

# Location-Based Management System

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## Introduction

Location-based management approaches assume that a project should be broken down to physical locations and detailed design, work and all project data should be planned and controlled using those locations. Locations are logical containers for project information because, in construction, crews move through locations. Locations stay fixed and can be easily monitored. (Kenley & Seppänen 2010: 123) Tracking crews is more complicated, although real-time labor tracking systems are being developed for crew monitoring.

Location-based planning methods can be compared and contrasted with activity-based planning methods. Traditional activity-based methods start from a Work Breakdown Structure (WBS). Although most WBS' include location on one of the hierarchy levels, activity-based systems do not enforce the use of the same locations everywhere or maintain a consistent hierarchy of locations. Locations can be used to filter activities, for example based on location code, but they cannot be used to automate logic generation or plan continuous work. As a result, activity-based systems of a real construction projects include hundreds or thousands of activities and their logic can be very complicated (Kenley 2005). In contrast, location-based planning systems use location as the basic unit of planning and control. Tasks are assumed to flow through locations. Logic is assumed to repeat in each location where the same two tasks exist which means that the number of logic dependencies is greatly reduced in location-based systems. Kenley (2005) wrote that the efficiency of combining similar work in different locations solves the complexity problem of activity-based schedules.

In addition to decreased complexity, tasks flowing through locations can be used to plan continuous work. Indeed, the emphasis of location-based planning is to plan for productivity. Continuous work means that the same crew is able to work on the same task continuously without breaks from location to location. The benefits of continuous work include increased learning effects, increased productivity, clear directions to crew members and smaller risk of subcontractor crews leaving the project or charging for waiting time. Discontinuous work or «Starts and stops» are a very important factor for subcontractor profitability and impact their decisions about which projects to prioritize. (Sacks and Harel 2006)

The Location-Based Management System (LBMS) uses these concepts of locations and tasks flowing through locations to augment the traditional Critical Path Method with concepts enabling workflow and using locations to automate the planning of logical relationships. In LBMS, work is continuous by default and it is a planning decision to break continuous flow. In that sense, LBMS is an improved CPM algorithm. The term LBMS also refers to a method of planning using the LBMS algorithm emphasizing the continuous workflow of crews and schedule optimization by synchronizing production rates and removing float between tasks. These LBMS planning guidelines have been combined with the social process of Last Planner System

(Seppänen, Ballard & Pesonen 2010) to make the planning process collaborative. LBMS as a planning process includes defining the Location Breakdown Structure of the project, defining tasks and their quantities by location, defining relationships between tasks, aligning production rates and optimizing the schedule. Finally, buffers can be inserted between tasks to account for variability and decrease the risk.

Takt time planning is another set of location-based planning guidelines. It can use the same LBMS algorithm for calculations but the planning guidelines emphasize exactly aligned production rates and rather than using time buffers between tasks, risk management is done by underloading resources (Frandsen, Seppänen & Tommelein 2015).

In contrast with activity-based methods, LBMS emphasizes production control during execution phase. Traditional controlling approach in activity-based systems is based on a thermostat model of project control, in effect reacting to deviations on the critical path after they have happened. Production control in LBMS emphasizes real-time information and forecasting problems before they happen. Seppänen (2009) defined how production can be forecast to alarm of upcoming production problems at least two weeks before they happen. Armed with this information, production control becomes proactive, aiming at preventing problems before they happen by adjustments to production rates and sequences. It can be said that LBMS puts more emphasis on production control than production planning and in that sense is clearly a lean technique based on pull controlling.

This white paper starts with a very short history of location-based planning. Next, the location-based planning system is presented. Although the differences between CPM and LBMS algorithms are described briefly, most of the emphasis is on discussing production system risk and how to plan optimal schedules using LBMS or takt time planning methods. Then, location-based controlling system is presented. Again, the mathematics are briefly described but most of the section is devoted to reviewing assumptions of production control, a location-based controlling process and empirical results related to production control. Finally, the proposed process to combine the Last Planner System and Location-Based Management System is described. It should be noted that other methods, such as cost-loading schedules, management of detailed design, scheduling of deliveries, safety aspects etc. are also heavily dependent on location. Many of these additional methods have been discussed by Kenley & Seppänen (2010: 163-200) but they will not be discussed within the scope of this paper.

## **A short history of location-based planning**

Location-based planning and control methods have a long history. The earliest documented case study using location-based planning was the Empire State Building which was built by Starrett Brothers. They completed the 102-story building in record time, in 18 months from sketch designs to opening, completed structure at the speed of one floor per day and completed under budget and with a high safety record (for the time). The management of the project was based on repetition, continuous flow and trying to achieve an assembly line of production (Willis & Friedman 1998). Shreve (1930) first introduced the concept of cascading delays and stated that to achieve high speed, they needed to disconnect the different portions of the work as much as

possible. This concept of buffers is an important part of current LBMS methodologies. However, the location-based approach of Starrett Brothers did not have an analytic method based on calculations and was more of a method of presentation.

Line-of-balance was the first such analytic method. It originated from US Navy where it was used as a planning and control tool (Lumsden 1968). Lumsden (1968) described that the technique is a way to model repetitive construction. Repetitive units were modeled with their own CPM network and two lines were drawn in a line-of-balance diagram: one for the start of sub-network and one for the end of sub-network. The vertical axis showed the number of produced repetitive units. Line-of-balance also included balancing production rates by changing the number of crews (Lumsden 1968). The line-of-balance relied heavily on having exactly repeating locations and was mainly used for housing schemes of repeating units. Line-of-balance approach was expanded to have more flexibility later by Arditi, Tokdemir & Suh (2002).

Flowline approach by Mohr (1979) is based on the work of Selinger (1973,1980) and Peer (1974). Flowlines specifically show crew movements. Each task is represented as a single line, rather than the dual lines of line-of-balance. Rather than having the number of repetitive units on the vertical axis, the flowline method was based on discrete locations. However, flexible location breakdown structures were not considered in the flowline method and the method was still largely a visualization technique. Flowline visualization (Figure 2) is still being used as the primary schedule visualization method of LBMS.

Several location-based methods can be considered *integrated* methods in the sense that analytic CPM methods are integrated with location-based methods. As an example, Russell and Wong (1993) first tried to solve the complexity problem of activity-based schedules with a system they called *representing construction*. They created a classification of logic types that could be automated based on locations. These logic types are very similar to the layered logic used in LBMS. Repetitive Scheduling Method is another attempt to integrate CPM and location-based methods. (Harris and Ioannou 1998),

The Location-Based Management System builds on the earlier work and is based on an augmented CPM algorithm which incorporates *layered logic* (related to Russell and Wong's (1993) work) and *continuity heuristics* to plan for continuous work. The planning and controlling methodologies and processes are heavily based on the work of Kankainen and Kiiras from Helsinki University of Technology (Kiiras 1989; Kankainen & Sandvik 1993). The controlling methods and calculations have been developed by Seppänen (2009). The controlling methodologies have been improved over the years by empirical studies (Seppänen 2009; Kenley & Seppänen 2010; Seppänen, Evinger & Mouflard 2014). The system has been presented in numerous IGLC conferences (first appearance Kankainen & Seppänen 2003). Recent development has focused on the combination of Last Planner System and LBMS (Seppänen, Ballard & Pesonen 2010; Seppänen, Modrich & Ballard 2015; Dave, Seppänen & Modrich 2016) and comparing the LBMS and takt time planning methods. (Seppänen 2014; Frandson, Seppänen & Tommelein 2015).

## **Location-based planning system**

The Location-Based Management System builds on the foundation of a location-based plan. The location-based planning system is described in this section. It is composed of a technical system based on the LBMS algorithm, flowline visualization and guidelines and best practices for planning and optimizing a schedule and analyzing its feasibility and risk levels. This section starts by describing the various components of the location-based plan, then the flowline visualization of a plan is described. Logic and calculations related to the LBMS algorithm are briefly described. Risk management and buffers are an important part of location-based planning and they are described next. Finally, the guidelines for optimizing a plan are described from two alternative viewpoints: location-based planning system and takt time planning. These viewpoints are then compared and contrasted.

### **Location Breakdown Structure**

The Location Breakdown Structure (LBS) is one of the most important up-front planning decisions in LBMS. LBMS is the first location-based planning tool which allows for a hierarchical LBS with unlimited hierarchy levels. For example, the project can first be divided into buildings, buildings can be subdivided into structurally independent sections, which can be divided to floors and then to interior zones. Different construction phases can have a different breakdown. For example, exterior work can ignore floors and be divided based on the side of the building and structural work can be divided based on pour areas. The most important thing is to have the same LBS for all tasks of the same phase because sharing the same LBS decreases complexity and increases the power of the system. For this reason, when combining LBMS and LPS, the phase scheduling sessions start by defining a common LBS for all tasks of the phase (Seppänen, Ballard & Pesonen, 2010).

Visually, the LBS can be shown vertically with the hierarchies shown in columns (Figure 1). The Figure shows two LBS's from different projects. Project 1 is a small Medical Office Building and it has first been divided into quadrants and a center lobby area and Project 2 is a hospital of 12 floors and a roof. The first four floors have been divided to six areas (A-F) and floors 6-12 have been divided to three areas (A-C). The locations of Project 2 have been sorted to match construction sequence from bottom to top.

Although it is possible to quite easily to add new locations later in LBMS, it can be time-consuming to alter the hierarchy because of logic which is automatically generated based on locations. Therefore, LBS is one of the most important decisions early on in planning because major changes can lead to substantial rework.

Project 1		Project 2	
Quadrants	Floor	Floor	Area
Center	Roof	Tower Roof	STR C
	3	Level 12	STR C
	2		STR B
	1	Tower Roof	STR A
Northwest	Roof	Level 12	STR B
	3		STR A
	2	Level 11	STR C
	1	Level 10	STR C
Northeast	Roof	Level 09	STR C
	3	Level 08	STR C
	2	Level 11	STR B
	1		STR A
Southwest	Roof	Level 10	STR B
	3		STR A
	2	Level 09	STR B
	1		STR A
Southeast	Roof	Level 08	STR B
	3		STR A
	2	Level 04	STR F
	1	Level 03	STR F
		Level 02	STR F
		Level 01	STR F
		Level 03	STR E
		Level 02	STR E
		Level 01	STR E
		Level 04	STR D
		Level 03	STR D
		Level 02	STR D
		Level 01	STR D
		Level 07	STR C
		Level 06	STR C
		Level 05	STR C
		Level 04	STR C
		Level 07	STR B
			STR A
		Level 06	STR B
			STR A
		Level 05	STR B
			STR A
		Level 04	STR B
			STR A
		Level 03	STR C
		Level 02	STR C
		Level 01	STR C
		Level 03	STR B
			STR A
		Level 02	STR B
			STR A
		Level 01	STR B
			STR A

Figure 1: Location Breakdown structures of two projects. Project 1 shows the interior construction phase, Project 2 the structural phase of a hospital

## **Tasks, Location-Based Quantities and duration calculation**

In LBMS, tasks are packages of work, which can be completed in a location by the same crew with no breaks and share the same external dependencies to other tasks. A task usually contains work in several locations. This is a key difference to CPM, where activities are always located in one location. In a way, tasks are collections of CPM activities. The basic assumption of LBMS is that tasks are performed continuously, without breaks from one location to the next.

The work content of a task can be based on quantities. There are two ways to achieve this. Firstly, if the project's cost estimate has been created by location, for example by using BIM tools, it can be used as the basis for scheduling. Alternatively, tasks can be determined first, for example by integrating the collaborative Last Planner System(tm) phase scheduling process and LBMS, and then quantities can be estimated for each collaboratively determined task separately. In each case, one or more quantity items will be assigned to a task. Quantities describe the scope that will be accomplished when a task is finished in the location and make it easier to evaluate whether the task is complete. For example, the same Drywall crew can install different types of drywall in a location before moving to the next location. The quantity items could include installing full-height drywall for corridors, water-resistant bathroom wall, double board wall for meeting rooms etc. Each quantity item can have its own resource consumption, measures as manhours / unit (for example 0.46 manhours / m<sup>2</sup> for standard living room wall). By multiplying each quantity by its labor consumption, the total number of manhours in each location can be calculated.

Duration calculations of LBMS are based on these total manhours. To calculate the duration, more planning input is required related to crews, shift length and the difficulty factor of a location. The basic assumption of LBMS is that tasks have an optimum crew composition which will most efficiently complete the work. However, duration can be changed by increasing or decreasing the number of crews of optimal composition (Arditi et al. 2002). If the locations are big enough to accommodate multiple crews, the assumption of LBMS is that adding crews will not impact productivity (but will increase risk as described later in risk management section). Therefore the number of crews becomes a critical planning decision. The duration in number of shifts can be calculated using the following steps (Kenley & Seppänen 2010: 133).

1. Quantity of manhours needed to complete the location
2. Divide by the total number of crew members (duration in hours)
3. Divide by the shift length (duration in shifts)
4. Multiply the duration in shifts by the difficulty factor.

In addition to duration calculation, the quantities can be used in several ways in other parts of the LBMS. For example, deliveries can be planned when the need time for each quantity item is known. On the other hand, quantities can link together the production schedule and procurement schedule or be used for cost loading the schedule. These additional methods are not within the scope of this paper but are described in Kenley & Seppänen (2010: 163-193).

## Flowline visualization

Quantities determine the locations where each task is located and the duration of these tasks. This information can be used to plot the flowline of a task. In a flowline figure, the Location Breakdown Structure is shown on the left and the time is shown horizontally going to the right. Each task is shown as a diagonal line. The slope of the line signifies the production rate of the task. Assuming that the difficulty factor of each location is the same, the flowline slope reflects quantity variation between locations. When multiple flowlines are shown together, work sequence can be read horizontally. Optimization opportunities and wasted time can be seen in the schedule by looking at empty areas between tasks. Figure 2 shows a sample flowline figure.

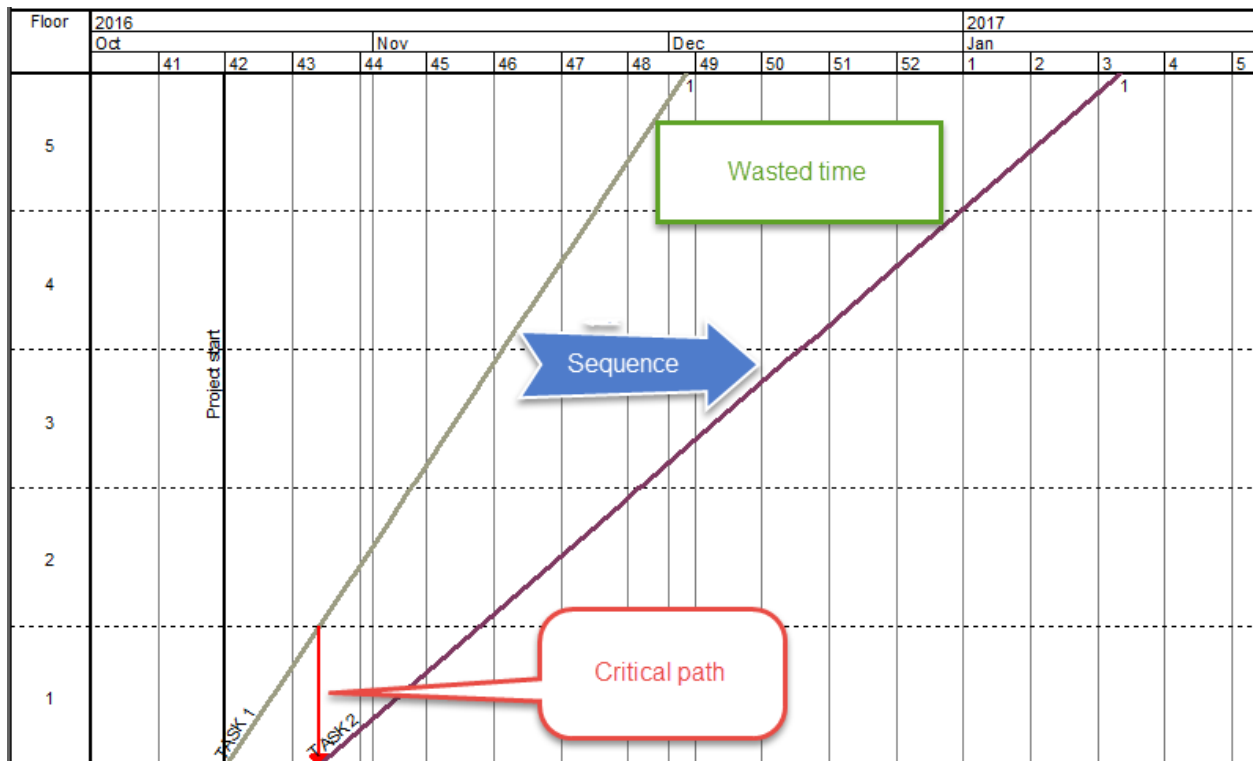


Figure 2: A Flowline figure of two tasks. It is possible to see optimization opportunities by looking at empty space between two flowlines, work sequence by reading horizontally and the critical path of the project from one diagram.

Compared to Gantt Charts flowline figures are a very efficient way of showing information and they enable seeing the big picture. It is very easy to see if the flowline schedule has been optimized or not but it is very hard to see the same from a Gantt chart. Large Gantt charts can include thousands of activities on dozens of pages. Typically even large construction phases can be represented in one flowline diagram. However, any schedule (even one created with CPM) which has locations and dates can be shown as a flowline diagram or as a gantt chart. We will next move to the LBMS calculations and methodologies which are the real difference between activity-based and location-based approaches.

### Layered CPM logic in location-based schedules (Kenley & Seppänen 2010: 133-142)

LBMS uses the locations to automate the creation of logic between tasks. The *layered logic* of LBMS includes *five layers* which use locations or hierarchy levels in a different way to do this.

These logic layers are described next in text and finally a flowline figure illustrating all the different layers is presented.

*Layer 1: External logic relationships between activities within locations*

In this logic layer, a relationship applied between two tasks will be applied in each location where both tasks exist. For example, a relationship stating that **painting** (a task) must happen after **drywall** (a task) on each floor, would be a layer 1 logic link. (Figure 3)

*Layer 2: External logical relationships driven by different hierarchy levels*

Layer 2 extends Layer 1 logic by allowing a different hierarchy level of the LBS determine the logic link. For example, a relationship stating that **roofing** (a task) must precede **drywall** (a task) in each building, would be a layer 2 logic link. (Figure 3)

*Layer 3: Internal dependency logic between locations within tasks*

Layer 3 links are unique to LBMS. They are used to model the movement of crews through locations. The basic assumption of LBMS is that a crew completely finishes a location before moving to the next location. The links are generated based on a task's location sequence which can be planned individually for each task or for several tasks at once. For example, **drywall** (a task) can be planned to proceed from Building A, first floor, up through the building and then to Building B, first floor and up through building B. (Figure 3)

*Layer 4: Additional location-based links*

Layer 4 links account for location lags in external logic. This is similar to layer 1 logic but includes a location lag which can be positive or negative. For example, in a cast-in-place structure, **the pouring of horizontal concrete** (a task) precedes the **formwork** of the floor above with a location lag of 1 floor. It also precedes **masonry walls** with a lag of -2 floors. (Figure 3)

*Layer 5: Standard CPM links between any tasks and different locations*

Final layer 5 allows for any task and any location to precede any other task in any location. This is the only layer of logic in the standard CPM. In LBMS, layer 5 links are typically used to tie different construction phases together because construction phases often do not have the same locations. For example, fireproofing could be the last task of Structural phase and kick off interior rough-in phase which uses a different location breakdown. In this case, fireproofing would need to be linked to the first task of interior rough-in with layer 5 links.



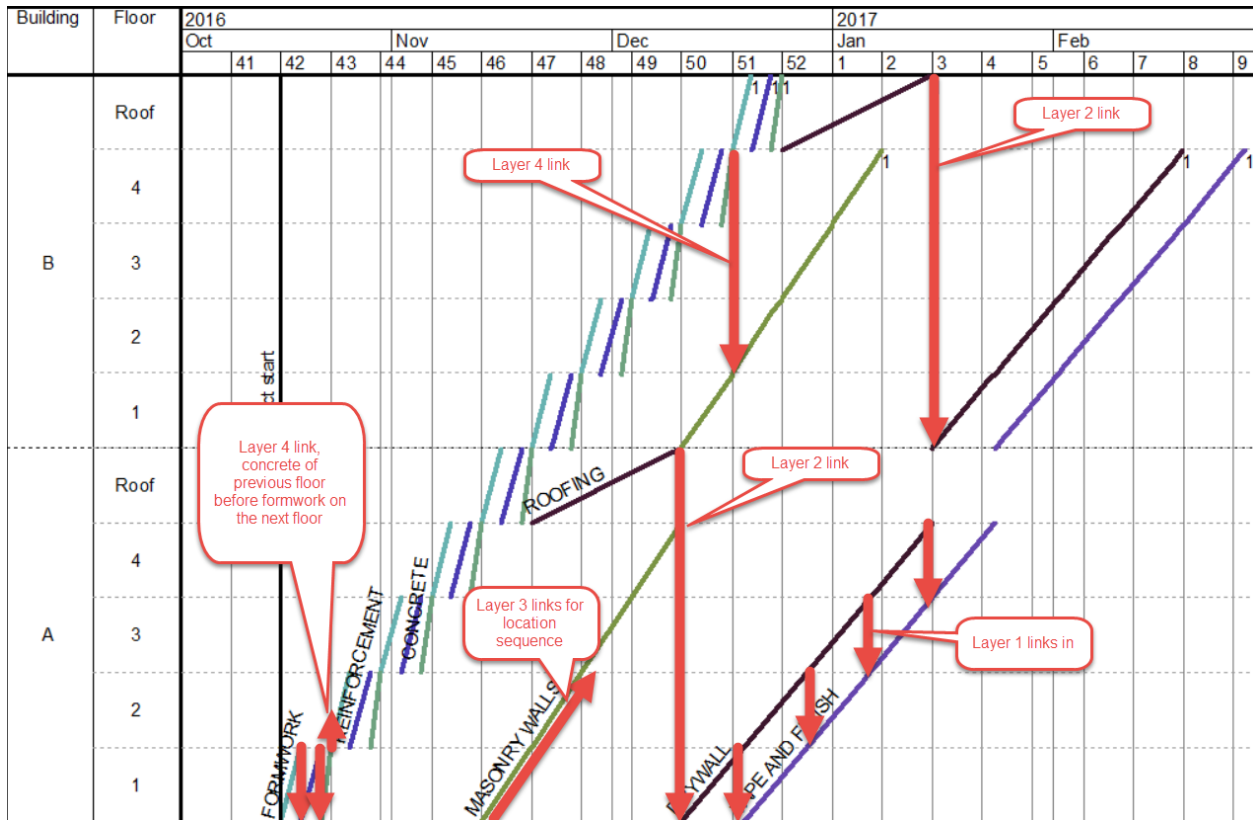


Figure 3: A flowline figure illustrating different layers of logic. The figure calls out layer 1 links between Drywall and Tape and Finish. Roofing has a layer 2 link to drywall. All tasks have layer 3 links to model internal location sequence (masonry walls called out in the figure). Two examples of layer 4 links are shown – concrete of the previous floor must be completed before formwork on the next floor and the concreting must be ready two floors above before masonry walls can start in a location.

Layered logic reduces the complexity of schedules because the same project can be modeled with much fewer links (Kenley 2005). For example, the schedule of Figure 3 has four layer 1 links (not all shown in the figure), one layer 2 link, seven layer 3 links and two layer 4 links, in total 14 links. To model the same in CPM, layer 1 links would need to be modeled with 36 links, layer 2 links would require 2 links, layer 3 links would require 50 links and layer 4 links would need 14 links, in total 102 links. The benefit of LBMS increases with more tasks and more locations.

### Differences of LBMS algorithm and CPM algorithm

LBMS algorithm is not presented in detail here, interested readers can refer to Kenley & Seppänen (2010: 147-156). However, a few key differences are worth mentioning here. In schedule planning, the difference of LBMS and CPM calculation relates to planning continuous work and to float and criticality calculations when continuous work has been planned.

Figure 4 illustrates four tasks, a task of standard production rate, a slower task, a faster but continuous task and a faster but discontinuous task. The third task, faster and continuous, is only possible with the LBMS algorithm. The earlier locations of the task are “pulled” by the later locations enabling continuous work. In standard CPM, faster tasks are always discontinuous due

to the lack of this continuity heuristic. This is a critical difference because forcing work to be continuous enables schedule optimization.

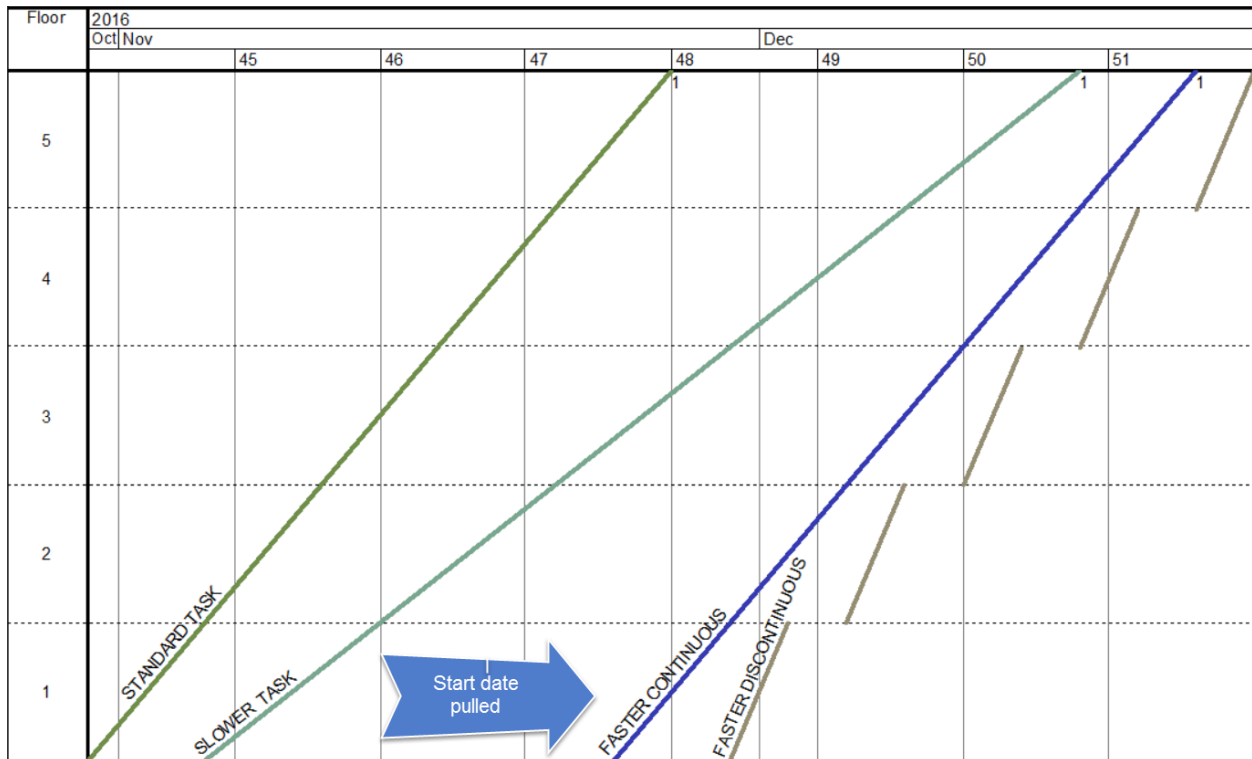


Figure 4: The main difference of LBMS and CPM algorithms illustrated with a flowline diagram. The start dates of tasks can be pulled by the later locations in LBMS algorithm to make work continuous. Ordinary CPM would leave faster tasks discontinuous.

### Risk management and buffers

One of the main goals of LBMS is to decrease the risks related to schedules. There are several types of uncertainties which can impact production, for example uncertainties related to environment and prerequisites of production. Most important ones handled directly by LBMS include uncertainties related to adding resources, resource availability, productivity rates and locations (Kenley & Seppänen 2010: 181).

Every time a new mobilization is called for by the schedule, there is a risk that the resources will not be available when needed. This risk applies for the first mobilization as well as for any subsequent ones if the work is discontinuous or additional resources are required in the schedule. (Kenley & Seppänen 2010: 182). This risk can be minimized by planning continuous work and protecting the continuous workflow from variability by adding buffers.

Resource availability is always a risk. It is possible that the subcontractor does not have enough crews available or could have more important projects which are delayed at the time when task commences. Similarly, a subcontractor could have too many resources available and mobilize with too large a crew if other projects have lower demands. (Kenley & Seppänen 2010: 182-)

183). This risk can be mitigated by collaborative phase scheduling where commitments are made to resource levels required to achieve the phase schedule.

Productivity rates used to plan a schedule are always based on averages and set a good target productivity. However, there are huge individual differences in productivity and even the same individual can have different productivity over time (Kenley & Seppänen 2010: 182). This risk can be mitigated by first run studies (first brought to construction by Parker and Oglesby 1972) and by active production control during construction.

All the different types of uncertainty lead to variability. Lean construction aims at minimizing variability. However, some variability will always remain in the production system. LBMS protects against remaining variability by including buffers in the schedule. Buffers are inserted to protect the continuous flow of critical tasks. Figure 5 shows a flowline schedule with a buffer of five days inserted between Task 1 and Task 2. Buffers delay the start date of the succeeding task from the earliest possible start date. They can be absorbed during production if predecessors get delayed. This gives time for control actions.

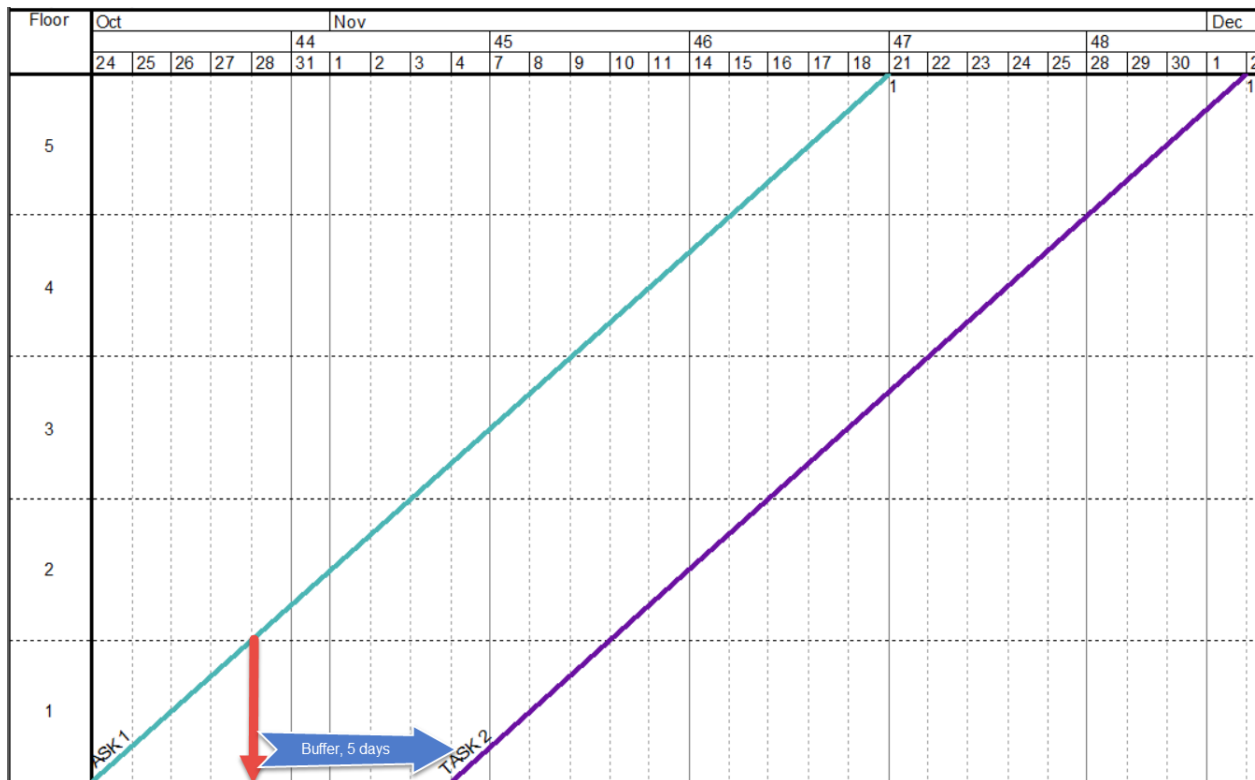


Figure 5: A flowline schedule with two tasks. A buffer of five days has been inserted between the tasks.

It should be noted here that the main difference between takt time planning and LBMS approaches is the type of buffer used. Takt time planning protects against variability by underloading resources (i.e. having more resources than needed to do the work). When the workers run out of work in takt time planning, they will work in other, non-repetitive work in the building (Frandsen, Seppänen & Tommelein 2015). Figure 5 above illustrates a time buffer which has been the primary LBMS buffering mechanism.



The ability to complete the building earlier by decreasing manpower is called the *location-based planning paradox*.

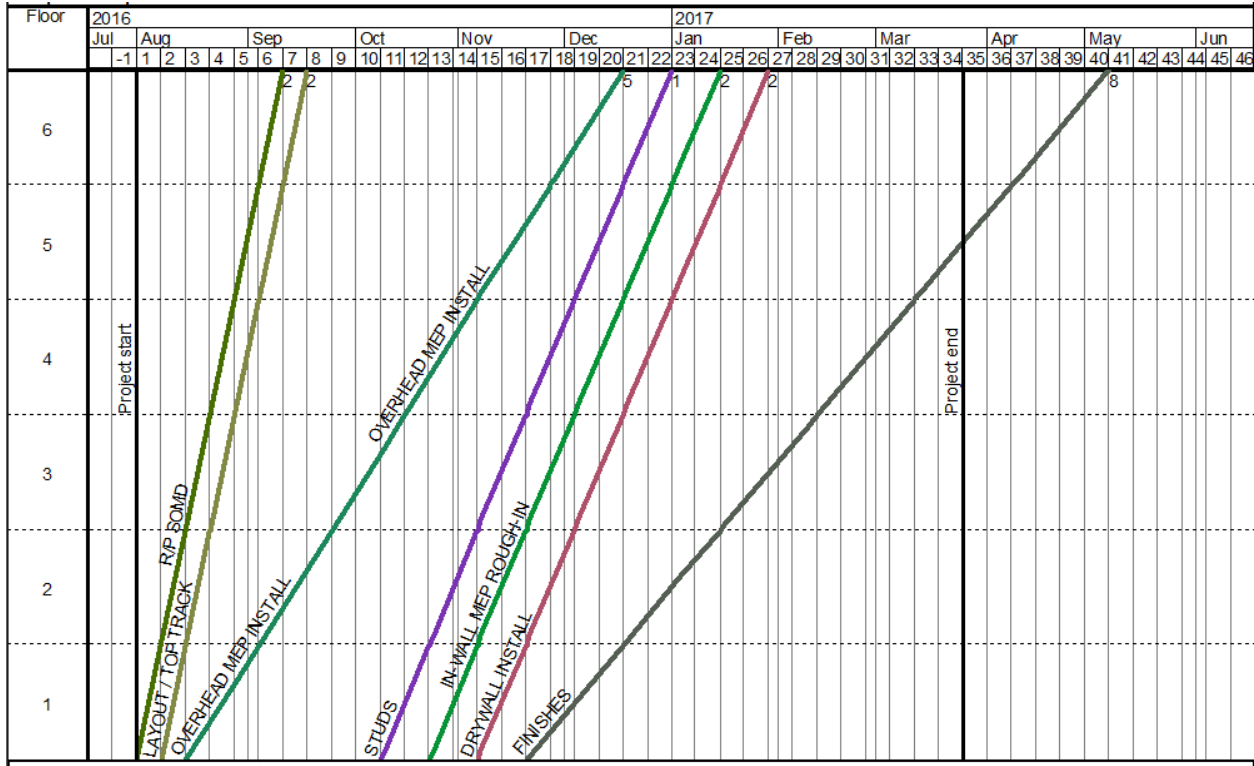


Figure 7: Flowline figure of the six story building, one crew decreased from Studs

As the final alignment step in this simple example, more resources are required to Overhead MEP install and Finishes tasks. Resource constraints should be reviewed with the subcontractors when increasing resources. Increasing MEP crews to 8 from 5 (optimal crew of 2) and Finishes crew size from 8 to 16 would perfectly synchronize all tasks from Overhead MEP to Finishes. Figure 8 shows the results of these two changes. The project duration has decreased to 22 weeks which is 12 weeks earlier than the deadline (vertical line in the figure).

The schedule of Figure 8 does not include any buffers and resources have been increased so it is more risky. To account for variability, buffers can be added to the schedule. In real application, risks and variability related to each task would be considered and buffers would be added after tasks with high variability. Structure is prone to weather delays, so in this example, we add a buffer of five days between R/P SOMD (Reinforcement and pouring of slab on metal deck) and Layout / Top Track tasks. Drywall contractor who is responsible for Layout / Top Track, Studs and Drywall Install tasks is reliable and thus does not need extra buffers. However, there is a lot of uncertainty related to MEP tasks, so a buffer of 10 days is added between overhead MEP install and Studs and another ten days between In-wall MEP and Drywall install. The resulting schedule is shown in Figure 9. The resulting schedule finishes on week 27, 7 weeks ahead of

deadline.

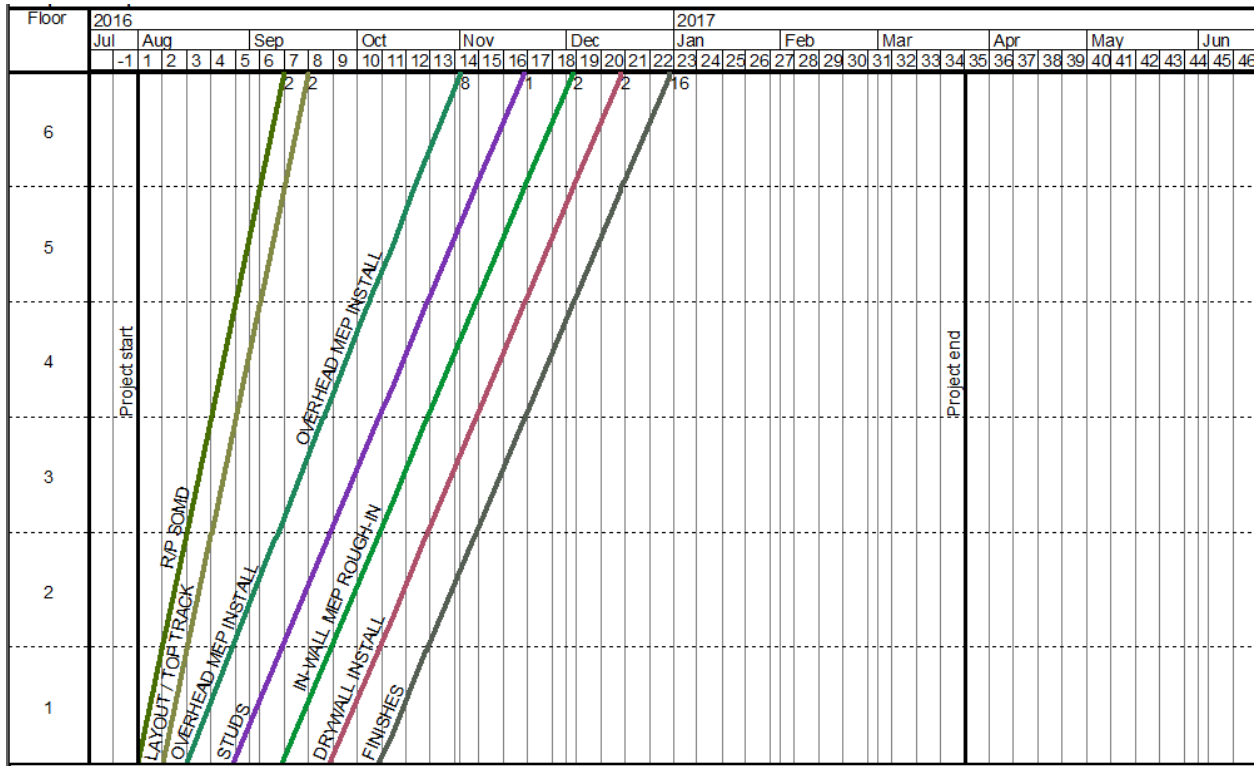


Figure 8: Aligned schedule

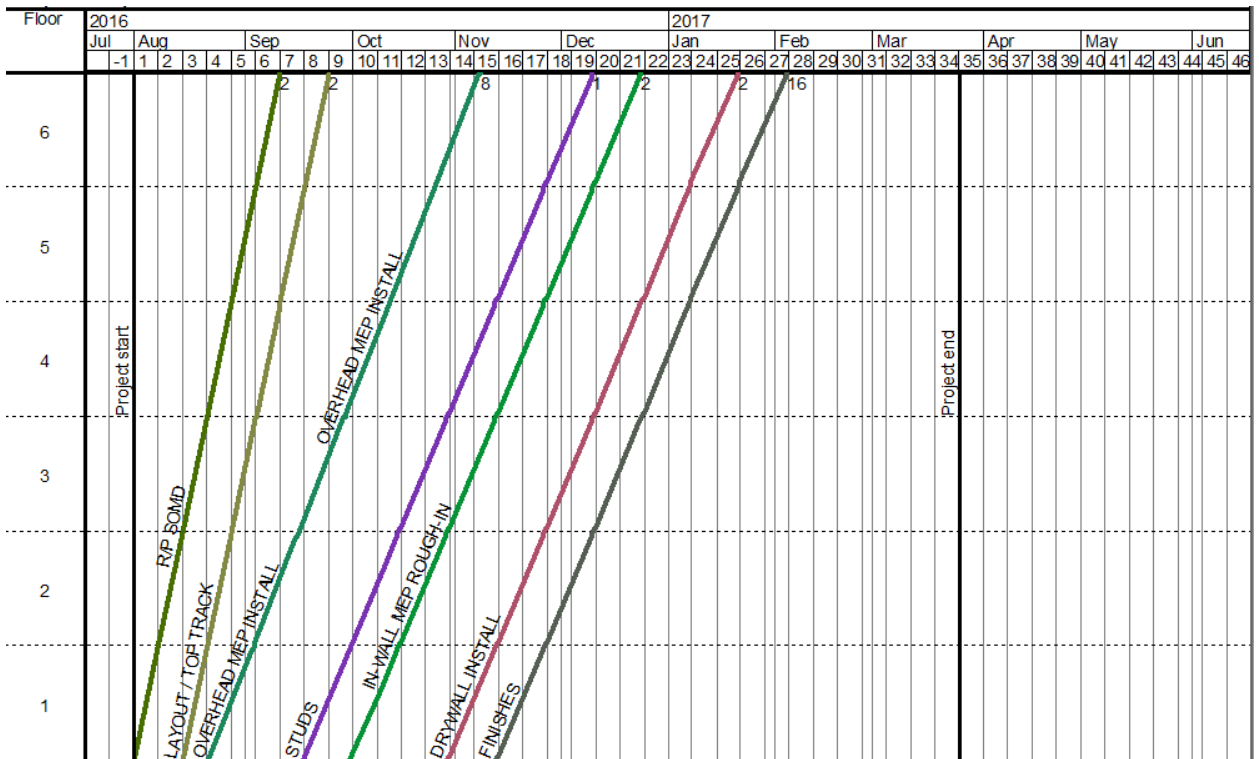


Figure 9: Synchronized Flowline schedule with buffers added

In real projects, optimization can be quite a bit more challenging than in the example presented above. For example, quantities can vary a lot between locations. In those cases, additional crews can be deployed to locations with higher quantity to improve alignment. It is also possible that some locations become accessible later which may require breaks in workflow or delayed starts to tasks. This can often happen when all the logic layers are used to model a schedule. Much more detail about schedule optimization can be found in Kenley & Seppänen (2010: 201-246).

Takt method

Schedule optimization process using takt time planning method is very similar to the one described above. In takt time planning, the goal is to find locations with minimum variation of work density. Each trade must complete their work within the takt time. Takt time is a design parameter which remains constant for the construction phase. All the trades commit to the takt time. In effect, takt time plans can be visualized as Flowline diagrams with all the slopes going perfectly parallel. Rather than using time buffers, takt time planning uses capacity buffers, so that trades assign production units to work at, for example, 80% of capacity. If the production units run out of work, they will work on other work which has been planned «off takt». Often locations with unbalanced work density are left «off takt» (Frandsen, Seppänen & Tommelein 2015).

## **Location-based controlling system**

In LBMS, controlling is given more weight than planning. Plans are always based on assumptions and the best way to control the project is to collect as real time information as possible, react to any deviations and proactively make things happen according to plan. This is in contrast to the “after-the-fact” approach of controlling which is at the core of CPM controlling model (Meredith & Mantel 1995). Koskela and Howell (2001) called the activity-based model the *thermostat* model of controlling which is overly simplistic.

Controlling in LBMS includes monitoring status of locations and labor on site to calculate actual productivity, visualizing status in control charts and flowlines, forecasting progress based on actual production rates and giving alarms to warn of upcoming problems to enable proactive control.

## **Location-based status monitoring**

The basic progress monitoring in LBMS focuses on four aspects (Seppänen & Kenley 2005)

1. Actual start and finish dates and interruptions
2. Actual quantities
3. Actual resources
4. Actual shift length and days off

Actual start and finish date of each location is a basic requirement for tracking and is required for all downstream calculations and visualization. If actual start dates and finish dates are known, it is possible to show status in a control chart (Figure 10) or plot progress in a flowline diagram (Figure 11). It is also possible to calculate actual production rates (quantities / shift). However, actual production rates get distorted if any interruptions longer than a day are not recorded.

Because the goal of LBMS is to minimize interruptions, the number of interruptions is an important metric in its own right. (Kenley & Seppänen 2010: 273).

Tracking actual quantities enables for each location enables detecting quantity deviations which can get critical if they repeat in other locations. These can be caused by measurement errors, undocumented change orders or an attempt by a subcontractor to invoice for work outside their scope. (Kenley & Seppänen 2010: 272) If quantity deviations are not detected, any attempts to calculate production rates (units / shift) or resource consumption (manhours / unit) will be based on incorrect quantities and are not usable for estimating future work. Actual quantities can be easily measured by using BIM tools assuming that the model reflects as-built conditions.

Actual resources are important for the calculation of actual resource consumption and can be useful to detect root causes of deviations. For example, a poor production rate may be caused by higher labor consumption than planned (lower productivity) indicating incorrect estimates or problems with production. It could also be caused by fewer resources than planned. It is particularly interesting to monitor changes in resource consumption because this can indicate problems in production. Actual resources have traditionally been hard to track and are often based on self-reporting by subcontractors. However, it is common that subcontractors report the information only as total workers on site and it is hard to figure out where the resources were working. (Kenley & Seppänen 2010: 272-273). Seppänen (2009: 111-112) proposed a way to estimate what the resources were doing. In the future applications of automatic tracking technology, labor can be tracked automatically and this problem can be resolved. Actual shift length and days off are important to track for calculating resource consumption because resource consumption is based on manhours. This is also difficult to do in practice but the labor tracking methods of the future should address also this problem.



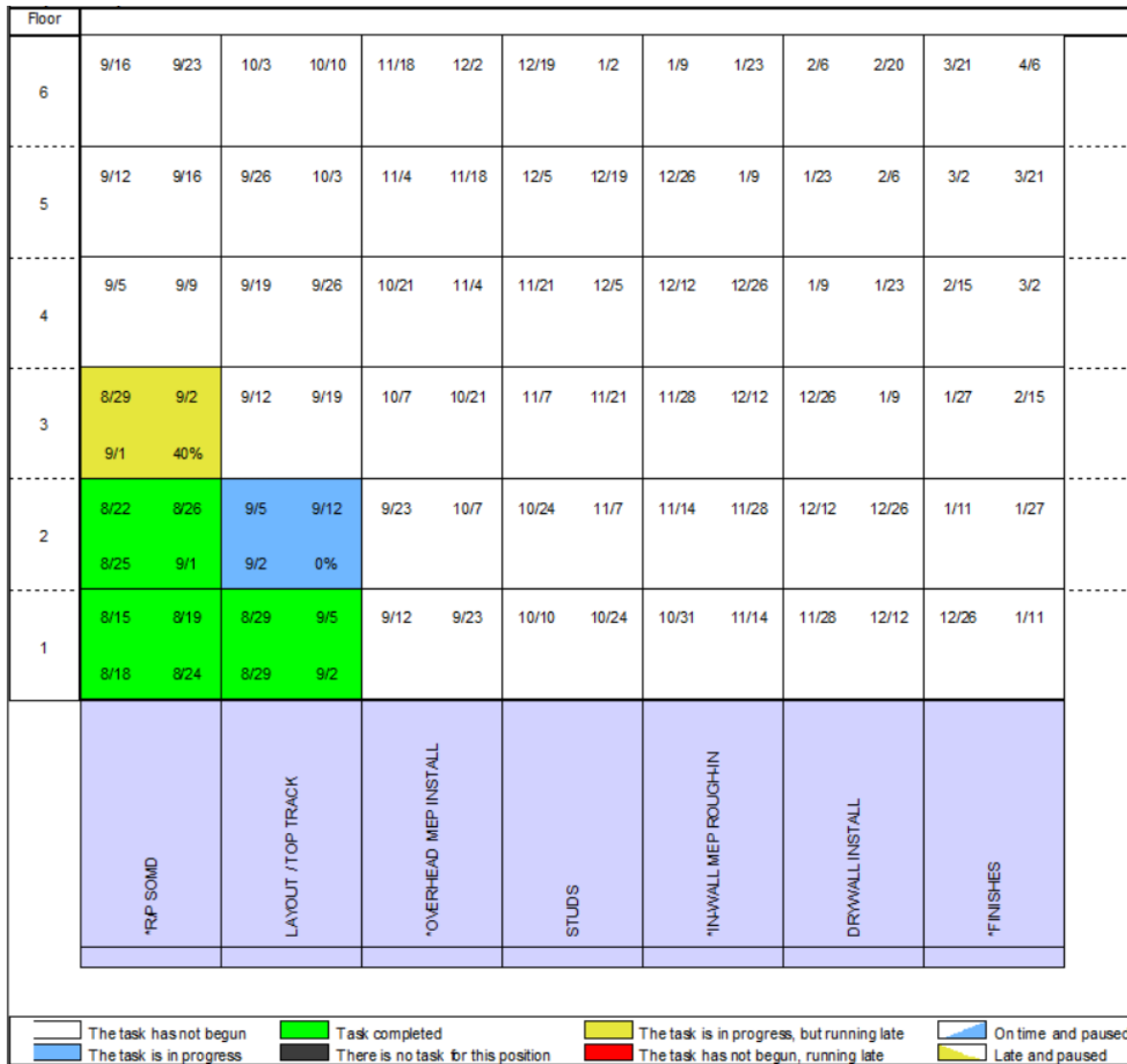


Figure 10: A schedule control chart for showing location-based progress. Location breakdown structure is shown on the vertical axis and tasks on the horizontal axis. Cells are tasks in a location. Green color means that a task has been completed in a location, yellow means that the task is late and blue that the task is in progress and on time. Planned start and finish dates are on the top and actual start and finish dates (or % completed) in the bottom of each cell.

## Forecasting and alarms

The actual progress can be used to calculate forecasts. Forecasts are based on the actual resource consumption (if available) or on actual production rates. The assumption is that the task will continue with the same resources and the same productivity unless control actions are taken. Alarms are generated when a predecessor is going to interfere with the successor. The goal of proactive production control is to prevent the alarms from turning into actual production problems which can start a chain of cascading delays. The mathematics of calculating forecasts were described by Seppänen (2009: 113-115). Figure 11 shows a flowline figure with planned schedule, actual progress, forecasts and alarms.

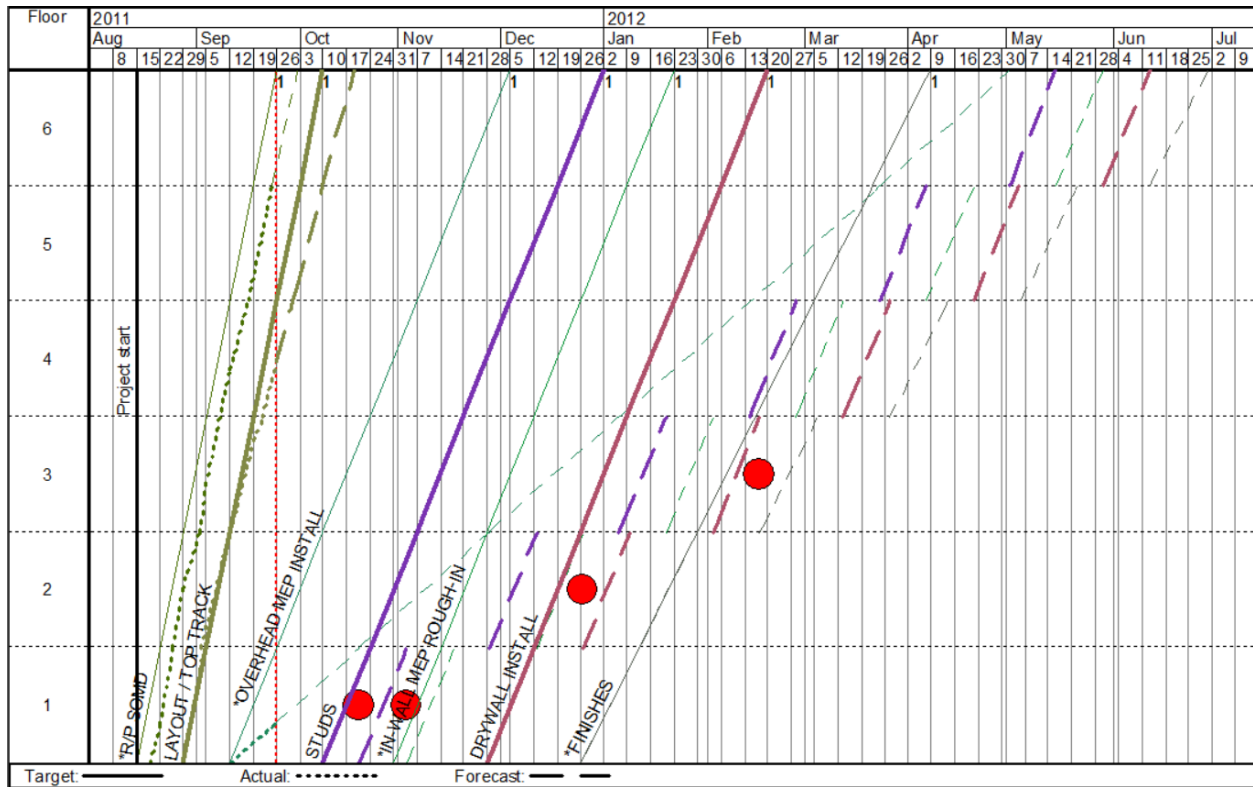


Figure 11: Flowline figure with planned lines (solid), actual lines (dotted) and forecasts (dashed). Tasks R/P SOMD and Layout / Top Track are a bit behind of schedule but have not caused any alarms. Overhead MEP Install is one week behind but is going slow. It will impact Studs in two weeks and cause a cascading delay if the production rate is not corrected.

### Planning control actions

Control actions are taken to recover from a deviation in order to prevent interference with other tasks or project delay. In LBMS, plans (solid lines in flowline) are not updated. Rather a control action is defined with the specific goal of preventing interference. Control actions adjust the forecast (the dashed lines in flowline). Examples of possible control actions include: improving productivity by reducing waste, changing the number of resources, working overtime or on weekends, changing sequence, delaying successor task etc. (Kenley & Seppänen 2010: 283)

For example, in the situation of Figure 11, the control actions could target the task causing the problem: Overhead MEP Install. First, the root cause of the problem would be identified. Then, an action plan would be documented (possibly as an A3 report) and its likely impact reflected in the forecast to see if the plan solves the problem. If the root cause was understaffed crew, a control action could be mobilizing additional resources (assuming same productivity). Doubling the crew would lead to the situation in Figure 12. The alarm has shifted much farther into the future allowing for more time to monitor the situation before taking further action.

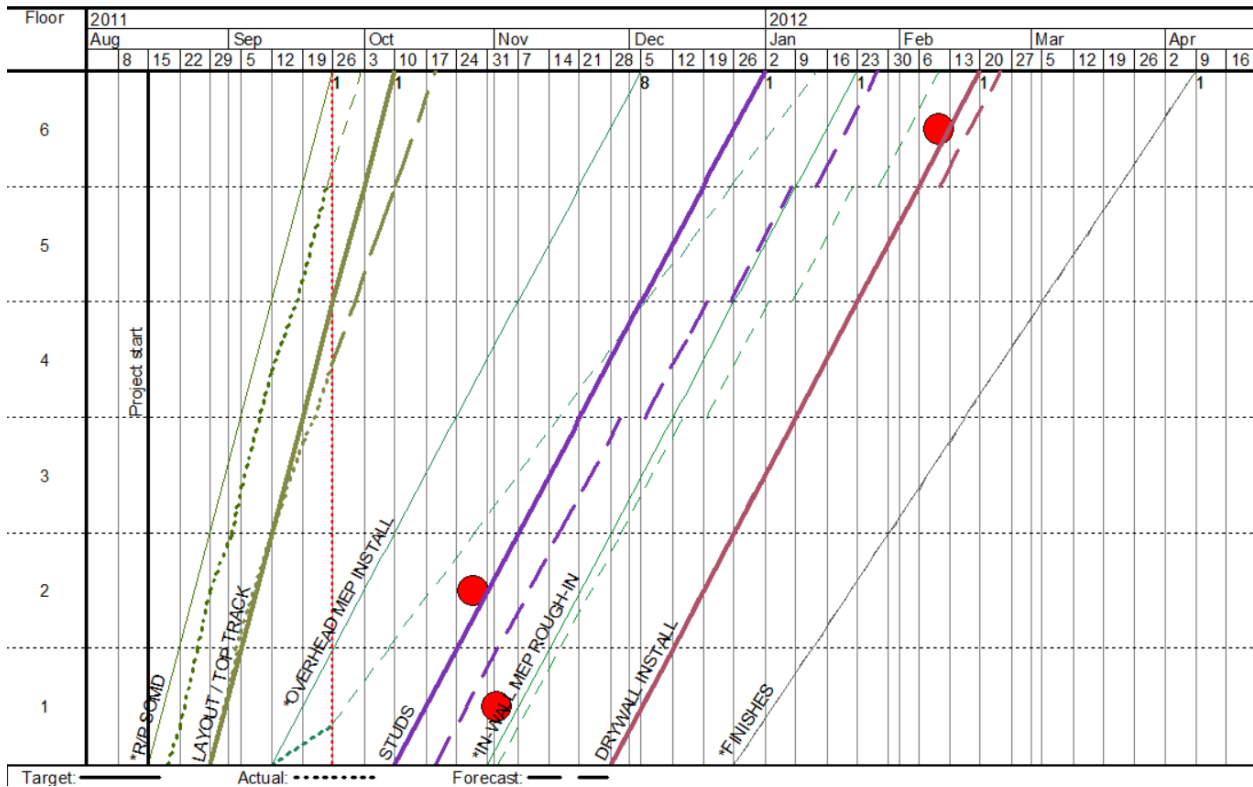


Figure 12: Schedule forecast considering control action of doubling the crew for Overhead MEP install

### Cascading delays in construction

Seppänen (2009) investigated the impact of production problems on production. A production problem was defined as a start-up delay, discontinuity or slowdown caused by interference from other tasks. Production problems were found to cause downstream problems via multiple mechanisms. Cascading delay chains were started by complex combinations of resource issues, production management decisions and out-of-sequence work. These led to multiple contractors working in the same location resulting in slowdowns and demobilizations with the associated return delays. However, LBMS was able to create alarms before they happened and in the study the LBMS forecasting method was further developed by adding more information about resource availability to generate alarms even earlier (Seppänen 2009: 162).

Cascading delay chains can be illustrated in flowline figures. Figure 13 shows a flowline figure of interior phase of an office building project. Just the tasks involved in the cascading delay chain are shown. Numbered red circles in the figure reflect problems. For example, the vinyl floor covering task started too slow and caused a delay in electric cabling (2) and a start-up delay of system walls (6). System walls did not come to the site immediately when the predecessor was completed but there was a return delay of three weeks. This delay led to a series of other problems (8,9,10). (Seppänen 2010: 140-142).

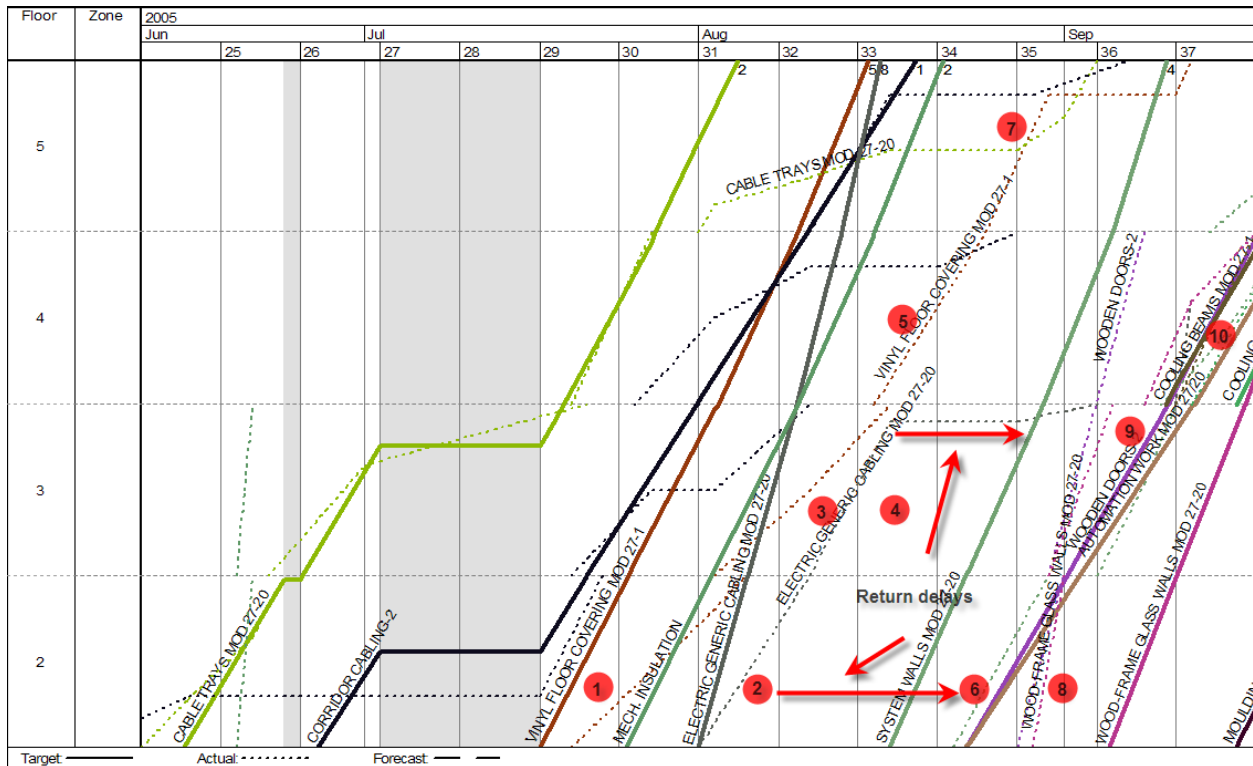


Figure 13: Cascading delay chains illustrated in flowline. Figure from Seppänen (2009:140)

### Empirical results of location-based control

Several empirical studies have been done related to location-based control. A series of 30 master's theses based on action research were done in Finland when the control methods were first being developed in 1980's and 1990's. Each thesis brought some improvements to the controlling techniques. The overall results were documented in Finnish in a handbook of production control, published in three editions (Kankainen & Sandvik, 1993; Kolhonen, Kankainen & Junnonen 2007). However, the research method on all these was action research.

Empirical research based on 6 projects, including 4 residential projects, a business park and a school building, was conducted by Seppänen & Kankainen (2004). The analysis was based on archival analysis where the planned and actual flowlines were analyzed for start-up delays, production rate deviations, interruptions and final delays. The findings included serious problems related to the controlling of interior work. In general tasks started on time but had interruptions or slower than planned production, resulting in a typical delay of 2-4 weeks for each interior task. Overall 71% of tasks were planned to be continuous but only 33% of tasks were actually continuous. Buffers between tasks were found to have a statistically significant correlation to interruptions. The study also calculated the prevalence of production problems. Tasks which started late had fewer slow-downs. The conclusions of the research included that just planning continuous work is not enough and controlling is a critical process, discontinuities are the hardest deviation type to recover from and starting too early results in slowdowns.

This study led to the doctoral thesis of Seppänen (2009) where the goal was to find out how production control on site works, how reliable are the production plans, which factors explain

the success or failure of the plans and attempts to improve the LBMS controlling system to give better information to decision makers. The study was based on archival review but also detailed observations of process on site to find production problems. The factors related to the success and failure of the plans were found to be cascading delay chains, resource problems, detailed planning process, not taking control actions and uninformed production management decisions including push controlling start dates. However, it was possible to forecast many of the problems before they happened. All three case studies had a lot of cascading delays and production problems but still managed to achieve substantial completion on time, although in each case the time for hand-off and self-commissioning activities were compressed. One of the projects was able to achieve a duration compression of 10% through the use of schedule optimization, others achieved durations comparable to other projects of the same type.

Kala et al. (2012) evaluated the production control approach from three perspectives on a large hospital project in California: 1) time used running LBMS technical system compared to keeping a CPM schedule up-to-date, 2) quality of information for decision making from LBMS 3) reliability of the planning process. The researchers found that CPM schedule required more man-hours to operate the technical system than the LBMS process. LBMS was also able to provide better information for superintendents for decision making to enable proactive control. In contrast with Seppänen (2009) study, start dates had variation of three weeks on average but the production rates were very close to planned. It could be that the improved forecasting ability of LBMS based on Seppänen (2009) and the actual use of forecasts to guide decisions helped to keep the production rates in control. An interesting result related to man-hour estimates by subcontractors was found. Subcontractors were over-estimating their resource consumption by 30-40% on average. This could either reflect considerable capacity buffers (in addition to time buffers) or substantially better than average productivity on this project.

Evinger et al. (2013) evaluated the productivity effects of following the standard practice of starting as soon as possible. They used two case studies where one was performed with a CPM schedule and traditional management practices and one had a mix of CPM and LBMS strategies. The most interesting results were in project two where similar work was carried out on different floors based on CPM or LBMS. The floors were patient floors and had identical scope. CPM floors had on average 18% higher labor consumption (poorer productivity). On average, CPM floor tasks had 10% lower production rates than LBMS floors. The authors concluded that running the project with a CPM methodology resulted in lower productivity and lower production rates than using LBMS methodology.

Seppänen et al. (2014) evaluated the impacts of LBMS on production rates and productivity. They tracked the production alarms generated by LBMS and what kind of control actions were taken by the production team in three projects. 39% of LBMS alarms resulted in control actions agreed with the team. 65% of actions related to improving production rates were actually able to achieve a higher production rate and the increase was on average 37%. 50% of the actions were able to prevent a production problem. In several cases, the number of resources did not increase correspondingly but the productivity of the subcontractor increased. The authors suspected that production rate increases were mostly achieved by actions targeting productivity rather than

requiring more resources. The authors concluded that the General Contractor can impact subcontractor production rates with active control based on LBMS principles and thus decrease project durations.

In recent years, several studies have been done related to takt time planning and its relationship to LBMS (e.g. Seppänen 2014; Frandson, Tommelein & Seppänen 2015). There is limited empirical evidence of results using takt time planning because most of the studies have focused on planning or individual construction phases. However, Heinonen & Seppänen (2016) presented a case study of a cruise ship refurbishment project where project durations were decreased by 73% in three years of development and after several projects. This indicates that takt time planning is a more aggressive strategy and can result in large time savings. However, its success in construction projects has not yet been documented. Seppänen (2014) presented a simulation analysis where it was shown that the takt time approach requires a large buffer of work outside the takt or otherwise a lot of waiting hours can occur. This presents a challenge in subcontractor environments and traditional contracts where the subcontractors tend to leave the site if they run out of work. However, this could be alleviated with new contract forms, such as Integrated Project Delivery. More empirical research is required to see when takt time is more suitable approach and when LBMS would work better. It can be that a mix of these two approaches is required for optimal results, depending on uncertainty of the project.

### **Location-based controlling process based on the combination of LBMS and LPS**

LBMS controlling is focused on preventing cascading delays caused by interference between trades (Seppänen 2009). LPS focuses on the social process, constraint screening and commitment. Both of these views are critical, so the systems are complementary and raise different issues for discussion and resolution (Seppänen, Modrich & Ballard 2015). The process combining LBMS and LPS process includes the following steps: (Seppänen, Modrich & Ballard 2015).

- Identify tasks and locations in the look-ahead window (LPS / LBMS)
- Break down tasks and locations to operations (LPS)
- Identify, assign and remove constraints (LPS)
- Review actual production to identify ongoing production problems (LBMS)
- Review forecasts and alarms to identify future production problems (LBMS)
- Root cause analysis for problems (LPS)
- Re-plan to address current and upcoming problems (LPS / LBMS)
- Release constraint-free operations, tasks and locations to workable backlog (LPS)
- Preparing for upcoming operations (LPS)

LBMS supports the process by providing data on ongoing and future problems and the system where the phase schedules and look-ahead schedules are stored. Root cause analysis of LPS tackles all the problems identified based on constraint identification, constraint removal or actual production. LBMS provides numerical support, for example actual production rates and labor

consumptions, which can be used to drive LPS discussions. Any agreed actions which impact the crew size or future productivity of an operation will trigger recalculation of the LBMS forecast to see if the actions are sufficient to fix the problem. The control chart can visualize the workable backlog by color-coding tasks in locations based on constraints and status. (Seppänen, Modrich & Ballard 2015). For example, any tasks with constraints can be greyed out (Kenley & Seppänen 2010: 329).

Based on the ideas above, a weekly production control routine, including collecting and reporting progress, analyzing LBMS and LPS data and superintendent and subcontractor meetings can be defined. The routine should be based on regular superintendent look-ahead meetings, daily huddles, weekly production planning and commitment meetings and phase scheduling meetings for up-coming phases. The actual routine will be defined based on project size, organization and requirements and it is impossible to define a routine that would work in all cases. Some parts of the process related specifically to LBMS are elaborated below.

The weekly routine including LBMS always includes progress data collection and reporting. There are several ways to approach data collection. Data collection can be *centralized*, which requires the person responsible for monitoring status to tour every location to observe and record the status of work. (Kenley & Seppänen 2010: 337) This approach can give an accurate snapshot of status on the status date but does not get accurate actual resources or what happened within the monitoring period. It is also very labor-intensive. It is possible to *decentralize* information collection, where subcontractors or superintendents self-report work status. This method presents the risk that the status data may be incorrect but decreases the workload of any one actor. (Kenley & Seppänen 2010: 337-338). Digital tools make the data collection easier because *decentralized* strategies may be implemented with mobile tools with subcontractors recording progress using a mobile phone (e.g., Dave, Seppänen & Modrich 2016). Regardless of the technology used, in most documented case studies, the General Contractor verifies the information provided by others. (e.g. Seppänen, Evinger & Mouflard 2014).

After data collection, the LBMS software (for example, Trimble Schedule Planner) is updated and forecasts and alarms are reviewed. In larger projects, this is typically done by a production engineer who can be a full-time resource or a person spending some work time on LBMS-related tasks (Seppänen, Evinger & Mouflard 2014). Their task is to identify either ongoing (based on actual progress) or upcoming (based on forecasts) issues and prepare reports and recommendations to review with the project team. Typical reports reviewed by project teams to address issues include just two or three flowlines with plan, actual and forecast to make it easy to understand for subcontractors. Any agreed control actions are reflected back in the forecast and logged in a control action log (Seppänen, Evinger & Mouflard, 2014).

Seppänen, Modrich & Ballard (2015) concluded that a critical part of production control is to reveal as many problems as possible and as early as possible. By combining the LBMS progress data, forecasts and alarms to LPS constraints and weekly commitments and verifying that weekly commitments meet the requirements of LBMS production rate, more problems can be raised earlier for discussion. They presented a hypothesis that the amount of problems identified increases and the information from the combined system can help in resolving the problems

(Seppänen, Modrich & Ballard 2015). This hypothesis has not yet been tested empirically, although several practical implementations are ongoing.

## Conclusion

The location-based management system is composed of a planning and controlling system. Both systems include a technical system and best practices or guidelines how to best use them to improve planning and controlling results. The differences compared to other planning systems are mathematical and process-related. In terms of the LBMS algorithm, locations can be used to greatly simplify the planning. On the other hand, the LBMS algorithm enables continuous work. In contrast with CPM, more emphasis is placed on controlling than planning. LBMS controlling includes collecting detailed location-based progress data and refining it by calculating progress metrics, forecasts and alarms. These can be utilized to raise problems for resolution, for example by using the social process of LBMS. Empirical data of the results has been reported and there is convincing evidence that LBMS outperforms CPM. Takt time planning is a related location-based technique. It can use the same technical system but emphasizes different things in terms of guidelines. In a closely related industry of cruise ship refurbishment, impressive benefits have been documented. However, construction use cases have not yet been systematically documented. It can be concluded that location-based systems outperform CPM in both planning and controlling but more research is required to determine the best location-based planning and controlling strategy. It is likely that the best strategy is a mix of LBMS and takt time planning approaches and depends on project (or phase) characteristics.

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