THE DESIGN OF PRODUCTION SYSTEMS FOR LOW-INCOME HOUSING PROJECTS

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ABSTRACT

In Brazil, the Federal Government has recently increased investments in Programs for low-income housing. This change has encouraged several construction companies to get involved in the development of house-building projects, which demand different capabilities compared to other market segments. These projects usually consist of fairly large number of house or apartment-building repetitive units, require a relatively short lead-time, and are limited by a fairly small profit margin. The design of the production system has a key importance on the project cost and time performance of such projects. This paper discusses the scope and the main requirements of the production system design in this context. It is based on multiple case studies carried out in the South of Brazil. The main contributions are concerned with the set of decisions involved, tools for the design of the main production flows, and the management of hand-offs between crews.

KEY WORDS

Production system design, low-income housing, critical processes, work structuring, planning.

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INTRODUCTION

The launching of several housing construction programs intended for low-income population by the Brazilian Federal Government has motivated several construction companies to operate in a market sector that has not been well explored yet. This market has peculiar and distinctive features different from those found in other construction market sectors, such as industrial and commercial building, in which projects tend to be very different from each other.

In general, the house building projects financed by Brazilian Government Housing Programs are carried out in a relatively short duration (between 10 and 12 months for the construction stage), considering the fairly large number of housing units (between 120 and 400 units per project) and the use of traditional labor-intensive technologies. Usually, the Government establishes the duration of the project, the minimum gross floor area, and the minimum specification of some key components. Also, in most programs there is a cost yardstick.

For that reason, the companies that operate in this market are much concerned with the reduction of the project lead-time and costs, in order to keep their profit margins within an acceptable level. The financial resources from the Government are paid in monthly instalments, according to the development of the site activities and based on a previously approved schedule of payments.

The type of production system found in these projects has some similarities to those found in repetitive manufacturing environments (Bashford et al., 2003), since one kind of housing unit is produced in a repetitive way, using specialized crews for different phases.

Besides being repetitive, these projects are characterized by a perfectly defined demand. The product specifications, the volume and the duration, as well as the price are defined before the beginning of the construction stage. Under these conditions, speed and efficiency are critical for improving the performance of the production system. In that sense, the management of hand-offs between different crews plays a key role. In this context, production management plays a very important role in terms of reducing costs and lead times, and increasing profit margins.

For that reason, production management in this kind of project has been the focus of a research project, the Management of Social Interest Housing Projects (GEHIS), led by the Building Innovation Research Unit (NORIE) of the Federal University of Rio Grande do Sul. The main goal of this study has been to develop an integrated model for managing both design and production. The production planning and control model proposed by Bernardes and Formoso (2002) and the Last Planner system for production control (Ballard, 2000) were used as starting points to devise the proposed model.

One of the key processes of the proposed model is the design of the production system. The emphasis in this process was established due to the fact that in several case studies carried out in low-income housing projects the implementation of the production planning and control process at the medium and short term levels was insufficient to make the production system stable (under control), i.e. this was not enough to reduce the variability in the production system to an acceptable level. Despite the repetitive character of those projects, very little learning was achieved. Also, much of the variability and uncertainty was caused by absence or inadequacy of the decisions carried out before the beginning of the construction stage. For example, in some projects the execution sequence had not been adequately defined causing work interruptions.

Their performance was strongly affected by the combined effect of variability, interdependency, and speed of some key production processes.

Therefore, this study aims to investigate the role and the content of the production system design as a necessary step that should be part of the design stage, before the beginning of the construction stage. According to Koskela (2000), the production system design is a major step to avoid waste formation by removing undesirable features of the production system such as high variability. In the case of repetitive projects, the goal is to establish a non-stop synchronized workflow that is necessary to achieve the project deadlines (Bashford et al., 2003) and to keep costs under control.

This article discusses the purpose and the main decisions involved in the design of production systems. A sequence of steps and a set of tools are proposed, keeping in mind the need to manage hand-offs between different crews. A comparison to other approaches to synchronize production, such as just in case, just in time and theory of constraints (TOC) is also made. This study was based on multiple case studies developed in low-income housing projects in the South of Brazil.

THE PRODUCTION SYSTEM DESIGN

In current practice, construction management is often centred in activities or contracts. The coordination between the various crews is governed by a central plan that establishes the sequence and the timing to start each activity. Improvements, such as the reduction of project costs and duration, are typically sought mostly by increasing productivity or changing the sequence of activities.

By contrast, in the view of the lean construction community, a construction project should be managed in "project-as-production-system" terms, i.e. project total cost and duration are more important than the cost or duration of any specific activity (Howell and Ballard, 1998). Construction must be seen as a production system that involves specialised crews and hand-offs of partially finished work between them. Workflow in construction is considered as the flow of several crews moving from location to location and completing the work which is a requirement to be fulfilled before the next crew initiates the following task (Tommelein et al., 1999).

Production management is understood in terms of designing, operating (including planning, controlling and correcting) and improving productions systems (Koskela, 2000). The objective of the production system design is to discuss and translate the intended production strategy into a set of decisions, forming the structure that will manage the different activities (Slack et al., 1997), i.e. the production system design should create appropriate conditions for control and improvement (Ballard et al., 2001).

According to Askin and Goldberg (2002), "*production system design and operation involve managing production resources to meet customer demand*". That requires the development and execution of production schedules specifying how to use resources to convert raw material into finished products. Gaither and Frazier (2001) state that the design of production systems must begin early, at the product design stage, when the way the product is manufactured and the production system is organized should be established. Taking into account how the product design decisions can influence the production process is the first opportunity available to increase the performance of the production system.

There are three main goals in the design of the production systems (Koskela, 2000): (a) deliver the project, (b) maximize value, and (c) minimize waste. At a strategic level, the production system design focuses on the broader chain of processes that involve not only on-site production but also suppliers and consumers (Slack et al., 1997). In operational terms, the concern is to devise the layout and the material and information flows in order to create favourable conditions for a high performance production system (Slack et al., 1997). In low-income housing projects, the production system design represents the most basic form of minimizing the effect of variability, contributing to achieve the major project goals, such as the reduction of costs and lead-time.

PRODUCTION SYNCHRONIZATION

The ideal situation in production systems with repetitive features is to have processes working in a continuous way so that the components flow without any delay or queue in a synchronized mode (Rodrigues and Mackness, 1998). Traditionally the approach used to achieve this purpose is balancing the capabilities of different production processes (Umble and Srikanth, 1995). Balancing means to equalize the processing time of different processes, while synchronizing refers to the effort of establishing a rhythm for material flows. Nevertheless, even if the processes are balanced, stocks might exist if the processes are not synchronized (Black, 1991)

According to Rodrigues and Mackness (1998), there are three theoretical approaches to production synchronization. The first one is the traditional way known as just-in-case (JIC). It is based on the assumption that maximizing the efficiencies of the individual process leads to the optimal performance of the system. This can be achieved by the definition of economical lot sizes, local cost measurements, and managing resources to work with 100% utilization.

The just in time (JIT) approach seeks to synchronize the production by attempting to create a chain of balanced production processes, in which products are fabricated as needed, pulling them from the market backwards to raw-materials, process by process. However, this synchronization approach finds some limitations. In some cases, it is difficult to create a balanced flow and, even if that is possible, the production system can stop whenever a process breaks down (Rodrigues and Mackness, 1998).

The third approach to production synchronization is the Theory of Constraints (TOC), which is a mix of push and pull systems, known as drum-buffer-rope – DBR (Goldratt and Fox, 1986). Differently from the previous ones, this approach recognizes the existence of a critical process (bottlenecks) in any production system, and seeks to identify and define the maximum utilization (drum) of this process and then subordinates all other processes to this decision (rope) (Cox and Spencer, 1998). In this way, components are pulled from the bottleneck process from upstream processes and then pushed from those to the downstream processes until the end process. In order to ensure throughput, buffers are used in the system. These are located before the bottleneck process to preserve its full utilization, and before the market in order to protect due dates (Rodrigues and Mackness, 1998). Thus, the DBR approach tries to focus the attention only on the process that compromises the production levels, the bottleneck, simplifying the task of production system management.

RESEARCH METHOD

Six house-building projects financed by the Brazilian Government Housing Program were investigated in this study. These are located in Pelotas, Rio Grande and Santa Maria, all of them medium-size towns of the State of Rio Grande do Sul, in the south of Brazil. Table 1 presents a brief description of those projects. The three companies involved in the six projects were all small sized: they typically carried out two to three low-income housing projects at a time.

In the first stage of the study, which involved three of those projects, a preliminary scope of decision-making for the design of the production system was established. Based on these findings and on the learning of the research team on the nature of those projects, the scope of decision-making was reviewed and applied in the other three projects.

Table 1: Brief description of the projects investigated

Project	Company	Number of Units	Lead Time	Main components
Cidade de Águeda	A	356 houses	10 months	Pre-cast concrete panels, fibre-cement tiles
Duque de Caxias	C	02 buildings (112 apartments)	12 months	Load-bearing brick walls, pre-cast concrete slab, ceramic tiles
Solar dos Carvalhal	C	136 houses	10 months	Load-bearing brick walls, pre-cast concrete slab, ceramic tiles
Cruzeiro	B	03 buildings (111 apartments)	10 months	Load-bearing brick walls, pre-cast concrete slab, fibre-cement tiles
Noel Gurarany	C	10 buildings (200 apartments)	12 months	Load-bearing brick walls, pre-cast concrete slab, fibre-cement tiles
Novo Tempo	B	10 buildings (200 apartments)	12 months	Load-bearing brick walls, pre-cast concrete slab, fibre-cement tiles

In both stages, the design of the production system was carried out in weekly meetings involving the production management team – usually the production manager, the foreman, and the material supply manager, and, occasionally, the company top manager. In general, each meeting lasted for two hours, and for each project between 10 to 14 hours were spent in the design of the production system. The meetings were initially chaired by members of the research team, since this type of discussion was new in the companies involved. An agenda for discussion was usually prepared, and the participants were encouraged to discuss different alternatives for the production system design. The critical problems, the tasks to be carried out by each member, and the decisions made in each meeting were documented in the meeting minutes. At the end of this process a full report of the production system design was produced to be used in future projects.

The impact of the application of the production system design to some extent was assessed during the construction phase of those projects. The implementation of a planning and control system, based on the model proposed by Bernardes and Formoso (2002) and on the Last Planner System (Ballard, 2000), was monitored by the research team. This assessment was limited by the fact that some of those companies have had difficulties in implementing their production planning and control systems.

SCOPE OF THE PRODUCTION SYSTEM DESIGN IN LOW-INCOME HOUSING PROJECTS

Based on the six case studies, a proposal was made for the scope of decisions involved in the production system design for low-income housing projects. Also, some tools for supporting its implementation were devised. Figure 1 outlines the six main steps involved in the design of production systems in this particular kind of project. In spite of the sequential representation of these steps, most decisions are interdependent. For this reason, several iterations are usually necessary (represented by decision and revision flows), as indicated in Figure 1.

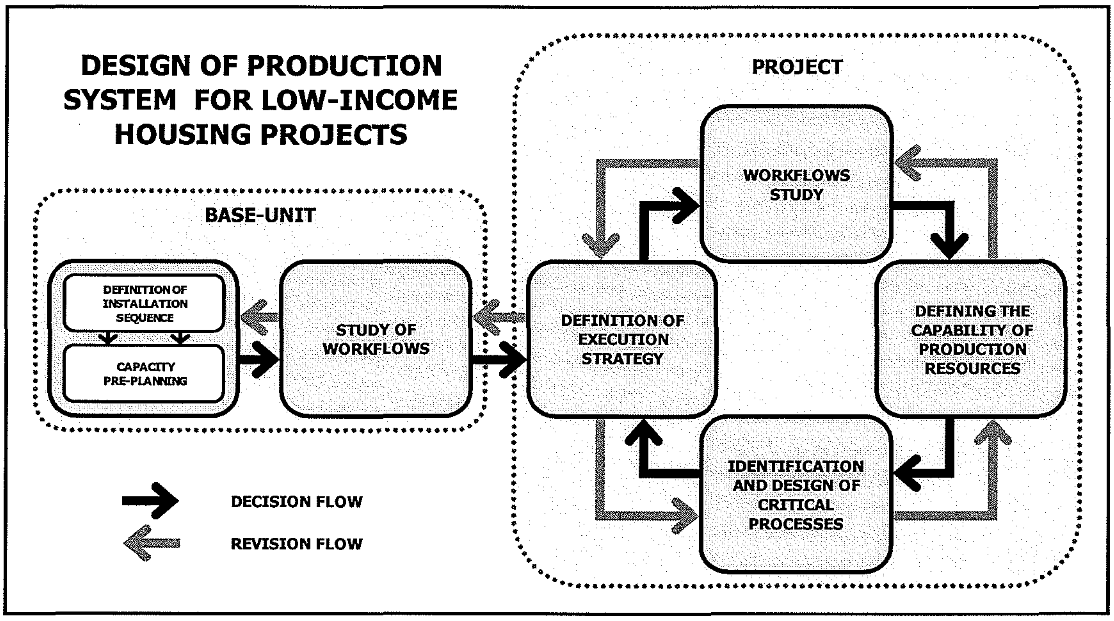

Figure 1: Decisions involved in production system design in low-income housing projects

In the following sections each of the steps presented in Figure 1 is explained. One of the case studies in which this process was implemented, the Novo Tempo project, is used as example. This project consisted of ten five-story buildings, each one of them containing twenty 37.15 sq.m. apartments. Those buildings were grouped in two blocks of three buildings and one block of four buildings. Besides those buildings, car parking, playground and a community centre building were built.

DEFINITION OF THE BASE-UNIT INSTALLATION SEQUENCE AND CAPACITY PRE-PLANNING

Based on some preliminary information about the project, the first step to be accomplished is the definition of the installation sequence and activity durations for the production base-unit. The production base-unit is defined as the smallest repetitive unit for each process. This can be a pavement, an apartment or a house, depending on the type of dwelling provided. It might be possible to have different base-units for distinct processes – for example the base unit for the load-bearing walls is often a pavement, while for the external plastering the base-unit is an apartment building or a façade.

In this step, the focus is on the definition of the conversion activities involved in the production of a base-unit. A network can be drawn to represent the precedence relationships between activities. In general, this might be based on the experience of the production management team and on the consideration of the technical constraints related to the construction technology.

The length of each activity is based on the historical productivity rate of those activities. These lengths are selected in a deterministic manner, in such a way that they are unlikely to be exceeded. It means that a small time buffer is added to the duration of each activity. Although this strategy increases work-in-progress in the system, it was used because it increases the predictability of activity starts and in the material and pre-cast component supply, making control easier. However, if a work crew ends their work sooner than the scheduled date, they are allowed to start work in the next unit, provided the resources are available.

Besides the preliminary definition of the processes involved, a pre-plan of the required capacity should be made, as well as an initial definition of the production resources (equipment and crews) available. This pre-plan can be based on previous data from past projects, if available, such as size of crews, their productivity rates, and the capacity of the equipment likely to be used. This information should be properly documented in order to be available for the next steps – this is often neglected in construction projects and some of the discussions and decisions made are often forgotten, especially if there are changes in the production management team.

STUDY OF BASE-UNIT WORKFLOWS

In this step, the flow view of production management is emphasized. The workflows of several production crews along consecutive base-units are established in terms of both space and time. The Line of Balance technique (figure 2) can be used to define and simulate the workflows and the pace of each crew. The objective is to identify the interferences between the several production crews and, if necessary and possible, to change their paces or the sequencing in order to avoid such problems. Sometimes, it may also be necessary to make changes in the capacity of the production resources.

In the line of balance, no time buffers are added between the activities because their durations had already been established with some slack in the previous step. However, time buffers are added at the end of building execution, in order to protect the system against variability in the total duration of the construction stage.

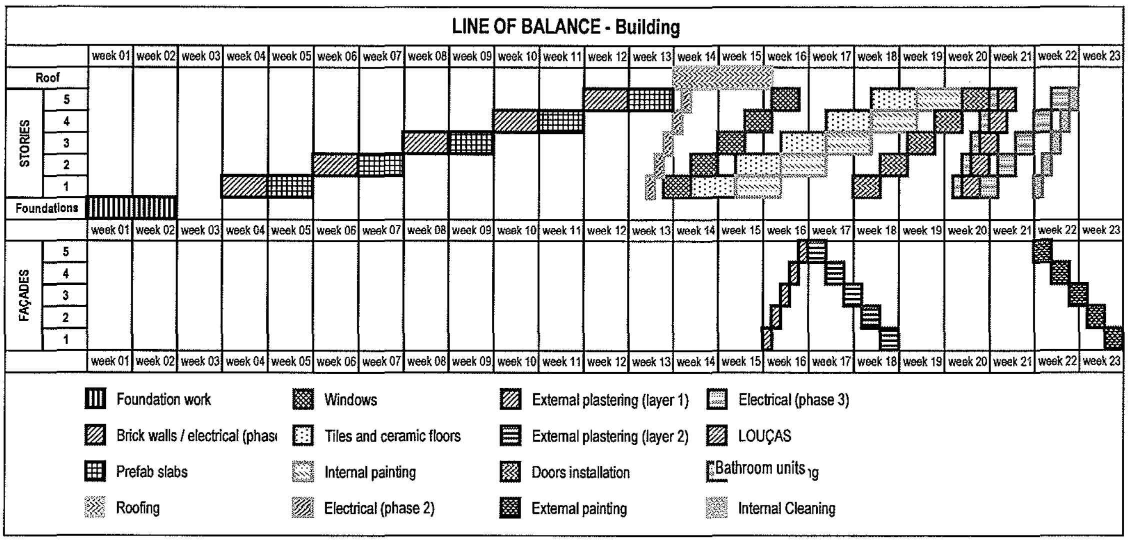

Figure 2: Line of balance for a project base-unit floor and wall tiling /wiring/door

DEFINITION OF THE PROJECT EXECUTION STRATEGY

The execution strategy for the project is one of the most important steps in the production system design, since it has a strong impact on the performance of the production system concerning costs and time. From this step on, the focus of the analysis begins to be on the whole project and not only on the base-units.

The definition of the execution strategy covers a chain of decisions related to project segmentation in work zones, in order to create "small projects" within the whole project (Birrel, 1980). These zones contain a certain number of base-units. The working crews will be assigned to those small projects, and should develop their activities in a continuous flow following an execution pace. In this sense, these segments should be executed independently from each other in a parallel or sequential manner.

Besides the project segmentation, it is necessary to define the size of transfer and production batches[4] for each process. Appropriate sizing of these batches contributes to achieving a synchronized workflow, reducing the level of stocks and the production lead-time (Umble and Srikanth, 1995).

Some product design decisions establish limits on the way the project can be segmented and how these segments can be assigned to different production crews. For example, in the case studies the definition of some production and transfer batch sizes depends on the form by which the base-units are grouped together and on their location in the site. For instance, in one of the projects the base-units were grouped in 28 terraced-house blocks. For that reason, the roof-building process could only start after the brick walls of 28 houses were concluded. If smaller

[4] The process batch is equivalent to the quantity of one product that is processed by a resource before starting the production of another product, and the transfer batch is the quantity of units that will be moved at the same time from one workstation to the next. According to Umble and Srikanth (1995), the transfer batch does not need and should not be the same as the process batch and the transfer batch should be ideally as small as possible.

blocks of houses had been designed it would have been possible to expedite the start of the roof construction, and consequently of the subsequent processes, reducing the lead-time of these units.

In this stage of production system design, several alternatives must be considered. The final choice of the execution strategy should be based on the following considerations: (a) impact of the strategy on the total project duration; (b) capacity of the material suppliers to fulfil the estimated demand; (c) production capacity of the critical processes (bottlenecks), in terms of crews and equipment; (d) impact of the strategy on the total project cost. In the case studies, S-curves were used to assess the financial impact of different execution strategies.

Although the most suitable execution strategy alternative should be chosen at this stage, the other alternatives should not be totally discarded, since one of them may become suitable if the original one cannot be implemented due to some unexpected change in the project. Figure 3 shows the graphical representation of an execution strategy for the project under analysis.

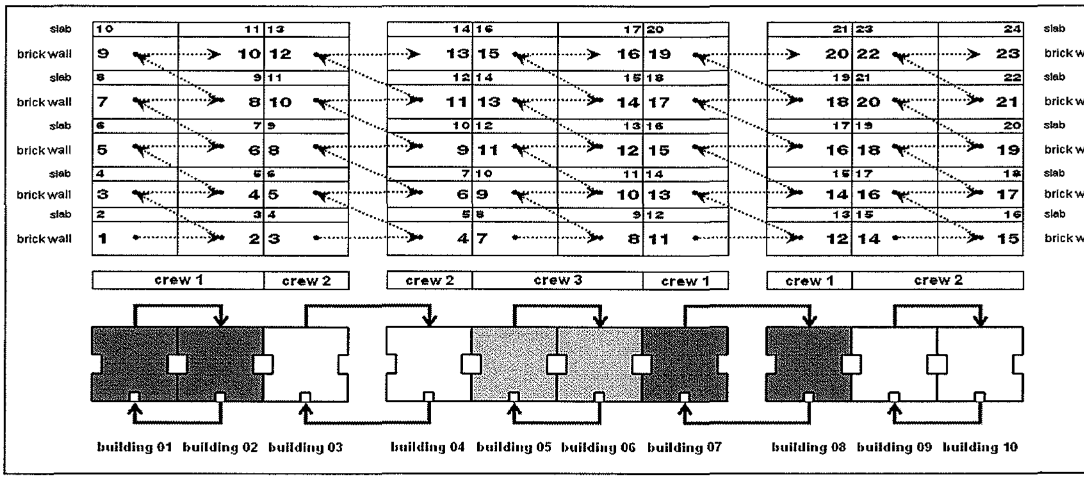

Figure 3: Partial execution strategy of the Novo Tempo project

In the Novo Tempo project, the sequencing of the execution of load-bearing walls had a strong influence on the execution strategy for the whole project. The construction started from the back to the front of the site in order to make it easier to move materials. The block-wall work was divided into three parts and each one of them was given to a different crew. The established pace was one story (base-unit) each five days. Each crew moved between two buildings. For example, in Figure 3 crew 1 moved between buildings 1 and 2 and then to buildings 7 and 8. While crew 1 was working at building 2, the pre-cast slab assembly crew worked in building 1.

STUDY OF PROJECT WORKFLOWS

The study of the project workflows consists of analysing the impact of the chosen execution strategy on the relationships between the base-unit workflows. The main concern is to focus on the production resource flows that are common to the different segments in which the project was divided, seeking its synchronization. The Line of Balance technique can also be used at this stage. Based on this study, it is possible to establish the timing for the beginning and the conclusion of each construction process, as well as the total duration for the project. In addition, it is important to compare and evaluate the deadlines established in this study against the lead-time demanded by the Housing Program.

Another tool used in this stage was the synchrony chart. Figure 4 presents a chart used to synchronise the execution of load-bearing walls (black) and the pre-cast slab assembly process (hachured), for 4 of the 10 buildings, which were designated to the block-wall crew 1. The following analyses were carried out: (a) the maintenance of even work flow for the block wall crews; (b) the establishment of a time window long enough to allow the pre-cast slabs to be assembled, considering the installed capacity of the equipment; (c) required production capacity for the off-site production of the pre-cast slabs; (d) impact on the total construction time.

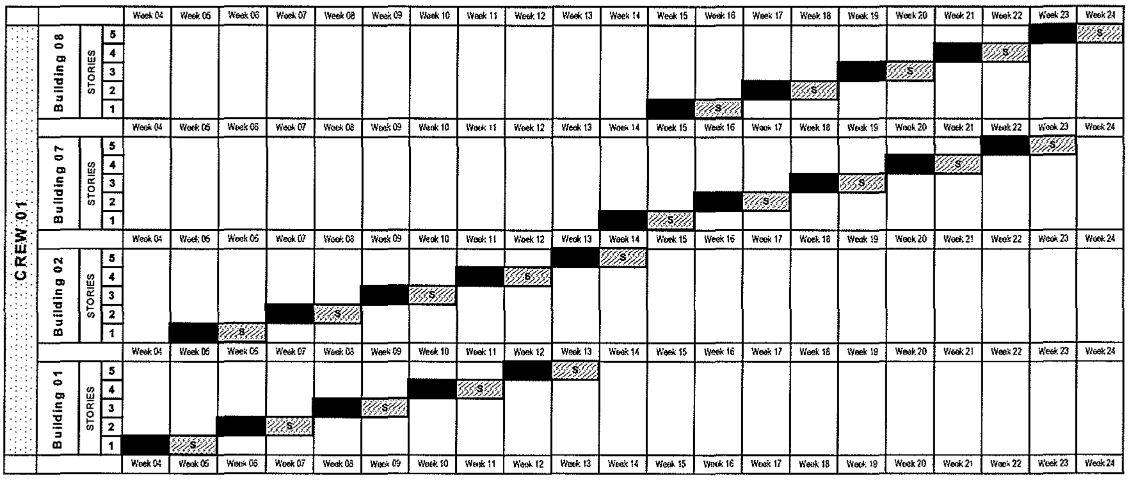

Figure 4: Synchronisation Chart between the execution of load-bearing brick walls and pre-cast slabs assembly (for one crew)

DEFINING THE CAPABILITY OF PRODUCTION RESOURCES

Based on the definition of the project execution strategy and considering the pre-planned capacity, it is possible to define the capacity of the main production resources that are required for carrying out the project. In this step, usually information about the necessary amount of resources (e.g. labor and equipment) is produced – for instance by using histograms. Based on this information, it might be necessary to change the execution strategy, due to the need of levelling resources or to the maximum availability of resources. Different from the long term planning, the aim of this step is not to plan the amount of resources for each construction activity, but to plan beforehand the necessary capacity of key production resources, considering the chosen execution strategy.

IDENTIFICATION AND DESIGN OF CRITICAL PROCESSES

One of the key elements in the production system design is the design of critical processes. Although all production processes should receive an adequate degree of attention, some of them must have their design carried out earlier in the project and to a greater level of detail. These processes are called critical processes because they pose some risks to the production system, which might be related to safety, environment or production capability (Juran, 1992). In this study, the critical processes were the ones that created production bottlenecks. In other words, the design of the critical process imposed limits on the capacity of the entire production system (Cox and Spencer, 1998).

The identification of critical processes must be based on the analysis of the production process capability in comparison to the demands originated in the preceding steps. Based on the execution sequence, the production capabilities available and the existing demands, the processes considered to be critical for meeting the project deadline are identified. At this stage, the experience on previous projects is often very useful.

In most case studies, the critical processes were the prefabrication and assembly of concrete slabs and the execution of load-bearing walls, which are interdependent. After the conclusion of the shell, several other processes can be performed in parallel and protected from inclement weather conditions. In that sense, the load-bearing walls pulled upstream processes (that should have their capabilities properly designed) and pushed the production of downstream processes. A capacity buffer is often introduced in the production of pre-cast concrete slabs, aiming to protect the flow of the brick wall process, since delays in the installation of concrete slabs could cause delays or lead to need of changing the execution strategy.

IMPACTS OF PRODUCTION SYSTEM DESIGN IN THE PRODUCTION PLANNING AND CONTROL PROCESS

During the implementation of the production planning and control process in the construction stage, some positive impacts on the application of the production system design were observed. Firstly, the production of the long-term (master) plan became much simpler, since the main decision related to pace, capacity and deadlines had already been taken. In this case, long term planning played a different role compared to the traditional practice used by the companies involved in the case studies. These companies typically produce their long term planning based only on the production manager experience and on the deadlines jointly established with sub-contractors and suppliers.

In addition, it was possible to assess the impacts of deviations in the critical process production rates on the total project duration. Therefore, production planning has simply the role of implementing the decisions made in production system design.

Some critical factors for the implementation of the production system design were identified in the case studies:

- The production manager must have a more strategic view of the production system, instead of simply being concerned with operational decisions;
- There must be effective means for communicating the execution strategy among the production management staff and the crews;
- There must be an emphasis on process transparency in terms of dissemination of plans and goals;
- The most critical uncertainties in the construction process (for instance suppliers lead-time) must be identified and properly tackled; and

- The supporting tools must have a clear objective and the production plans must be simple in order to be understood by all.

FURTHER STUDIES

The aim of this research study so far has been to define the scope of the decisions involved production system design for low-income housing projects. Further studies will be required to evaluate more deeply the impacts of different execution strategies concerning in terms of project lead-time and costs. Moreover, computational simulation could be used to analyse the implications of variations in batch and buffer sizes and in execution strategies on the system throughput. An additional area for new studies, which is out of the scope of this paper, is the investigation of resource and capacity management issues from system design to short term planning in this kind of project.

CONCLUSIONS

This paper proposed a sequence of steps for structuring the decision making process involved in the design of production systems for low-income housing projects. Through multiple case studies, it was possible to assess the importance and the impacts of the production system design in the management of these projects.

The proposed approach for the design of production systems made it possible to connect a series of decisions that ought to be taken, considering the improvement of the whole production system, rather than of individual activities as it is often emphasised in the traditional view of project management. The importance of the hand-offs management between the production crews is also emphasized.

The discussion and formalization of decisions, made by the companies involved in the case studies, contributed to reduce improvisation in production management and also provided a focus for dealing with uncertainty before the beginning of the construction stage. This can potentially have a positive impact in the reduction of production costs and lead-time.

The emphasis on the critical processes provides the focus on those processes that limit the capacity of the production system as a whole. It is essential to consider the impacts of product design, since this can affect the definition of the execution strategy. In this respect, the production system design plays a key role in the interface between the design and production processes. In this way, the production system design provides some criteria for evaluating production management, since it establishes a reference for production planning, control and improvement.

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