Productivity-Based Management System for Offsite Manufacturing: Case Study of Noralta Lodge

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ABSTRACT

Large-scale projects entail a zero-tolerance policy in regards to on-time project delivery and project quality. Severe winter conditions in Canada challenge conventional on-site construction activities and raise the risk of project delays and deficiencies. Industrialized (modularized) construction stands as an alternative that provides high quality products in a timely manner. Moreover, modular construction offers manufactured building components in a controlled environment, which ensures that quality standards remain consistent regardless of weather conditions. Once manufactured, modular units are then shipped to the site to be assembled. Two major geographical phases are common in offsite construction: the manufacturing phase, and the on-site installation phase. Consequently, management teams face challenges related to productivity and optimum work sequence in both phases. Traditional project planning and control methods consider the duration of a task as a static entity resulting from the direct relationship between the sizes of the crews on-site and labour productivity. Learning curves, skill-based task-labour matrices, and resource levelling techniques are factors that imply the dynamic nature of construction tasks; delays in one task may affect other subsequent tasks both directly and indirectly. The Productivity-Based Management System (PBMS) provides opportunities to increase the production rates of task duration, and decrease actual task duration. The proposed research introduces a framework for a PBMS to manage and control the on-site phase of modular construction. In this research, the PBMS is developed, implemented, and then applied to a 1,700-bedroom workforce camp in Fort McMurray, Alberta, Canada.

KEYWORDS Offsite manufacturing**,** Productivity analysis, Resource Usage, Resource Allocation

INTRODUCTION

Considering the dynamic nature of construction and the high level of competitiveness within the industry, it is important for construction experts to enhance success (Lee et al. 2005). In this regard, introducing the concept of industrialization into the construction industry has significantly improved the building process. Industrialization has impacted almost every aspect of the industry; it ensures economical products, as it reduces material waste and provides optimal uses for available resources. Regardless of construction method, the success of a project depends on many factors such as scope, size, complexity, and technical implication (Bradley 2008). However, to ensure success, the management team must pay special attention to project control and monitoring. Although project control is an iterative process, it is crucial for project success (Kumar 2005). Therefore, as the project size increases, its time constraints become more restricted, which requires efficient controlling and tracking efforts in order to meet client requirements. Performance analysis and data collection must be conducted and compared with the work planned on a regular basis (Olawale and Sun 2013). This ongoing process is key to tracking and analyzing labour productivity during the course of a project. Meanwhile, though modular construction has remarkably improved construction performance, it has added additional challenges to the management team such as maintaining a firm supply chain, and management and enhancement of on-site productivity (Vrijhoef and Koskela 2000).

The proposed research focuses on the management and control of on-site tasks for modular projects. In general, productivity is defined as the ratio of *outputs* to *inputs*. To maximize productivity pertaining to quality and safety, two options can be considered: (1) maintaining the same level of outputs while decreasing inputs; (2) or increasing outputs while maintaining the same level of inputs. The proposed PBMS utilizes a dynamic resource re-allocation system based on task type, complex or simple, and labour skill level. An increase in total production rate is expected as a result of the task-labour match method. Increased quality, which reduces rework during the inspection phase, plays a key role in meeting the project goal, and is another expected outcome from the proposed productivity management system.

METHODOLOGY

The proposed Productivity-Based Management System (PBMS) consists of two phases:

(1) Data collection and dynamic resource re-allocation, where data about tasks and labour are collected and checked through an interactive multidisciplinary system that ensures its accuracy, and resources are assigned according to the collected data on a daily basis.
(2) Productivity analysis. Figure 1 illustrate the overall proposed methodology.

Data Collection and Dynamic Resource Levelling

Because of work force size and task diversity in terms of complexity and number, data collection is a unique task that requires verification to ensure its accuracy and reliability, and in return, the accuracy and reliability of the management system PBMS. Data in this phase comes from three different sources:

(1) Daily site manager reports
(2) Daily job description (DJD)
(3) Graphical tracking (GT)

The following section discusses each of these sources in details:

(1) Daily site manager reports

The daily site manager report is a document produced by the site manager describing all on-site activities. This high-level document represents the upstream view of project progress, daily tasks, and force-count for on-site labour, in addition to any other notes or comments that may occur on a specific day. The subjectivity of those reports may not accurately reflect the status of the project. The number of site managers required to supervise on-site activities is directly correlated to the size of the project, which makes assigning an accurate progress percentage for the overall project a challenge. Combined with phases (2) and (3) of the data collection sources, these reports represent a valuable baseline to better understand the overall project.

(2) Daily job description (DJD)

The DJD is the second phase of data collection that involves different levels of the project management team to control the project and validate its plan from upstream to downstream; this means that instructions are issued from upper management to workers

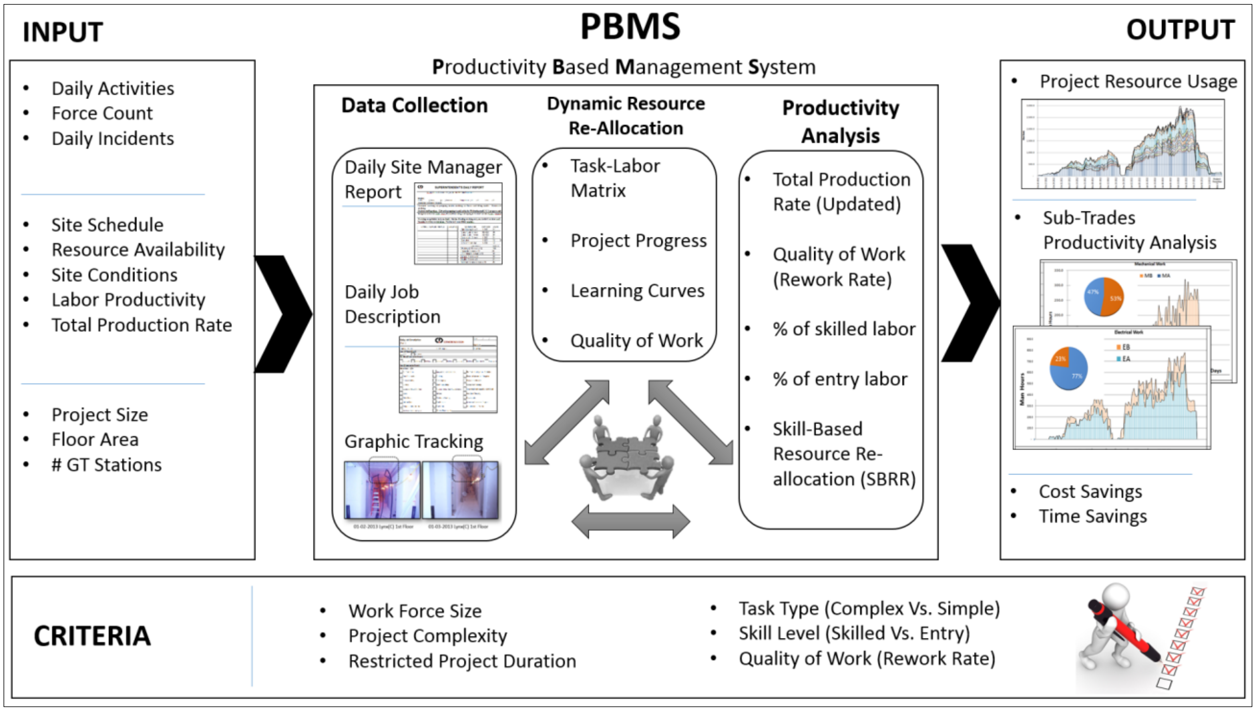

Figure 1: Main proposed methodology

Moreover, it helps validate the project plan through daily reporting. DJD functions as a daily work permit ticket issued to the workers on-site; it contains assigned task information for each worker during that specific day, the estimated timeframe to finish the assigned tasks, and the location and sequence of those tasks. DJDs are issued based on the site schedule, the resources available, the worker's skill set, and the timeframe required to finish the project. They are generated automatically once the project managers along with the site managers assign the available resources to the tasks needing to be performed. As projects are dynamic in nature, and unforeseeable changes to conditions can frequently affect on-site activities, the workers are asked to record the actual hours spent on particular tasks, in addition to any variation in the completion or assignment of the task. The workers re-submit their DJD at the end of the work day, and a comparative study is conducted on a daily basis in order to study and analyze the tasks performed, level of skill required for the crew completing those tasks, and register any abnormality that could occur while performing the tasks. Using the learning curves during the project, a calibration of the task-labour matrix is to be done to balance the production rate (See Figure 3).

The task-labour matrix is a decision support tool that helps the management team allocate available resources effectively. The columns of the matrix in Figure 3 refer to the names of the work force (Labour 1, Labour 2, Labour 3, etc.), while the rows are dedicated to the tasks to be performed within the scope of the project. A four-ranking system is followed to complete the matrix. *High Productivity* (HP) represents a task that can be performed in the best capacity, with the highest production rate with the specified work. *Medium Productivity* (MP) refers to whether the worker is qualified to do the work, and has sufficient experience to perform the task independently with little to no supervision; however, this task is not a familiar task to the worker and may take more time; *Low Productivity* (LP) is the task-labour combination under this ranking represented by the tasks where the worker has the necessary training and certification to perform the task, and direct supervision is required at all times to ensure the task is performed in a satisfactory manner. *Not Applicable* (NA) represents those tasks where the worker is not allowed to perform the task due to the lack of proper certification or necessary training.

The task-labour matrix is dynamic in nature, and labourer rankings can change on a daily basis; for instance, an HP task-labour ranking can change to NA if the labourer's safety certification has expired and the labourer neglected to renew it on time. Another example is a task-labour ranking changing from LP to MP if the labourer has performed the task for a long period of time and their direct supervisor recommends that the labourer is able to continue the task without direct supervision. In this way, the task-labour matrix is an essential tool for the site managers during the resource allocation task. Once the DJDs are submitted and a task-labour analysis is completed, a resource reallocation analysis is performed among the crew members to optimize the production rate of each task based on matching the labourers with the tasks that best suit their skill-sets.

(3) Graphic tracking (GT)

GT is a tool used to measure the physical progress of the project onsite. With a dynamic daily work scope, the actual progress of the project in general, and the percentage of completion of each task individually, cannot be captured accurately through a written description from the documents produced on site by the site managers and the labourers. This data can be subjective and may differ between the site manager report and the DJD recorded the workers; GT is vital for project tracking and control. It represents impartial tools that help clarify any ambiguity while tracking the project progress. GT provides a daily tracking analysis for the project progress.

The number of stations set up depends on two factors:

(1) Size of the project, which can be represented in the designed floor area, in addition to the size of the lot the project is built on.
(2)Completion rate of the project; as most of the projects are multi-floor projects, assigning the GT stations requires a completion of physical floors to advance.

Figure 4 shows the relationship between the life of the project and the number of GT stations. The number of stations peaks close to the end of the weather tight stage of the project and at the start of the finishing stage, then it decreases as the finishing stage progresses. Once a defined zone of the project is at a 100% completion rate, the GT station assigned to measure the progress of that zone will be removed. Those zones can be rooms, offices, or any predefined space of the project. Cross-referencing the three data collection sources, in addition to filtering and forming the data, provided the accurate data needed to perform the analysis.

		Labors				
		Lbr1	Lbr2	Lbr3	.....	Lbr(n)
Daily Tasks	Task 1	HP	NA	HP	.....	NA
	Task 2	HP	MP	NA	.....	NA
	Task 3	LP	NA	LP	.....	HP
	:	:	:	:	::::	:
	:	:	:	:	::::	:
	Task (m)	NA	NA	MP	.....	HP

Figure 3: Task-labour matrix

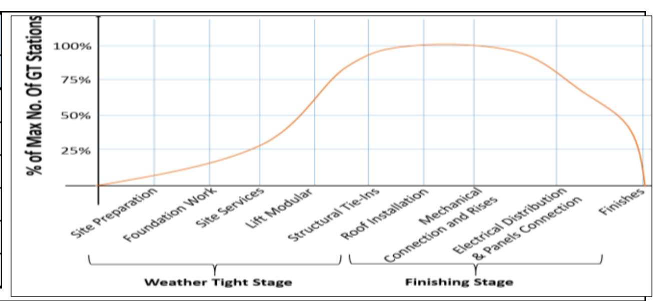

Figure 4: Graphic tracking station quantity over construction process

Productivity Analysis

The daily nature of the proposed PBMS implies an interactive and dynamic approach between the data collection and productivity analysis. The productivity analysis is performed during the second phase, the DJD phase. The analysis was based on two criteria:

(1) Total production rate
(2) Quality of work (rework rate)

Task type, labour skill level, and quality of work are the main factors targeted for the analysis. The expected results of the proposed research are an increase in the production rate and reduction in rework, which can be translated in terms of time savings, and consequently, in cost.

(1) Total Production Rate:

The relationship between labour skill level and total production rate is considered non-linear proportional. Highly skilled laborers have higher productivity than low skill labourers. The industry productivity lists, such as RS means, are based on an average skill level, where the worker has the required training and certification to do the required task. Many researchers focused on improving the overall performance and productivity, on a high level, through applying different techniques such as lean principles, list planner, and line of balance, among others. Increasing the production rate through improving work flow and reducing or eliminating waste were the key components in those studies. Few studies have focused on the relationship between the labour skill level and task nature in terms of complexity, especially in time-restricted projects, where the dynamic nature of onsite tasks imposes a wide range of tasks to be completed by the same crew. For instance, the tasks associated with a framing crew range from cutting wood studs according to specified lengths, framing and installing window and doors, connecting the wall and the slabs, and so forth. In this case, an understanding of the steps and sequence of the sub-tasks is vital for the completion of the project. Moreover, the limited available resources and short task duration may not allow for sufficient time to train the low skill labour on-site during the construction process in order to increase their productivity level to meet the required timeline. The decision of the percentage of work force with high skill level vs. entry skill level can have a significant impact of the project time and cost. The accurate understanding of the tasks at hand allows for a more precise selection of required work force.

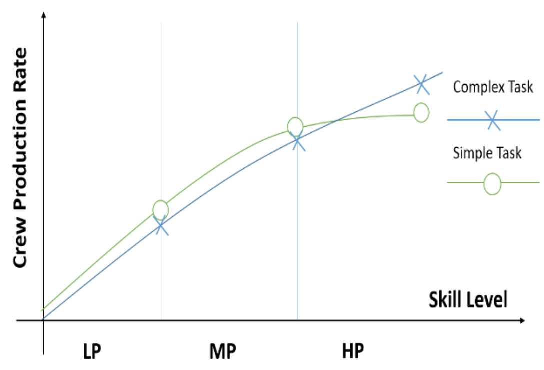

Figure 5: Skill Level Effect

Skill-based resource re-allocation (SBRR) improves the overall production rate through optimizing the labour productivity. A task-labour analysis specifies the actual labour productivity when performing a specific task. The proposed research is based on this hypothesis: labour productivity is related not only to the labour skill level defined by number of years of experience and specified training, but also the type of task assigned to those labourers. Figure 5 shows the on-site observation when comparing the total production rate for two crews on two tasks. The increase of labour skill level has a different effect on productivity when assigned to different tasks. With complex tasks (tasks requiring specialized training), the increase of labour skill is met by an increase in productivity, proportionally; with simple tasks (tasks that do not require any specialized training), the skill level effect is neutralized at certain levels, where the increase of skill level does not affect productivity. The task-labour matrix is completed daily based on the SBRR during the second phase of data collection, and the project schedule is updated accordingly.

(2) Quality of work:

The quality of work is represented by the amount of rework needed due to deficiencies discovered during the inspection phase of the project; this can have a negative effect on the project completion date. A failure in a building component due to unsatisfactory quality or a defect rarely has a singular limited effect on the component itself. Similarly, a deficiency or defect affects multiple components. For instance, a leak in a waterline due to poor sealant application at one of the pipe joints will affect the walls and floors: the drywall will have to be cut, the moist insulation must be replaced, and the flooring and wood studs need to be dried to prevent any potential mold issues due to moisture.

The large scale effect of rework can interrupt the whole flow of the project, which in turn can postpone the completion date, impose extra cost, and even accrue financial penalties. The proposed research studies the effect of labour skill level on rework. An identical scope of work assigned to two distinct labour crews is recommended. While the task-labour relationship studies the effect of individual labour skill on the overall production rate, rework rate deals with the crew skill level and the effect of their interactions, because a deficiency or a defect that results in rework is usually a result of a combinational error from multiple members in the crew. For instance, an insufficient sealant on a waterline pipe is the result of poor labour and inadequate supervision from the crew foreman and other workers during the performing and completion of the task. As rework happens upon the completion, the outcome of this section of the study can help understand the task-crew skill level effect, which in turn emphasizes the importance of the selection of the appropriate crew in similar projects.

CASE STUDY

The chosen case study for the proposed research is a modular-built large-scale work force camp consisting of two identical lodges, with a total of 1,700 suites, each with a private bathroom. Namely, Noralta Lodge, Lynx and Wolverine camps. The project had a strict timeline of 6 months from the day the construction crew moved to the site until the final occupation date. The short time line and high financial impact for any delay drove the project management to take all necessary measures to ensure the timely completion of the project as well as maintaining the proposed budget. Applying the proposed research played a key factor during the construction phase to counteract the unexpected delay in the modular unit production and delivery, which imposed a sudden change in the baseline schedule. The fluctuation in the modular factory production resulted in performing about 80% of the project in the second half of the project timeline. The proposed PBMS aided the project by optimizing the available on-site labour, and accurately calculated the extra work force needed to fill the gap in the baseline schedule. As a result, the project was completed on time with a 15% cost savings. Accurately measureable project progress, a detailed description of daily tasks, and well analyzed resources available onsite resulted in a dynamic productivity analysis system, which influenced the total project progress and played a key role in the successful delivery of the project.

The nature of the project provided ideal ground for a comparative productivity study. With two identical camps, each with eight buildings, and all of which having the same unit design, the repetitive nature of the project illustrated the effect the crew skill level had on the production rate and quality of the work. The large scale of the project entailed the use of multiple sub-trades for various portions of the project. Consequently, two sub-trades were assigned for each major work category. Figure 6 shows the total resources utilized on site for the construction phase of the project. The nature of offsite modular construction implies that electrical and mechanical categories are the two major scopes of work on-site; they account for all the main distribution, modular unit tie-in work, finishes and fixtures, and inspection and testing. The first management plan was to assign the sub trade crews to perform the same tasks in different locations. Having completed the first two buildings, the productivity analysis showed a large gap in the production rate of the two electrical crews; a savings of 1,744 hours (34%) was realized for performing identical tasks. Table 1 shows the difference in man-hours spent between the two sub-trades.

Table 1: Electrical sub-trades man-hours comparative study

Sub Trade	Daily Crew Size			Skill Level (%)		Electrical Service/Distribution	Lighting and Branch Wiring/Branch Circuit Wiring	Communication and Security	Total
	Min	Avg	Peak	Skilled	Entry				
EA (hrs)	6	10	13	100%	0%	1776	2956	415	5,147
EB (hrs)	20	30	36	20%	80%	1604	1560	239	3,403
Diff. (hrs)						172	1,396	176	1,744
Diff. (%)						10%	47%	42%	34%

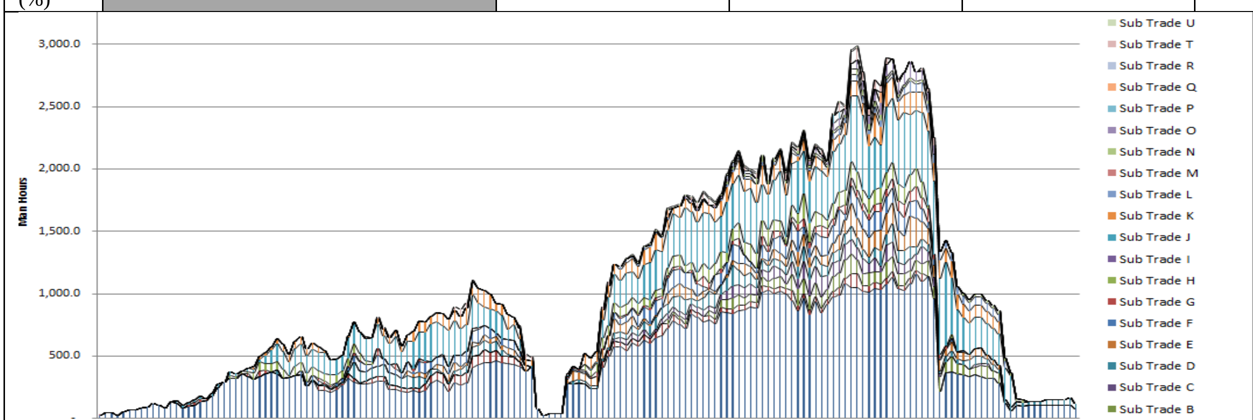

Figure 6: Project onsite resources

Sub-trade EA was composed of 80% entry level labour apprentices, with only 20% skilled journeymen; on the other hand, sub-trade EB had 100% skilled journeymen. The difference in skill level accounted for the 34% improve in production rate, knowing that the scope of work was the same for both sub-trades. In addition to the total production rate savings, the comparative study illustrated a fluctuation in the distribution of the savings, while in some tasks it was as low as 10%, it reached up to 47% in others. A detailed analysis of the nature and requirements of those tasks confirmed that the labour skill level effect on the task performed is limited to the task itself. The difference in productivity between an entry level and a highly skilled labourer is minor when both are assigned to simple tasks that do not require multiple steps, and the more complex the task, the greater the difference in productivity. The outcomes of productivity analysis on the two electrical sub-trades influenced the whole management plan for the project, and resulted in a change of scope assigned for each crew. At the completion of the project, the reallocation of the two crew members on the project tasks proved to have a higher effect on the production rate. Representing the production rate by number of units finished, the crew member of the first sub-trade proved to have more than three times the production rate of the other crew. Figure 7 shows a productivity analysis comparison between the two sub-trades.

With the mechanical sub-trades, the productivity analysis showed the effect of learning curves between the two crews. While the first crew, represented as MA, had previously worked on similar workforce projects in the same area and under the same conditions, the second crew, MB, took the project as a pioneer project. Both sub-trades had similar distribution among their crew members in regards to skill level, they also both had a good reputation and good records. During the first two buildings, the production rate between the two crews was within the acceptable range. As a result, the original management plan in assigning the same scope of work for each sub-trade was continued. The final productivity analysis results only showed a 3% difference in their production rate; however, the quality of work proved to be different. Upon final inspection, the sub-trade MA required no rework for any of the eight buildings they have been assigned to, while the sub-trade MB had major rework in two of their eight buildings. Figure 8 shows the production rate for two mechanical sub-trades.

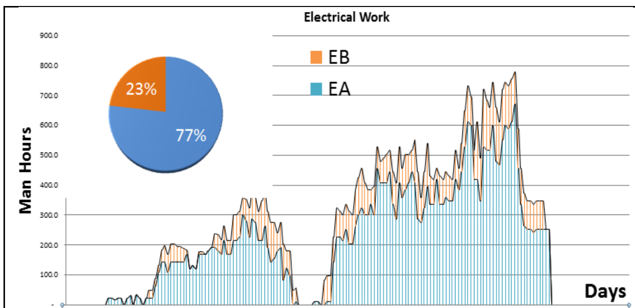

Figure 7: Electrical sub-trades PPR

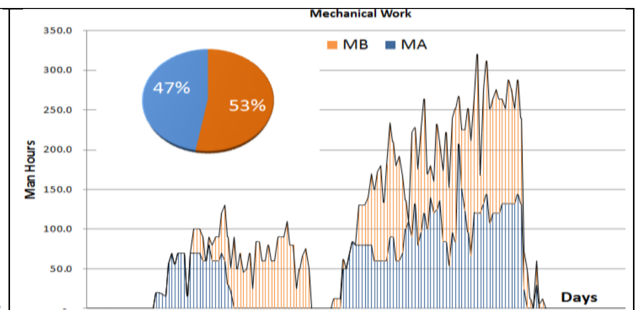

Figure 8: Mechanical sub-trades PPR

CONCLUSION

The proposed research introduced a framework for a *productivity-bases management system* (PBMS) to manage and control the on-site phase of modular construction. The study presented factors affecting the productivity-managing system. The research also introduced a concept regarding *skill-based resource re-allocation* (SBRR), which was proven to have a positive impact on the overall production rate and labour productivity. The proposed PBMS resulted in utilizing resource re-allocation based on task type, complex or simple, and labour skill level. It was proven in this study that labour productivity is related not only to the labour skill level defined by number of years of experience and specified training, but also the type of task assigned to those labourers.

In addition, the impact of reducing rework and increasing quality was discussed in this research, and assisted in meeting the project objectives as an expected outcome from the proposed productivity management system. A comparative productivity case study illustrated two identical camps, each with eight buildings, all of which had the same unit design. The data was collected based on three different sources and considered the quality of work as the amount of rework due to deficiencies discovered during the inspection phase of the project. The analysis showed growth, later on, in production rate and labour productivity. As such, the authors' work makes both contributions to practice and to academic knowledge regarding the PBMS and SBRR systems.

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