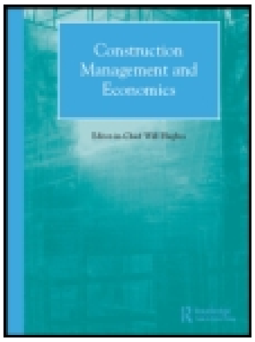

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Effects of the location-based management system on production rates and productivity

OLLI SEPPÄNEN[1,2]*, JAKE EVINGER[2] and CHRISTOPHER MOUFLARD[2]

[1]*Department of Structural Engineering and Building Technology, Aalto University School of Science and Technology Espoo, Finland*
[2]*Trimble Navigation Limited, Sunnyvale, CA, USA*

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Location-based management systems (LBMSs) are becoming more commonly used to plan and control production in construction projects. The main use has been to compress durations and improve resource efficiency through real-time production control and forecasting. LBMS theory proposes that instead of continuously updating the plan with actualized completion dates, as with the critical path method (CPM), control actions can be used to manage an effective response to deviations in production in order to realign the schedule forecast with the approved plan. Three healthcare construction projects in California were monitored to document the effects of planning and control decisions on production rates, resources and labour consumption. First, the authors hypothesize that proposed control actions based on the system led to real actions in the field. Second, these control actions helped in controlling production rates. Third, control actions decreased subcontractor labour consumption. The results show that control actions were implemented as a response to production alarms and half of the implemented control actions were able to prevent production problems. Many control actions successfully improved production and labour consumption rates with a long-term impact. However, adding resources often increased labour consumption and negated part of the expected production rate benefit.

Keywords: Production planning, productivity, project control, site management.

Introduction

Planning is one of the main tasks of project management (Project Management Institute, 2004). Critical path method (CPM) is currently the primary planning methodology used in the construction industry. In recent years, there has been a growing understanding that CPM schedules are not effectively used in day-to-day management of projects. CPM schedules are typically updated monthly (Galloway, 2006), based on actual completion dates, which cannot be considered a real-time controlling mechanism. Keeping plans up to date and properly implementing those plans is very challenging (AlSehaimi and Koskela, 2008). CPM has been criticized for not considering production rates, balancing of crews or continuous production (Arditi *et al.*, 2002). Activities are considered independent (by location) even though crews flow through locations doing work (Kenley, 2005). Although resource-levelling methods for CPM exist (for example O'Brien and Plotnick, 2009), a CPM algorithm cannot ensure a continuous procession of crews through repetitive work tasks (Arditi *et al.*, 2002).

The location-based management system (LBMS) is a method of construction planning and production control that is based on the movement of resources through the jobsite. The aims of LBMS include maximizing continuous use of labour and productivity and reducing waste and risk. LBMS includes a CPM engine with continuity heuristics. A task can include multiple locations which are equivalent to CPM activities. The concept of flow requires that locations are completed in sequence and resources flow continuously from location to location (Kenley and Seppänen, 2010). In addition to familiar Gantt charts, LBMS uses flowline visualization to present construction schedules. A flowline can be described as a visual representation of the movement of crews over time. An X–Y plane is

*Author for correspondence. E-mail: olli.seppanen@vicosoftware.com

used to present a calendar (X axis) and project locations (Y axis). Flowlines are represented by a task line shown in the X–Y plane (Mohr, 1991).

LBMS can be said to be the latest generation in location-based planning techniques. Line-of-balance was developed in the first half of the twentieth century (Lumsden, 1968) but required exactly repetitive work, such as modular housing units to be effective (the vertical axis of the line-of-balance diagram has quantity, not location). Flowlines (Mohr, 1979) removed this limitation but included locations of similar size instead of using a flexible location breakdown structure. Other location-based techniques include Arditi *et al.*'s (2002) attempt to integrate CPM and line-of-balance and Russell and Wong's (1993) RepCon (representing construction). These evolutions in development of location-based systems utilized the main features of LBMS for planning but largely ignored production control and forecasting during production (Kenley and Seppänen, 2010). The main contribution of LBMS over these previous location-based techniques is the use of a flexible location breakdown structure, combining CPM algorithms with location-based techniques through layered logic (Kenley and Seppänen, 2010), and its production controlling system which tracks actual quantities per location and forecasts future problems based on actual progress rather than planned progress (Seppänen, 2009).

Although LBMS is seeing increased commercial use, particularly in California and in Nordic countries, there is a limited amount of published academic research related to production control using the system. Literature on previous location-based methods mainly concerns theoretical issues or planning-related issues such as learning curves (e.g. El-Rayes and Moselhi, 1998; Arditi *et al.*, 2001; Yang and Ioannou, 2001; Arditi *et al.*, 2002). Previous empirical research on LBMS production control includes the comparison of progress information to baseline by Seppänen and Kankainen (2004) which found that there were large deviations from the location-based plans in six case projects and production control did not achieve good results. Seppänen (2009) used three case studies to gather more details about production alarms and the process being used and found that many production problems are caused by issues in social process and communication. Actual start dates, finish dates and production rates were compared to planned data and production problems were found from project records and compared to production alarms. Kala *et al.* (2012) reported that their case project in California was able to control production rates but actual start dates varied up to three weeks from planned start dates. Evinger *et al.* (2013) compared the labour consumption and production results of LBMS and CPM and found that similar tasks in LBMS projects were more productive and achieved better production rates than in CPM projects. All previously reported empirical research concentrates on comparing actual production rates or labour consumption rates to planned rates or to rates achieved using a different scheduling system. This research evaluates production control from a different perspective. Production rates and labour consumption rates are evaluated before and after a production alarm, identified by a production engineer, and categorized by a project team's response to the alarm. This comparison allows conclusions to be drawn about how much influence project teams have on work that has already started in the field.

Data were gathered from three hospital construction projects which were monitored using LBMS. The chosen research philosophy was positivist focusing on the use of quantitative data to answer research questions. The research strategy was archival analysis of data based on uniform data collection protocol. The motivation of this research is to reconcile the conflicting results of previous empirical studies related to production rates. Are improved results related to production rates in recent implementations (Kala *et al.*, 2012) caused by more aggressive responses to production alarms? How much influence do the general contractors have on subcontractor production rates? Are the control actions causing a win-win situation (better labour consumption for subcontractors and better production rates) or a win-lose situation (better production rate and poor labour consumption)? The effects of control actions were examined by comparing production rates, crew sizes and labour consumption before and after a control action decision. The interest was in long-term effects over several weeks.

Comparison of LBMS and CPM theory

LBMS is comprised of two parts: (1) a location-based planning system; and (2) a location-based controlling system. The planning system is used to generate a project baseline schedule. This stage of schedule development is used to make commitments to the owner, to plan procurement, to prepare the subcontract tender schedule and contract milestones. The system aims to create feasible schedules, which minimize risk and maximize continuous use of labour. LBMS focuses on optimizing the schedule and synchronizing production rates by changing the multiples of optimal crew composition (Arditi *et al.*, 2002). These optimized schedules are easier to control because they contain buffers that protect critical relationships and workflow (Kenley and Seppänen, 2010).

Similarities and differences between LBMS and CPM were explored by Lowe *et al.* (2012). The main differences in planning were found as follows. In LBMS multiple activities of the same type are combined into a single task. Quantities and labour consumption rates by location are used to calculate durations and LBMS has a special constraint for forcing continuity of work by delaying the start time of the first location. In terms of network calculation, LBMS is an extension of CPM. If the continuity constraint of LBMS is not used, the start and finish date calculations are exactly the same as in CPM (Lowe *et al.*, 2012). Combining multiple activities into one task is important for this research because it allows the controlling of production rates in multiple locations performed by the same crew. Any production rate gains achieved by implementing control actions are reflected in multiple locations of similar work. In addition to float arising from network calculations, LBMS includes buffers, which are absorbable allowances of time between two tasks to absorb any deviations of production rates and to allow time to react (Kenley and Seppänen, 2010). Buffers in LBMS are similar to lags in CPM when calculating the planned schedule; however, during the control phase the buffer is treated as float and can absorb any deviations in a predecessor's forecast (Lowe *et al.*, 2012). An alarm is generated only if forecast delays have exhausted all buffers and would result in an impact to downstream production (Seppänen, 2009).

Concerning project controlling methods LBMS and CPM are very different. CPM was designed so that 'the plan should form the basis of a system for management by exception … Under such a system, management need only act when deviations from the plan occur' (Kelley and Walker, 1959, p. 160). This 'management by exception' is an after-the-fact approach to control and does not allow preventive measures before problems occur (Meredith and Mantel, 1995). In CPM, actual start dates and remaining durations are updated to the planned activities and the network of remaining activities is recalculated. CPM forecasting uses the originally planned duration to generate its forecast (O'Brien and Plotnick, 2009). In contrast, LBMS controlling methods forecast production based on actual production rates (rather than those planned). Alarms are generated when a predecessor's production rate or completion date impacts on the continuity of a successor. The task of production management is to take control actions to prevent these collisions and cascading delays (Seppänen, 2009).

Research questions

We explore the controlling system of LBMS by concentrating on alarms and team responses to alarms. The questions driving this research are:

- Question 1: Which control actions were taken in response to production alarms? LBMS can be effective only if control actions are taken in response to alarms. For the first time it was possible to categorize which control actions were taken because they were explicitly recorded in a control action log. Seppänen (2009) examined control actions before but in most cases had to infer them from production data because there was no related project documentation. Subcontractor meeting minutes typically did not include any details about control actions or production problems even though problems were clearly happening based on production data.
- Question 2: Did control actions improve the production rate of impacted tasks or prevent production problems? This question is important to evaluate numerically how effective the control actions were. Did they cause a measurable impact on production rate? Did they successfully prevent production problems? Preventing production problems has been researched before by Seppänen (2009) but the study was based on inferred control actions because project documentation did not contain information about actual control actions.
- Question 3: Did control actions have an impact on subcontractor labour consumption or resources? This question evaluates the cost of controlling from a subcontractor's point of view. Were the production problems prevented or production rates increased by increasing manpower or decreasing labour consumption? Previous empirical research on LBMS has not been able to answer these questions because actual manpower has not been consistently tracked by task.

Methods

Project introductions

Data from three active LBMS projects were used to get a representative sample of events to complete this research. All of the projects are in California, USA. Projects were selected based on the decision of project teams to use LBMS as a construction planning and production control tool and based on their willingness and ability to follow a uniform data collection protocol. A CPM schedule was also implemented in parallel on each one of these projects because it was a contractual requirement. To be included in this research, the projects had to systematically log and respond to LBMS production alarms. Additionally, the effort needed to be separately staffed by at least one person dedicating half his time to the LBMS process.

- Project 1 is a class 1 Office of Statewide Health Planning and Development (OSHPD) replacement hospital in Oakland, California. It is approximately 93 000m^2 of medical spaces including 350 beds, 16 operating rooms and two hybrid operating rooms. The project had a full-time LBMS production engineer.
- Project 2 is a 20 900m^2 ancillary hospital support building to Project 1. It will be used for outpatient surgery services and specialty medical needs. Included in the design is a neonatal post-operative care unit and wellness healing gardens. The project had a production engineer spending 50% of his time on LBMS-related tasks.
- Project 3 is a 20 400m^2 Medical Center in Fullerton, California. This new healthcare facility will include 120 patient beds and 14 smart operating rooms. Included in the design are a healing garden and other acute care services. The project had a production engineer spending 50% of his time on LBMS-related tasks.

Data collection protocols and research questions

One person, the production engineer, was in charge of data collection and analysis on each project. In Project 1, the production engineer was one of the authors. In other projects, the production engineers had been trained by the authors. Actual work complete was recorded weekly as a quantity installed or percentage completed for each task in each location. The actual manpower used for each task was recorded daily as a number of workers by task and by location. The information was reported by the subcontractors' foremen to the general contractor's superintendents. Daily and weekly site walks with the trade and area superintendents were conducted by the production engineer to validate data. This provided an opportunity to verify work status and to assess crew flow through the project-specific location breakdown structures.

After validating the actuals with the subcontractors and superintendents, the data were entered into LBMS software Vico Schedule Planner by the production engineer. Special emphasis was placed on the completeness of information, especially for schedule tasks where some production information was lacking or missing. The entire process formed a loop, ensuring that collection, validation, and entry have quality assurance checkpoints and follow the best practice guide for production actuals collection and entry. The collection sheet was formatted similarly to the entry user interface within the LBMS software, minimizing the potential for user error. Data entry was also validated by making sure that all ongoing locations had been actualized per the data date or were suspended in the system if work had stopped

Finally, calculated, actual production rates were applied to the remaining quantities of work and forecast against the balance of the target schedule. Production trends which showed a deviation from the target schedule, or interference with other work, were flagged as potential issues and reviewed with the project team. Review of flowline views and resource histograms formed the basis of the weekly and monthly production reports. The analyses of the observed production deviations were documented with the alarms noted in the control action log. Subsequently, recommendations were added to the log when control action options had been analysed. It should be noted that the production engineers made the decision whether to elevate the issue to control action log and which recommendation to make. There may be additional issues which were not recorded and which are missing from the analysis. It is also possible that the recommendations did not always follow LBMS principles, although all production engineers had been trained in LBMS.

The control action log spreadsheet was developed as a way to document the response to production alarms and track status as part of the weekly report cycle. The log contains:

- Production alarm ID number
- Date the recommendation was made
- Description of the observed and research issue
- Proposed recommendation
- The owner(s) of the issue
- Response to the issue
- Actions status
- Sub-trade that is involved
- Task name and ID

Control alarms are created within LBMS for issues ranging from a delayed start to not meeting target production or consumption rates (Seppänen, 2009). However, on the projects used for this research not all alarms were documented in the control action log. This was because not all alarms may have been relevant and it would have been too time consuming to investigate all the identified issues. Control alarms were selected for evaluation based on the following criteria:

- Severity of production impact
- Impact on successor/predecessor task

- Risk of impacting on successful completion of milestone dates

Analysis started by reviewing the schedule forecast compared to the baseline schedule. When potential production problems were observed additional schedule and social investigations were undertaken to derive a root cause. Follow-up schedule analysis included reviewing a detailed set of production-based metrics to compare planned and actual production rates, resource counts and labour consumption rates. At this point, recommendations were presented and discussed with project stakeholders. The aim of these collaborative sessions was to get a commitment to implement an action. Recommendations were recorded as either 'accepted' or 'rejected' at the time they were presented; or, in the event no action was agreed on after two weeks, 'expired'.

From control action log to research data

Each control action line item in each project log was documented with the date it was observed and the date when a solution was suggested. The quantity of work, actual task duration, and actual man-hours to date were recorded for each task related to a control action for the date when the solution was suggested. To identify whether the production rate, resources, or labour consumption increased or decreased as a result of a control action the same production data to date was recorded for the task four weeks before and four weeks after the 'suggested' date. Using these data we calculated the average production, labour consumption, and manpower for each task for each four-week period. These metrics were calculated as follows:

- $PR_{i,j}$: $(Q_i - Q_j) / (D_i - D_j)$, where PR = production rate (units/day) in time interval i–j Q = quantity, D = duration, i = current measure date and j = earlier measure date
- $LC_{i,j}$: $(Mh_i - Mh_j) / (Q_i - Q_j)$, where LC = labour consumption between i and j Mh = man-hours
- $Mh/day_{i,j}$: $(Mh_i - Mh_j) / (D_i - D_j) / 8$, where $Mh_{i,j}$ = man-hours/day on time interval between i and j
- $\Delta PR_{CA,\ CA+4w} = 100 * PR_{CA+4w,CA} / PR_{CA,CA-4w}$, where $\Delta PR_{CA,\ CA+4w}$ = change (%) in production rate between control action date and four weeks after control action date
- $\Delta LC_{CA,\ CA+4w} = 100 * LC_{CA+4w,CA} / LC_{CA,CA-4w}$, where $\Delta LC_{CA,\ CA+4w}$ = change (%) in labour consumption between control action date and four weeks after control action date
- $\Delta Mh/day_{CA,\ CA+4w} = 100 * L_{CA+4w,CA} / L_{CA,CA-4w}$, where $\Delta L_{CA,\ CA+4w}$ = change (%) in man-hours/day between control action date and four weeks after control action date

By comparing the before/after manpower for each task it is possible to determine whether there was a change in resources at the time of each control action and whether it was implemented short term or long term. By comparing the rates of production and labour consumption, it is possible to determine whether a change in resources or some other factor at the time of the control action could have resulted in an increase or a decrease in performance or output.

There are various reasons why workdays over either four-week period (before or after control action) may be less than 20 workdays. The duration was calculated based on calendar weeks, so any holidays, rain days or other interruptions would decrease the amount of workdays. On the other hand, any weekend work could potentially increase the workdays in the period. The period before control action could be less than 20 days if the task had just recently started and similarly, the period after control action could be less if the task finished during the four-week period. Because some tasks involved discontinuous work and their data are not comparable to other tasks, only those cases where at least 10 workdays of data were available both before and after control action were included in the numerical analysis. This effectively removed all data points from Project 3, which tended to have shorter duration tasks and discontinuous work. Data from this project are included for classifying control actions used but not for numerical analysis related to effectiveness of control actions.

Table 1 illustrates the calculations with an example. The problem was related to duct main slowdowns due

Table 1 Example before/on/after data date calculations

				Input				Calculations				
	Date(2011)	Task name	UOM	Qty	D	Mh	PR	LC	Mh/day	Δ PR	Δ LC	Δ Mh
CA – 4w	23 Aug.	Ductwork Horiz Mains	LF	5089	36	3172						
CA	20 Sep.	Ductwork Horiz Mains	LF	7709	55	5540	137.9	0.904	124.63			
CA + 4w	18 Oct.	Ductwork Horiz Mains	LF	12 827	75	8183	255.9	0.516	132.15	186%	57%	106%

Notes: CA = control action date; UOM = Unit of Measure; LF = Linear feet; Qty = Quantity; D = Duration; Mh = Manhours; PR = Production rate; LC = Labour consumption; Mh/day = Manhours/day.

to insufficient crews and possibly fabrication issues. The control action recommendation was to deploy additional crews. This control action expired without response because the slowdowns were deemed to be subject to fabrication schedule and thus it was not the right time to increase manpower. Table 1 shows starting data for the three time points: four weeks before control action recommendation, on control action recommendation date and four weeks after control action recommendation. Production rate, labour consumption and man-hours/day are shown only on control action date and four weeks after control action because they relate to the interval between two data points (for example production rate shown on control action date is (7709 lf–5089 lf) / (55d–36d) = 137.9 lf / day). The percentage is shown only on the last row because it relates to the change between the two time periods. These percentages were used for analysis. In this example, the production rate increased to 186% of original. Manpower increased by 6%. Most of the production rate increase was achieved by decreased labour consumption, not by increasing resources.

Analysed tasks

Control action logs included entries related to substructure, superstructure, exterior, interior and mechanical, electrical and plumbing tasks. Altogether 44 tasks were included in control action logs. The following 10 examples are selected from different construction phases and illustrate the type of tasks included:

- Excavate pier caps/grade beams/sump pits
- Erect steel
- Weld metal deck: slab on metal deck
- Fireproofing
- Install fire sprinkler
- Heating, ventilation and air conditioning piping rough-ins (above duct)
- Ductwork horizontal mains + seismic
- In-wall electrical rough-ins
- Production drywall: side 1
- Install framing exterior

Question 1: Which control actions were taken in response to production alarms?

To answer the first research question, the control action logs were analysed and control actions were classified into 12 groups based on the proposed control action description. The groups were determined by reviewing the control action log and analysing different types of actions. Seppänen (2009) divided control actions into three basic categories: change of production rate, change of plan or suspending a task. In the case studies of Seppänen, production rate changes were common but did not typically have supporting documentation about what was actually decided. Plan changes were better documented and example sub-types included delaying start dates, changing the sequence of work or changing logic. In this research, Seppänen's classification was used as a starting point but it was possible to go into more detail in this study because all control actions were documented. The control actions were classified into the following groups.

Control actions related to changing production rate

- Add resources
- Work overtime
- Reduce resources

Control actions related to changing the plan

- Change logic
- Close location (i.e. finish work in a partially finished location)
- Create a new task
- Pull planning (to decrease labour consumption)
- Re-sequence work (sequence of locations)
- Review task data
- Split task
- Start work (in a specified locations)

Control actions related to suspending work

- Stop/hold work

Additionally, control actions were classified based on their underlying cause. In LBMS, alarms are raised if a predecessor task is about to impact on the continuous flow of a successor task (Seppänen, 2009; Kenley and Seppänen, 2010). This can be caused by a slow production rate of the predecessor, fast production rate of the successor, delayed start of predecessor, early start of successor or working out of sequence. Alarm descriptions were also reviewed and classified based on the cause.

The data from the log were used to calculate several metrics important for answering the research question:

- Distribution of underlying reasons for control action entry
- Percentage of recommendations resulting in a control action
- Distribution of different control action types:
  - % of recommendations accepted by control action type
  - % of recommendations rejected by control action type

- % of recommendations ignored by control action type

Question 2: Did control actions improve the production rate of impacted tasks or prevent production problems?

To answer this research question the average production rates of the time period four weeks before the log entry and four weeks after the log entry were compared to determine whether there was a significant change. Even though data were collected weekly, a four-week period was selected for analysis because in previous research, it has been shown that performance can fluctuate daily due to random variation (Thomas *et al.*, 2002). On the other hand, some control actions have previously been unsuccessful because they did not affect the production rate for a long enough period of time (Seppänen, 2009). Four weeks was deemed a long enough time period to balance random variation and to evaluate whether the control action was effective for a longer term.

Changes in production rates were calculated for all entries in the control action log if at there were at least 10 days of history before and after the alarm. Statistical median and quartiles were calculated based on this complete sample. The impact of control actions on production rates was analysed by categorizing the control actions which impacted on production rate to four groups based on the median, 25% and 75% quartiles.

Numerical production rate increase may not be significant if the underlying problem was not resolved. Control action log cause classifications were investigated and schedule data were examined to see if the problem was actually solved. Those log entries which related to interference between two tasks were included in the analysis. The control action was considered successful if there was no interference between the tasks during the next four weeks following the alarm.

Question 3: Did control actions have an impact on subcontractor labour consumption or resources?

The last question investigates whether production rate changes were caused by increased manpower or by decreased labour consumption or a combination of both. It is possible that control actions which increased production rate had an adverse impact on subcontractors' labour consumption. This was evaluated by calculating the man-hours required for a unit of work (labour consumption) before and after control action log entry. If labour consumption in the four-week time period after control action implementation increased, compared to the time period four weeks before, the control action may have resulted in lower productivity. Labour consumption percentage change and manpower percentage change were categorized based on the median and 25% and 75% quartiles. Consumption rates were also tracked for log entries of rejected or expired recommendations.

Results

Question 1: Which control actions were taken in response to production alarms?

During the research period 230 combined alarms were entered to the control action logs of the three projects involved in data collection. Of the 230 alarms 39% led to a control action and 21% were reviewed with no control action deemed necessary. Forty per cent were not responded to and were classified 'expired'. Table 2 shows the distribution of reasons why issues were elevated to control action logs. Issues related to potential clashes between predecessors and successors are 'authentic' LBMS alarms. The most typical case was that a predecessor task was too slow and was about to impact on a successor task. Many issues related to simply late starts or finishes in a location were also raised. These are not as important in LBMS theory because they do not cause cascading delay effects (Sep-

Table 2 Control action log classified by reason

Reason	Project 1	Project 2	Project 3
Predecessor too slow: potential clash	60	8	0
Forecast delayed	39	4	3
Locations available for start	24	5	0
Resources working in multiple locations	13	0	0
Successor too fast: potential clash	9	1	0
Out-of-sequence work	7	1	0
Predecessor started late: potential clash	3	0	2
Successor early start: potential clash	2	1	1
Incomplete locations	4	0	0
Production rate slowdown	4	0	0
Out-of-sequence work: potential clash	2	0	0
Forecast early completion	1	0	1
Discontinuous crew flow	1	1	0
Unable to classify	6	1	0
Total log entries	175	22	7

pänen, 2009). Other typical reasons included locations that had all prerequisite work completed (locations available for start) or the distribution of one crew into multiple locations.

Some examples of log entries and responses are listed below:

- The production engineer used the control chart and flowline to determine that a location was available for a fire sprinkler and all prerequisite work was completed. The recommendation to start work in that location was accepted by the site team.
- Schedule forecast for duct mains was forecasting delays with the current crew size. The recommendation was to increase crew sizes by the week of 24 October. The site team agreed to deploy additional crews to level 3 for low pressure ducts and additional medium pressure duct crews.
- Interference wall framing forecast slowed down from previous week to achieve planned production rate due to some rework on level 1. The recommendation was to maintain the current plan but to introduce new tasks to account for rework. The recommendation was accepted with the caveat that the start date of hanging drywall on level 1 should not change.
- Final wall closure inspections were being driven by electrical in-wall rough-in production rate. Inspections started to push the forecast of production drywall. The recommendation was to increase the crew size of the electrical contractor. The recommendation was accepted.
- Slow waterproofing production rate was impacting on the completion of successor activities. The recommendation was to increase resources. This recommendation was rejected because the slow production rate was caused by quality damage from rebar crew.

Figure 1 shows an overview of recommended control actions and the response to them. Adding resources was the most common recommendation, followed by closing-out locations and starting work in an open location.

Question 2: Did control actions improve the production rate of impacted tasks or prevent production problems?

Table 3 shows descriptive statistics for production rate changes of the full sample and based on the control action response. The values represent the production rate in the time period four weeks after the log entry compared to the production rate four weeks before the log entry. The log entries with under two weeks of history before or after the entry have been removed from the sample. Statistical means in each one of the groups are well above the median indicating that outliers are skewing the picture. In data with outliers, the statistical median gives a better picture for conclusions. All the averages of accepted control actions are higher than those of rejected control actions. When control actions were allowed to expire, results were similar to accepted. It is possible that action was taken even though it was not formally reviewed and documented.

Control actions were reviewed for production rate impacts by control action type. The 25% quartile, the median and the 75% quartile of the full sample were

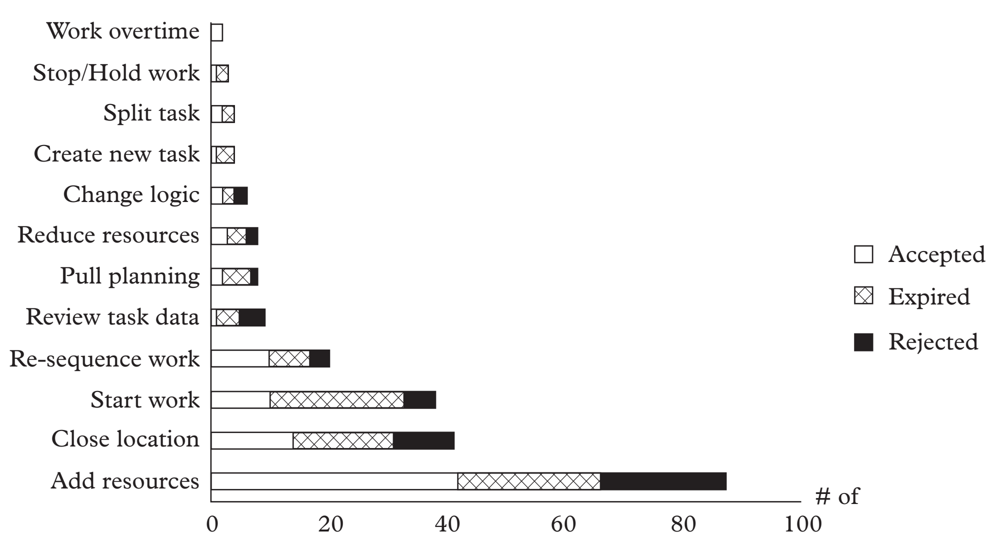

Figure 1 Recommended control action types and site teams' response

used to classify the events into four groups. Figure 2 shows the aggregate results of all control actions regardless of type. The top quartile (4Q) is similar for all groups but rejected control actions had very few entries in the third quartile and many more entries in the lowest quartile of production rate change. Expired and accepted control actions both show a similar pattern of slight overrepresentation in the top two quartiles and underrepresentation in the lowest two quartiles.

Table 3 Descriptive statistics of production rates

	Full sample	Accepted	Rejected	Expired
N	139	59	24	56
Mean	130%	133%	116%	133%
SD	87%	75%	108%	91%
Min	10%	23%	18%	10%
25% quartile	78%	86%	65%	83%
Median	109%	117%	80%	110%
75% quartile	160%	160%	123%	168%
Max	546%	391%	521%	546%

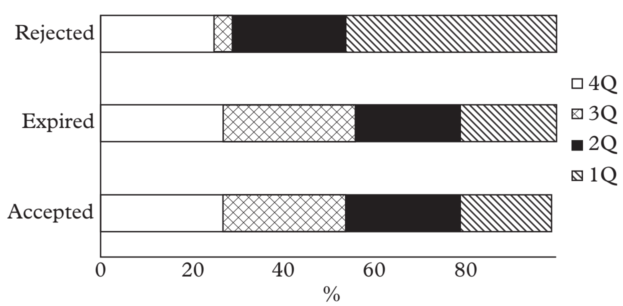

Figure 2 Impact of control actions on production rates

The most typical control action in LBMS is adding new resources for tasks with slow production rates. Figure 3 shows the production rate effect of control actions specifically aimed at increasing production rates. For comparison purposes, those control actions which do not directly target production rate (such as closing locations or re-sequencing) are shown in the same Figure. Production rate-related 'accepted' and 'expired' control actions have 60% or 65% of entries in the top two quartiles, while rejected production rate-related control actions have 31%. Non-production rate-related actions had fewer entries in the top quartiles, but accepted and expired control actions still performed better than rejected control actions. It should be noted that the median of the sample is 109% which can be interpreted as a general tendency for production rates to increase when production goes on. The top two quartiles achieved a production rate increase of more than 10% and the top quartile had production rate increase of over 60%. Results for the top quartile were similar for all groups which could be due to random variation or extremely slow production before alarm due to non-resource-related issues. The real difference shows in the 10–60% production rate improvement range which may be a reasonable expectation for successfully executed control actions.

For accepted control actions, lower than median impacts may not be detrimental effects of the control action itself; sometimes resources were added but they could not work productively because of other constraints. Sometimes resources were not actually added even though the control action was accepted by the site team and the subcontractor. It is also possible that the control actions were short term, affecting only the next few weeks so the effect could not be seen over the four-week period.

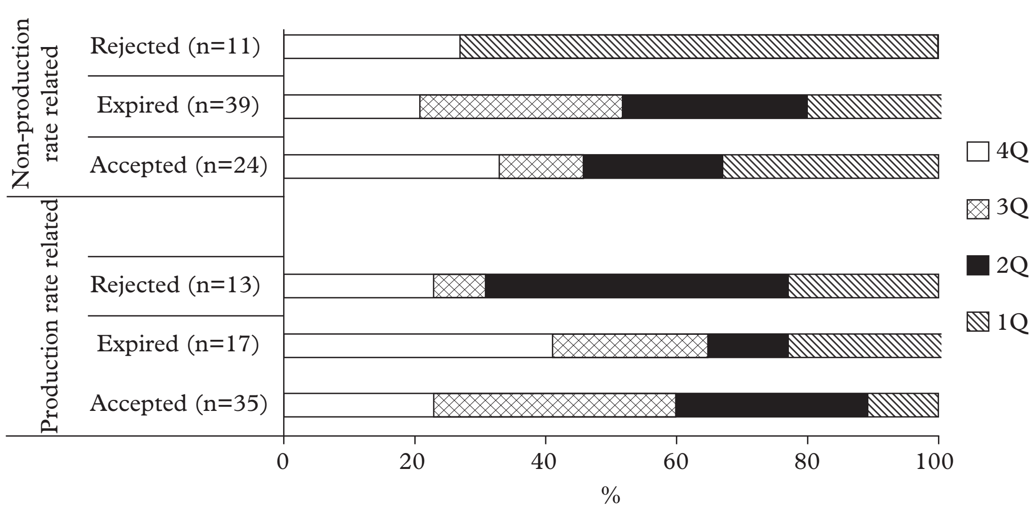

Figure 3 Impact on production rates by control action type

The effectiveness of a control action was analysed by looking at each entry in the control action log where the reason for the entry was related to interference between two tasks. There were 83 entries in the control action logs where interference between predecessor and successor was indicated. Forty-two (42) resulted in an accepted control action. Interference was evaluated by looking at the continuity and production rate of the successor over the four-week period after the log entry. If the successor was continuous during this time period, and did not experience production rate loss, the control action was deemed successful. Twenty-one (21), or 50% of the accepted control actions, were able to prevent interference between predecessor and successor. The average production rate increase related to successful control actions was 37%. All successful control actions did not increase production rate, for example re-sequencing work was successful in preventing interference six times.

A few examples illustrate these different types of events.

Example 1: Accepted control action with a small impact on production rate

The fire sprinkler task was delayed on a floor due to redesign. To prevent a negative impact on succeeding tasks it was recommended that the crew size would be increased to mitigate any further delays. The proposed control action was accepted by the general superintendent and additional resources were added. On average the crew size was 78% larger in the four-week period following the control action than before the control action. However, labour consumption increased by 63% during the same time period which negated most of the benefit. The end result was an aggregate increase of 9% in production rate which was classified to the second quartile.

Example 2: Multiple accepted control actions with positive production rate impact

The same task could be impacted by multiple control actions during production. A good example of this is spray fireproofing. Figure 4 shows fireproofing produc-

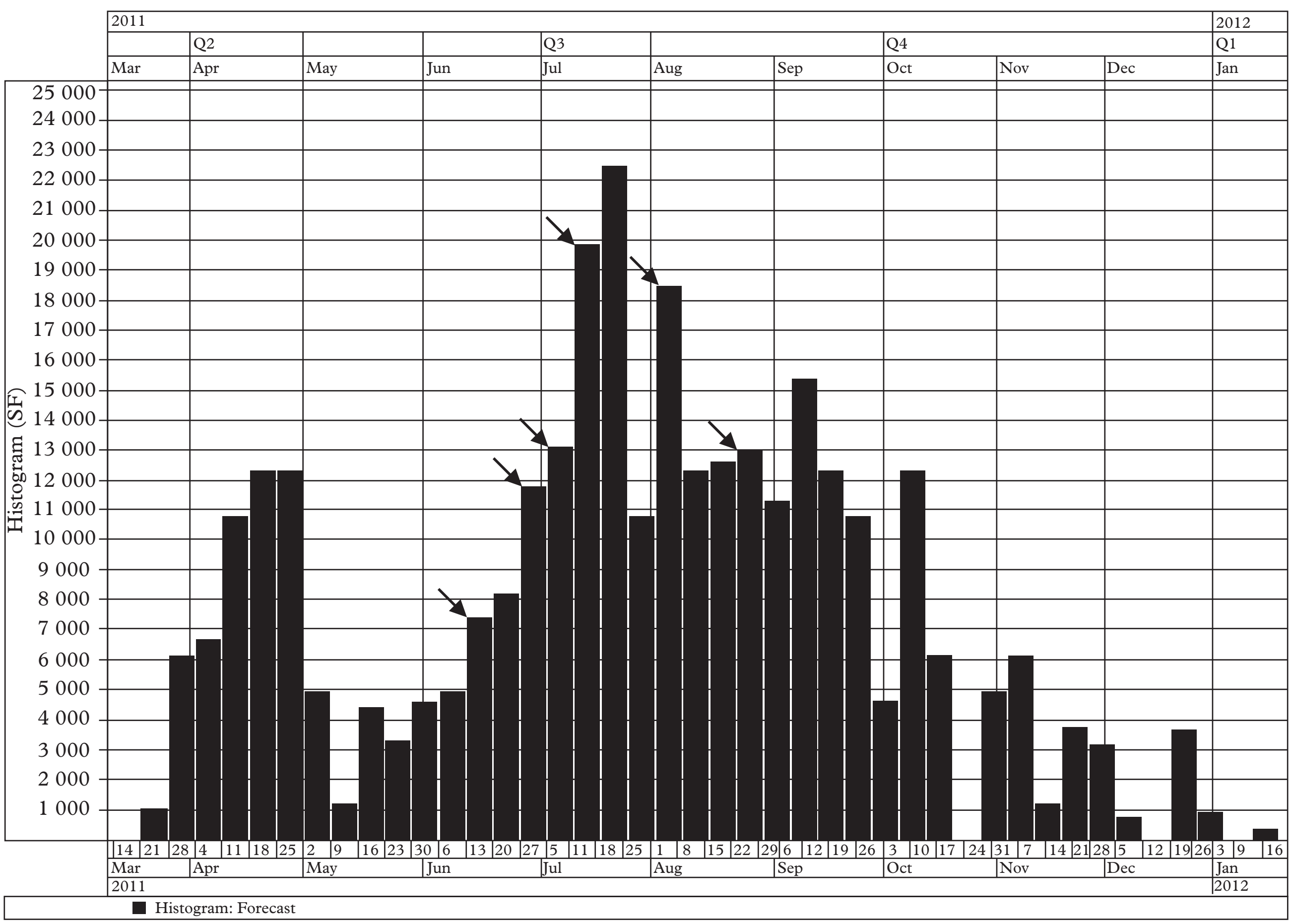

Figure 4 Impacts of control actions on production rates for fireproofing
Notes: Bars show production rate for each week with the quantity of work installed each week shown on the left Y-axis. Arrows indicate when approved control actions were taken.

tion and shows dates when control actions were accepted. The first four control actions called for more resources and were able to improve the production rate. Later control actions referred to sequence or logic and had smaller impacts. The period impacted by control actions shows much better production than other periods. This example shows well that control action impacts are temporary. Subcontractors bring more resources for a time but tend to go back to their own preferred crew size. New control actions were repeatedly taken to bring back the crews which had been demobilized. Decline in production in Figure 4 was related to fewer crews working later in the project.

Question 3: Did control actions have an impact on subcontractor labour consumption or resources?

Both labour consumption and average number of resources were calculated for each task impacted by a proposed control action. Results were classified into four groups defined by statistical quartiles calculated from the complete sample. Table 4 shows the descriptive statistics related to labour consumption. The overall median is 95%. The median of accepted and expired control actions is lower than this. Rejected control actions had a median of 124% indicating that the middle entry had higher labour consumption. Overall, the median of less than 100% shows that the majority of the tasks experienced some form of learning effects with later work being more productive than early work.

Figure 5 shows the impact on labour consumption of all items in the control action log. In the case of consumption, lower numbers are better (more productive), so the Figure has been organized by showing lower quartiles on the left. Accepted and expired control actions had more entries in the lowest two quartiles and rejected control actions had the highest percentage of entries in the top two quartiles.

Table 5 shows the descriptive statistics related to number of resources. Here the differences between groups are not as large as for production rate and labour consumption. The full sample shows a tendency for the median task to increase number of resources as time goes on but accepted and rejected control actions behave in the same way and expired control actions had smaller resource changes.

Figure 6 shows the impact of control actions on crew size. Resource changes of accepted and rejected control actions follow the same pattern. Both accepted and rejected control actions had a slightly higher representation of results in the top two quartiles. Expired control actions were underrepresented in the top two quartiles.

Control actions related to production rate and other control actions were analysed separately related to labour consumption and resources. Figure 7 shows

Table 4 Descriptive statistics related to labour consumption

	Full sample	Accepted	Rejected	Expired
N	134	54	24	56
Mean	123%	104%	179%	118%
SD	120%	60%	164%	135%
Min	15%	15%	18%	15%
25% quartile	67%	64%	88%	65%
Median	95%	89%	124%	92%
75% quartile	135%	136%	177%	115%
Max	1016%	382%	721%	1016%

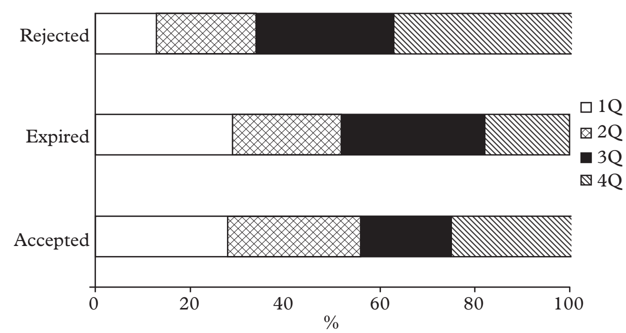

Figure 5 Impact of control actions on labour consumption

Table 5 Descriptive statistics related to number of resources

	Full sample	Accepted	Rejected	Expired
N	134	54	24	56
Mean	114%	118%	118%	107%
SD	48%	58%	46%	38%
Min	20%	20%	61%	40%
25% quartile	83%	89%	81%	81%
Median	106%	111%	111%	100%
75% quartile	133%	134%	149%	132%
Max	388%	388%	230%	207%

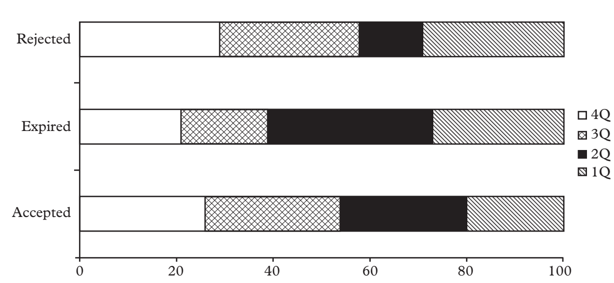

Figure 6 Impact of control actions on resources

the results for labour consumption and Figure 8 shows the results related to amount of resources. Production rate-related control actions had slightly higher portion of accepted and expired control actions in the lowest two quartiles than non-production rate-related control actions. The difference was most pronounced for expired control actions where the proportion of the lowest two quartiles was 65% in the production rate group and 48% in the non-production rate group. Rejected control actions were underrepresented in the

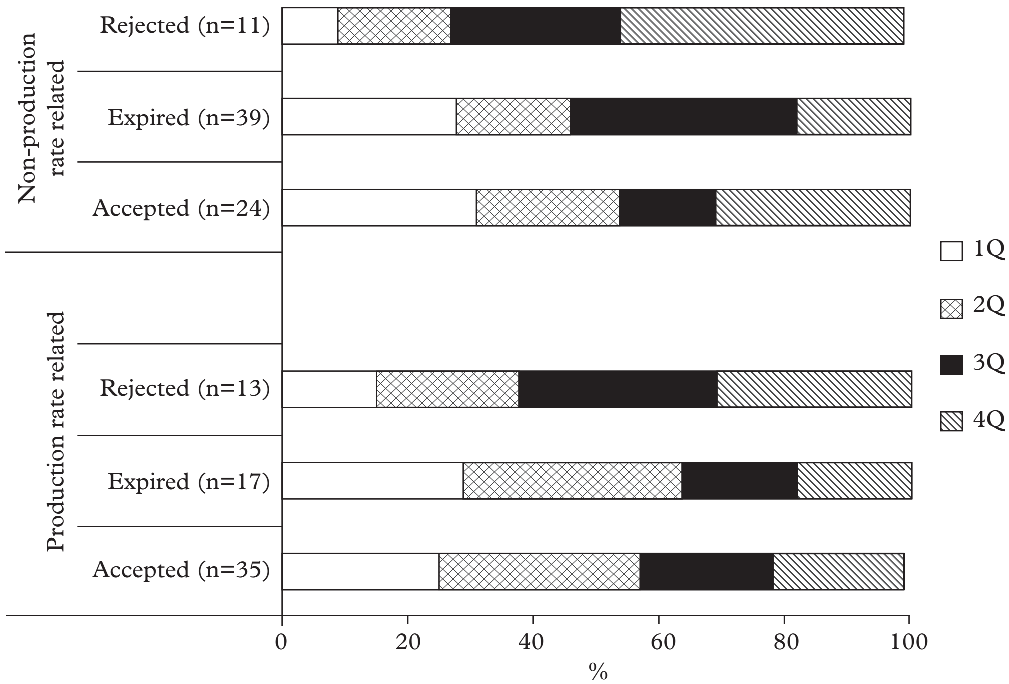

Figure 7 Impact of control action types on labour consumption

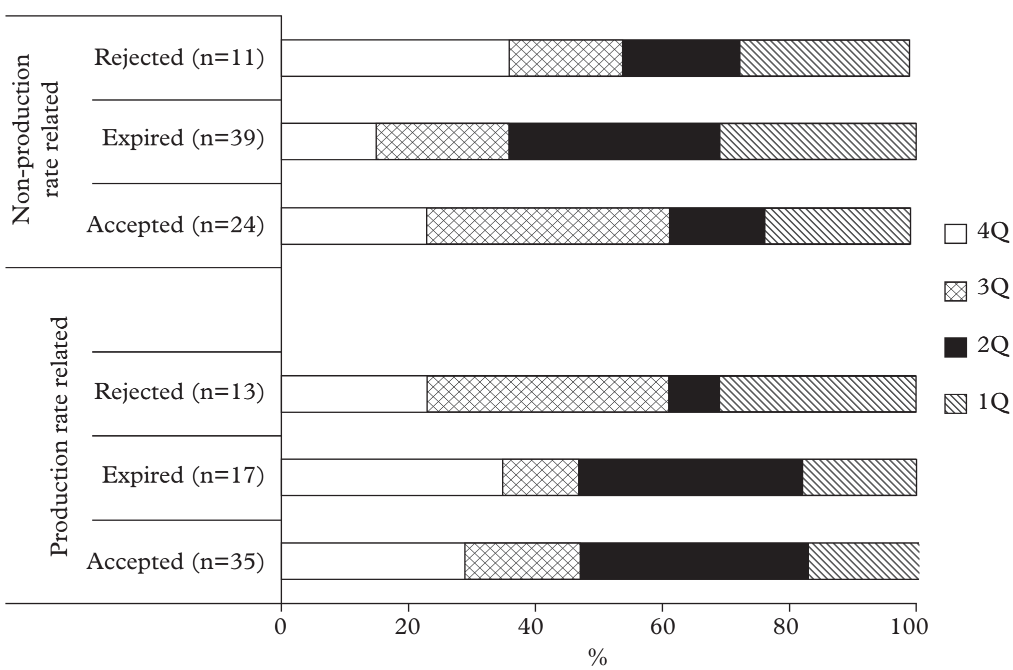

Figure 8 Impact of control action types on crew size

lowest two quartiles. In terms of resources, production rate-related control actions which were accepted actually had just 48% of results in the top two quartiles. Although they were underrepresented in the lowest quartile (18%) it seems that decreasing labour consumption was the more common method of increasing production rate than adding manpower.

Visual observation of the data showed some correlation between crew size change and labour consumption change. After four outliers with over 400% change of labour consumption or resources were removed from the data, the correlation between labour consumption change and crew size change was 0.37. There are many situations where labour consumption decreases when crew size is increased but adding resources often leads to increased labour consumption. Out of 159 log entries, 99 entries (62%) showed the same direction of consumption and crew size change and 60 entries (38%) showed the opposite direction of change.

Detailed examples of week-by-week production rate, expended man-hours and labour consumption and related control actions were reviewed to find more information about the interrelationships. Figures 9a, 9b and 9c show the data for 'frame rated and interference walls' in one of the hospital projects. In the Figures, diamonds indicate accepted control actions. Circles indicate expired control actions. Accepted control actions seemed to have an impact on the production

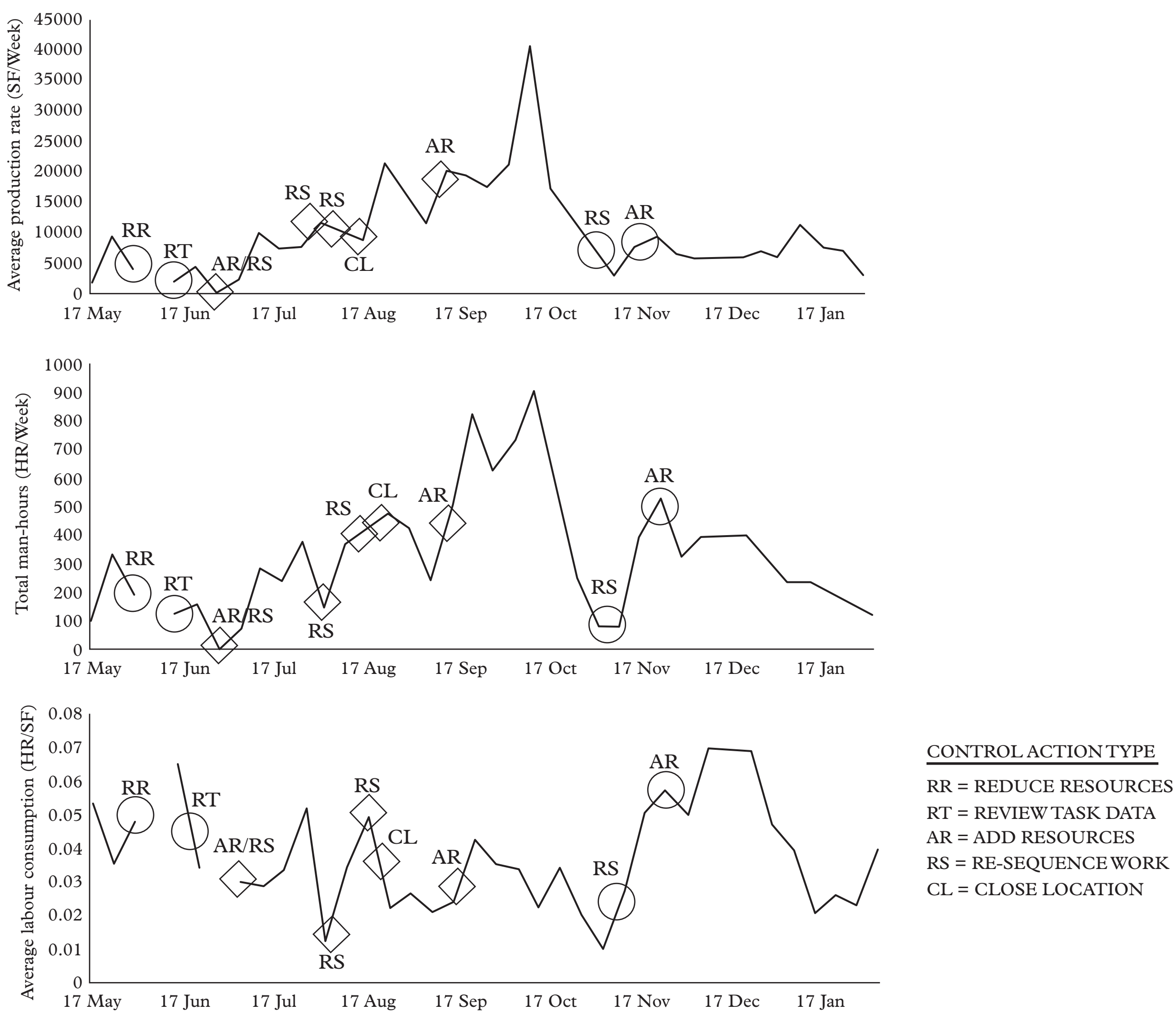

Figure 9 Interrelationship between production rate, crew size (man-hours), and labour consumption for the frame rated and interference walls task in one of the case study hospitals
Figure 9a Production rate (sf/week)
Figure 9b Resource amount (man-hours/week)
Figure 9c Labour consumption (mh/sf)

rates after the control action. Additional resources resulted in increased man-hours/week but caused the labour consumption to go up in several cases. Closing locations is followed by a large decrease in labour consumption and a subsequent production rate increase. Re-sequencing control actions were typically taken after out-of-sequence work was observed in the field. These unplanned movements of crews around the project resulted in increased labour consumption in many cases.

Discussion and future research

The purpose of this research was to carry out an empirical investigation into the effectiveness of production control using an archival research method. To the authors' knowledge, this is the first research effort where recommendations from LBMS were systematically logged along with their responses. The effectiveness of control was analysed by comparing production rates, labour consumption rates and resources before and after control action.

The first research question investigated which control actions were taken in response to production alarms. Thirty-nine per cent (39%) of the alarms (90/230 log entries) resulted in accepted control actions. This can be compared to Seppänen's (2009) case studies in Finland where control actions were implemented to respond to 47–62% of alarms depending on case study. Seppänen's research did not have a control action log but control actions were inferred based on production data. Most of the control action entries were based on a predecessor being too slow which was having an impact on the continuity of successor trades. This alarm type conforms to LBMS theory. Production engineers also raised many other types of issues such as just being delayed from schedule or there were locations available for starting. A textbook LBMS implementation would not raise these issues unless they caused production alarms. Seppänen (2009) did not consider other than textbook cases, which may have influenced the percentages.

Similar patterns related to expired and accepted control actions indicate that some actions may have been taken by superintendents even though they did not formally agree to the control action. Just seeing a production rate decrease on the weekly report may have triggered action. Alternatively, the subcontractors may have corrected production themselves after having noticed that they were falling behind. In future research, control actions should never be allowed to expire and more explanation should be sought for the reasons why control actions were rejected.

The second research question was about the effectiveness of control actions in terms of production rate or in preventing production problems. For production rate-related log entries where the recommendations were accepted or had expired (regardless of actual recommendation) 65% of events were above the median. The biggest difference to rejected control actions was in the production rate improvement range of 10–60%. Any improvement above 60% was equally common also in the rejected group. It is possible that very large production rate swings may be caused by random factors affecting production rather than determined action.

To analyse the effectiveness of control actions in terms of production problems prevented, the accepted control action log entries related to a predecessor causing interference to a successor were investigated. In 50% of the events (21/42), the production problem indicated in the alarm description was prevented over the course of the following four weeks. Seppänen (2009, p. 96) calculated the same result from three projects and 60 out of 165 control actions (36%) were effective. Direct comparison between these results is difficult to make because in Seppänen's (2009) case projects there was no control action log and most of the control actions were not documented; in particular production rate changes tended to just happen without any mention in subcontractor meeting minutes. Nevertheless, the 50% effectiveness rate and the average of 37% increase in production rate after a production rate decision compares favourably to the previous empirical research. More research is needed to find out if it is possible to increase this percentage by including more buffers in the schedule. The projects of this research did not utilize buffers in their plans, which means that it was difficult to react in time to alarms.

The third research question asked whether control actions impacted on subcontractor labour consumption or resources. Both labour consumption and number of resources affect the production rate of a task. The production rate is ultimately the main interest of the general contractor and also impacts on subcontractor cash flow. Labour consumption directly affects a subcontractor's bottom line. The results of this research indicate that the general contractor has, in many cases, the ability to have an impact on both production and labour consumption by taking action based on LBMS recommendations. Interestingly labour consumption showed a more marked decrease for accepted production rate-related control actions but the amount of resources was not similarly impacted. It seems that production rate increases were mostly achieved by taking actions to increase productivity rather than requiring more resources. In future research, it is important to explore which factors caused the labour consumption decrease. It is possible that the increased attention by the superintendents and demands to add more resources led to finding better ways to do the work or identification of constraints that caused the work to go slow. More information than was collected for this research is needed to further evaluate these factors.

This result may also be partially explained by another result of the research. There was a significant correlation (0.37) between change in resources and labour consumption. There are a few possible reasons for this. It is possible that even though the forecasts showed that enough work was available, there were external reasons related to information flows, material flows or equipment which prevented the additional resources from working productively. In these cases additional workers may have had to perform incidental work with low productivity (Thomas and Horman, 2006). Having too much work available can also lead to lower productivity because of the higher amount of disruptions (Thomas, 2000). Alternatively it is possible that resources were added but they were not multiples of an optimal crew size (Arditi *et al.*, 2002). In future research, the detailed factors impacting on productivity should be investigated. New best practices related to control actions could result. A systematic way to identify constraints and analyse which locations are available for work, such as the Last Planner System (LPS) (Ballard, 2000) could also help. Efforts have started to integrate LPS and LBMS (Seppänen *et al.*, 2010). In current implementations it may be too easy to recommend adding resources as a solution to each production rate problem even though additional resources may not be able to work productively.

For unknown reasons pull planning, reducing resources, working overtime or stopping work were rarely recommended. Pull planning, a lean construction technique, could help increase productivity by decreasing the amount of disruptions and making sure that all the constraints have been satisfied before starting work (Ballard and Howell, 1998). Reducing resources is an important control action for an overly fast task (Kenley and Seppänen, 2010). Stopping work in a location prevented production problems in Seppänen's research (2009). It seems that most control action recommendations focus on familiar general contractor control actions such as forcing the subcontractor to add resources and 'non-traditional' lean recommendations are not made by production engineers.

Some issues related to the reliability of data need to be highlighted. Because the data were collected by project engineers primarily to support production control it cannot be guaranteed that all of the information is accurate. This was mitigated by implementing standardized processes based on best practice documentation. To address these concerns with data reliability, classifications based on statistical quartiles instead of actual numerical labour consumption or resource change values were used in all analyses. Additionally, control action data were left out from analysis if they were clearly incorrect. We feel that this level of analysis is reliable for most line items. The production rate information tended to be more reliable than labour consumption rates because actual crew sizes were not always accurately reported by the subcontractors.

In general terms, the sample of events included tasks from substructure, superstructure, exterior and interior rough-in and finishes phases. Analysed events were all from hospital construction projects in California. It can be argued that project type may affect the results. Hospital construction projects can be classified as unique (Melles and Wamelink, 1993). They tend to have higher uncertainty due to the typically high number of owner changes during production. Many special engineered-to-order parts are required so delivery uncertainty can be argued to be higher than average. Process uncertainty is mostly associated with inspections due to the extremely high levels of quality required by the state agency OSHPD. Although hospital construction projects have their special challenges, the unit of analysis of this research was the production problem between two tasks. The analysed tasks exist in all building construction project types; however, these additional uncertainties may have impacted on production rates of some tasks and caused additional random variation.

Conclusions

The goal of this research was to evaluate whether LBMS recommendations led to control actions and whether these control actions had real production or labour consumption impacts. The research was conducted based on extensive data collection efforts on three hospital construction projects. The data were collected as a by-product of location-based production control processes employed to aid the delivery of each project.

The research found that control actions were implemented as a result of LBMS recommendations in 39% of alarms. Additionally 40% of alarms were allowed to expire without recording a control action but results show similar results to accepted control actions. Adding resources was recommended most often, followed by recommendation to complete a location before moving to the next, and then starting work in a new location. Re-sequencing was often recommended in response to a design change that delayed completion of an activity in a particular location. Other control action categories were comparatively rare; for example, overtime was recommended only in a few cases in response to production deficiencies. Control action log entries were most commonly identified based on a predecessor task interfering with the successor task based on LBMS theory. In addition, alarms were commonly raised when a task was forecast to be late or if there were free locations where work was not going on. It can be concluded that LBMS information led to real action in many but not all cases.

Events where control actions were accepted were more likely to result in increased production rates than events where recommendations were rejected or allowed to expire. The results were mixed for different control action types. For both production rate-related and non-production rate-related control actions accepted and expired control actions functioned in the same way indicating that action was taken for some of the expired items. For example, both expired and accepted control actions related to production rates resulted in higher than median production rate increase in over 60% of the cases, whereas only 30% of cases where control action was rejected had a higher than median outcome. Production problems could be prevented in 50% of the cases. The effectiveness of control actions is based on a small sample size (42 events) but the percentage of successful control actions is higher than previously reported. The conclusion related to the second research question is that in most cases production rates could be affected by control actions. In terms of prevented problems, the 50% success rate is better than previously reported. Further research is required to understand how much higher this success rate can be realistically expected to rise in an optimal implementation.

Accepted control actions had a higher percentage of entries in the quartiles representing decreased labour consumption and increased number of resources than expired or rejected control actions. Control action recommendations related to production rates seldom resulted in increased resources over the following four-week period. Analysis of individual cases shows that resource additions were often short term and the additional resources were demobilized soon after their arrival. Adding resources also increased labour consumption counteracting some of the increased production rate. It can be concluded that labour consumption can be impacted through control actions but the control action type affects the direction of the change.

The finding that production rates were primarily influenced by decreased labour consumption, not adding resources, challenges the basic LBMS control action of adding resources when production rates are too slow. The project engineers of these case studies most commonly recommended adding resources. It is technically easy to calculate how many resources should be added assuming the same labour consumption; however, the finding that labour consumption tends to increase with resource additions may invalidate this approach. More research is required to find out when resources should be added and what other ways to increase production rates are available. Naturally the subcontractors would be more motivated by control actions which decrease their labour consumption and still achieve the production rate benefit for the general contractor.

It is clear based on the results that production control by the general contractor can have an impact on subcontractor production rates and thus decrease project durations. However, more research is needed about the specific factors impacting on the success or failure of production control. Are there specific circumstances which facilitate production control? How much is production control facilitated by contracts and how much is based on social process and peer pressure? What is the role of the plan? What kind of plan makes production control easier? Archival analysis may not be the right strategy to get answers to these questions. A case study approach may be more suitable.

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