued that the FRS objectives were restricted and hence its success, but it should be remembered that this particular study was made possible due to a prototyping culture well established in the company.

CONCLUSIONS

The main contribution of this research work was related to the role of experimenting techniques (FRS and on-line learning) and the requirements for their implementation. Table 1 summarizes the main findings of each case study.

The most important contribution of the two prototyping techniques investigated was to understand work methods and to establish standard operation elements. The lack of produbúion constraint removal did not allow the standard work to be fully adopted, and interrupted the continuity of the cycle observation–reflection–action that could create in-depth knowledge on work methods. It is necessary to establish an appropriate environment for the full application of work-standards in the real world. In that case, it is possible that a new set of constraints concerning work methods might arise and consequently new directives would be defined. In this context a hypothesis must be investigated, concerning the capacity to deal with prototyping issues in a dynamic environment without the need to establishing detailed standards, but just basic directives.

Research Findings	1st Study Prefabricated stair	2st Study Hospital Apartments	3st Study Residential Apartments
Contributions	- Work content - Sequence of the operations - Capacity production - Set up operations - Method designs* - WIP*	- Work content - Sequence of the operations - Capacity production - Method designs	- Validation of the product built, assuring design dimensions
Requirements	- Design problems solved - Managers committed and in grounded on site - Simultaneous use of prototyping techniques	- Reduce manager work overload – include FRS on lookahead planning	- Quality control limits the dimensions variations– replication of solutions set up by FRS - FRS simplification –focus on uncertainties only - Partnership to manage resources supply

Table 1 - Summary of research findings

This appropriate and dynamic environment should result not only from the exploration of other prototyping techniques but also from the use of practices that support the prototyping process, as suggested by Ulrich & Eppinger (2000), such as cooperation among the organizations, enhanced communication, and learning activities. Those practices, if connected to the prototyping process, should mitigate the work overload caused by the realization of the prototype and increase the benefits that follow from its undertaking.

Regarding the application of other prototyping techniques, virtual models must be used for eliminating design uncertainties and errors (e.g. poorly defined column-beam joint, lack of space for fitting elements), removing product related problems that do not allow the prototyping exercise to focus on work-methods and standards. Also, RP could have been an effective way to make explicit the foreman's knowledge that was essentially tacit. It would allow the exploration of vicarious learning (learning from others' experience) which is the most basic learning method suggested by Chew et al (1991). This study has indicated that even virtual models for trying different work methods are useful because they provide opportunities for what-if discussions that make explicit the knowledge related to real world constraints.

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