POLITECNICO DI MILANO

Architecture Urban Planning Construction Engineering

Master of Science in Management of Built Environment

PLANNING AND CONTROL IN CONSTRUCTION: ANALYSIS AND INTEGRATIONS OF THREE METHODOLOGICAL APPROACHES.

Location-Based Management System (LBMS), Last Planner System (LPS) and

Critical Path Method (CPM)

Supervisor: Prof. Alberto Pavan

Candidate: Riccardo Poliani

ID: 927374

Academic Year 2019/2020

ABSTRACT

Among the five main managerial functions universally recognized by the literature, planning and control occupy the most important positions. Planning is the moment in which the project plan is developed and the activities and values of the variables necessary to achieve the objectives are defined. Control is the operational phase in which it is necessary to monitor the correct progress of the program, find any deviations from the plan and take appropriate corrective measures. To date, in the construction world there are mainly three different planning and control methods called Location-Based Management System (LBMS), Last Planner System (LPS) and Critical Path Method (CPM), developed starting from the late 1950s. Through a careful bibliographic analysis, the aim of this thesis is to, by formally and technically analyzing the three methods mentioned above and thus highlighting the respective advantages and disadvantages, trying to overcome the limits and criticalities of each one through a integration between them. Initially, the first attempt of the integration will be in pairs but, having discovered space for further improvement, the culmination of the dissertation will be reached with the proposal of an integrated theoretical model that simultaneously considers all the methods listed above.

Keywords: Project Management, Construction Management, Location-Based Management System, Last Planner System, Critical Path Method

SOMMARIO

Tra le cinque principali funzioni manageriali riconosciute universalmente dalla letteratura, pianificazione e controllo occupano i posti di maggior rilevanza. La pianificazione è il momento in cui si sviluppa il piano di progetto e si definiscono le attività e i valori delle variabili necessari al raggiungimento degli obiettivi. Il controllo è la fase operativa in cui è necessario monitorare il corretto procedere del programma, trovare eventuali scostamenti dal piano e adottare adeguate misure correttive. Ad oggi, nel mondo delle costruzioni esistono principalmente tre diversi metodi di pianificazione e controllo chiamati Location-Based Management System (LBMS), Last Planner System (LPS) e Critical Path Method (CPM), sviluppati a partire dalla fine degli anni '50. Attraverso un'attenta analisi bibliografica, l'obiettivo di questo elaborato di tesi è quello di, analizzando formalmente e tecnicamente i tre metodi sopra citati ed evidenziando quindi i rispettivi vantaggi e svantaggi, cercare di superare i limiti e le criticità di ciascuno attraverso un'integrazione tra di essi. Inizialmente, il primo tentativo di integrazione proposta sarà a coppie ma, avendo scoperto margine per ulteriore perfezionamento, il culmine della dissertazione si raggiungerà con la proposta di un modello teorico integrato che contemporaneamente consideri tutti i metodi sopra elencati.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

LBMS – Location Based Management System

LBS – Location Breakdown System

CPM – Critical Path Method

LPS – Last Planner System

BIM – Building Information Modelling

EVA – Earned Value Analysis

PM – Project Management

PPM – Project Production Management

WBS – Work Breakdown Structure

IGLC – International Group for Lean Construction

SI – Superintendents

SC – Subcontractors

WWP – Weekly Work Plan

PERT – Program Evaluation Review Technique

PPC – Percent Plan Complete

TA – Task Anticipated

TMR – Task Make Ready

PMICOS – Project Management College of Scheduling

AACEI – American Association of Cost Engineering

RFI – Request For Information

SPS – Schedule Planner Standard

MEP – Mechanical, Electrical and Plumbing

Chapter One: Planning and Control

1.1 Introduction

The path that led me to the choice of this topic for the final dissertation began many months ago, to be precise in October 2019, the month in which I approached the Construction Management course for the first time. I remember being particularly fascinated by how, behind the design phase, choice of materials or execution of the works that had accompanied me since the first year of Building Engineering, there was a world unknown to me, a world composed of operational and strategical management of a project.

This fascination increased even more starting from January 2020 when, about 2000km away from home, in the dark and cold winter of Helsinki, I had the opportunity to begin my Erasmus exchange program. During one of the first weeks of class, the attendance of a course called Operation Management in Construction, expertly taught by Prof. Olli Seppänen, convinced me even more. Thanks to the new notions learned, I had the opportunity to see the world of construction management from a new perspective, thus also appreciating its various nuances.

This new perspective was undoubtedly the engine that gave the decisive push towards the choice of the topic of the thesis and consequently outlined its development.

1.2 Planning and Control

Harold D. Koontz, an American professor of business management and organizational theorist, once said “Management is an art of getting things done through and with the people in formally organized group”. Part of his theoretical thinking is contained in the book “Essentials of Management”, written with Heinz Weihrich, in which the author defines the five essential managerial functions: planning, organizing, staffing, leading and controlling.

Planning is the most basic of all managerial functions. It involves selecting missions and objectives and deciding on the actions to achieve them; moreover, it requires decision making that means choosing a course of actions from among alternatives. Planning bridges the gap from where we are to where we want to go.

Instead, the managerial function of controlling is the measurement and correction of performance in order to make sure that objectives and plans devised to attain them are being accomplished. Basic control process involves three steps: establishing standards, measuring performance against these standards and correcting variations from standards and plans.

It's important to point out that planning and controlling are inseparable. Harold D. Koontz defined planning and controlling as the Siamese twins of management or, even more realistically, as the blades of a pair of scissors; the scissors cannot work unless there are two blades. Figure 1 shows the close relationship between the two managerial functions mentioned above.

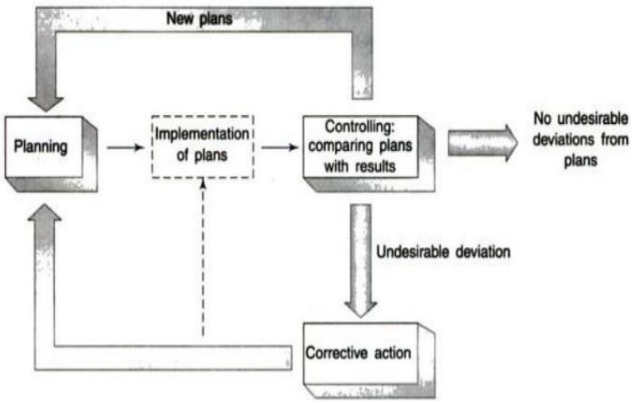


Figure 1: Relation Planning-Control (Koontz, Weihrich 2012)

1.3 Current status in the construction world

In construction, the most relevant systems used for project management (PM) and project production management (PPM) in planning and control phase are Location-Based Management System (LBMS), Last Planner System (LPS) and Critical Path Method (CPM). Until now, lots of studies from various authors have addressed these systems, mostly in isolated fashions, but no single system addresses all needs of PM and PPM.

Project Management (PM) considers the management of contracts and contractual requirements, including but not limited to the relationship between project stakeholders and their rights and responsibilities to deliver the project considering the overall requirements. PMI (2013) indicates that PM addresses five main process groups comprising the life cycle of a project: 1) initiating, 2) planning, 3) executing, 4) monitoring and controlling, and 5) closing.

Project production management (PPM) can be viewed as a subset of project management, which focuses more specifically on operations management. This includes but is not limited to production flow management and control; specifically, how tasks are defined, executed, and controlled where they are executed. PPM focuses on the resources, means and methods of production, and their organization to deliver value to the client.

The location-based management system (LBMS) is an integrated network of management system components potentially involving all stages of construction, from design through to completion. The system components are unified through their knowledge of location. Location provides the container for all project data and is used as the primary work division through a location breakdown structure (LBS), rather than the work breakdown structure (WBS) used in activity-based methods.

Critical Path Method is a planning, scheduling and control method widely used in construction projects. This method includes defining logical relationships between activities and using the CPM algorithm to identify the longest path (the critical path) through the network. It is defined as a classical activity-based method and it is widely widespread as contractual requirement.

Last Planner System considers planning and controlling as a social process focused on collaborative planning, reliable commitments, and continuous learning. The system contains five main elements (master planning, phase scheduling, look-ahead planning, weekly work plan and learning) which are used to connect the long, medium, and short-term planning levels. LPS includes a continuous learning process where every broken commitment is analyzed with a root cause analysis to ensure that the problem does not happen again.

1.4 Objective of the thesis

The goal that this final paper aims to achieve is to understand, through an in-depth bibliographic analysis of existing planning and control methods, how and if it is possible to improve the efficiency of a managerial process obviously applied to the construction world.

Given the purpose of this paper, the discussion will be divided into four sections:

- the first section, in turn divided into three parts, will focus on the theoretical explanation and methodological procedure of the three most popular planning and control methods to date, namely LBMS, LPS and CPM;
- the second section will focus on the integration in pairs between the methods listed above with the aim of trying to overcome the limits and criticalities that each method presents individually;
- the third section of the paper will focus, through two case studies created in Finland, on the practical application of planning and control processes using the LBMS method, which can be considered itself already as an improvement of CPM;
- the fourth and last section of the paper will envisage as a future development the proposal of a methodological process that simultaneously integrates all three methods previously discussed.

Chapter Two: Location-Based Management System

2.1 Definition

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. 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. 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. 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. 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.

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.

2.2 History

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. 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) 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. 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 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.

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 based on the work of Kankainen and Kiiras from Helsinki University of Technology. 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).

2.3 Operational steps

2.3.1 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.

2.3.1.1 LBS

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. 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. Visually, the LBS can be shown vertically with the hierarchies shown in columns (Figure 2).

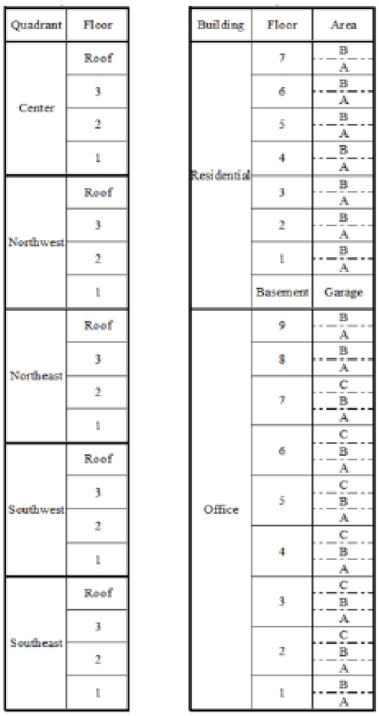


Figure 2: Location Breakdown Structure (Seppänen, Lecture at Aalto University 2020)

2.3.1.2 Task, 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. 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 phase scheduling process and LBMS (it will be shown in paragraph 5.1), 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. 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. The duration in number of shifts can be calculated using the following steps:

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.

2.3.1.3 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 3 shows a sample flowline figure.

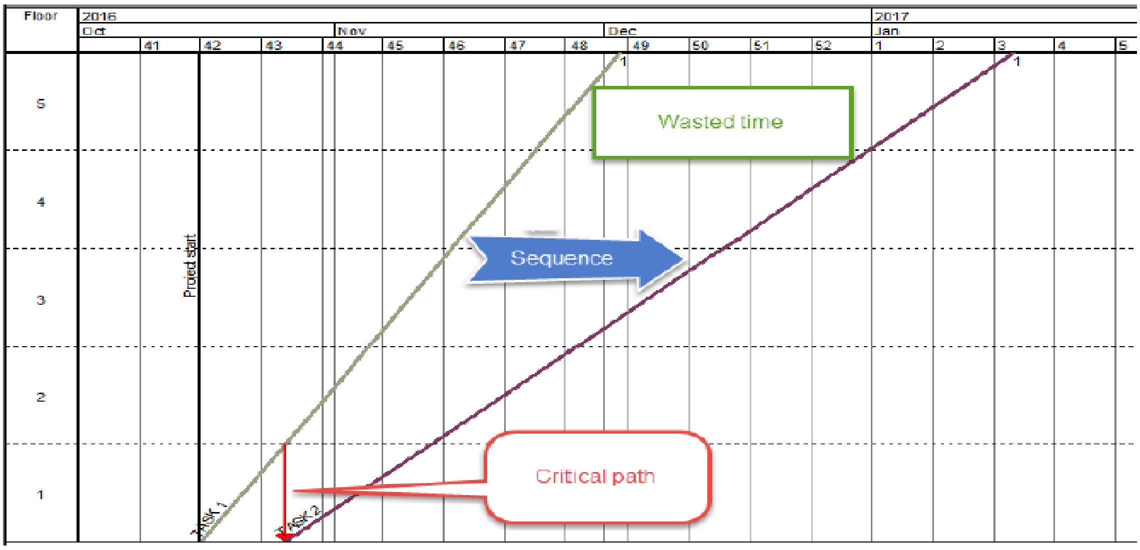


Figure 3: Flowline Visualization (Seppänen, Lecture at Aalto University 2020)

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.

2.3.1.4 Layered CPM Logic

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 in this section and after each description a flowline figure will be 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 4)

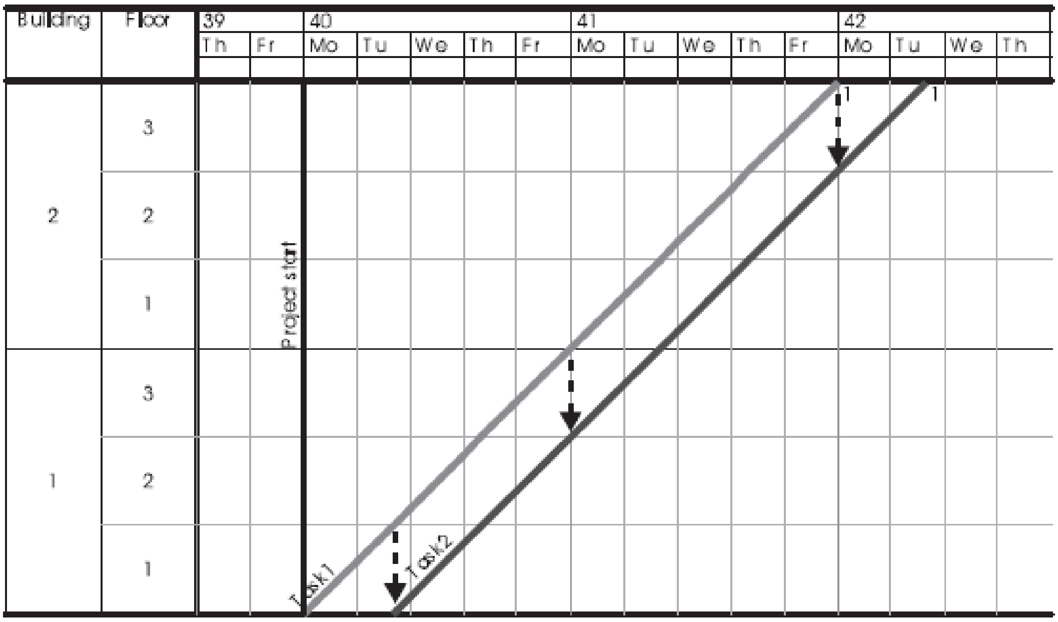


Figure 4: Layer 1 logic (Kenley, Seppänen, 2009)

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 concrete floor finishing (a task) in each building, would be a layer 2 logic link. (Figure 5)

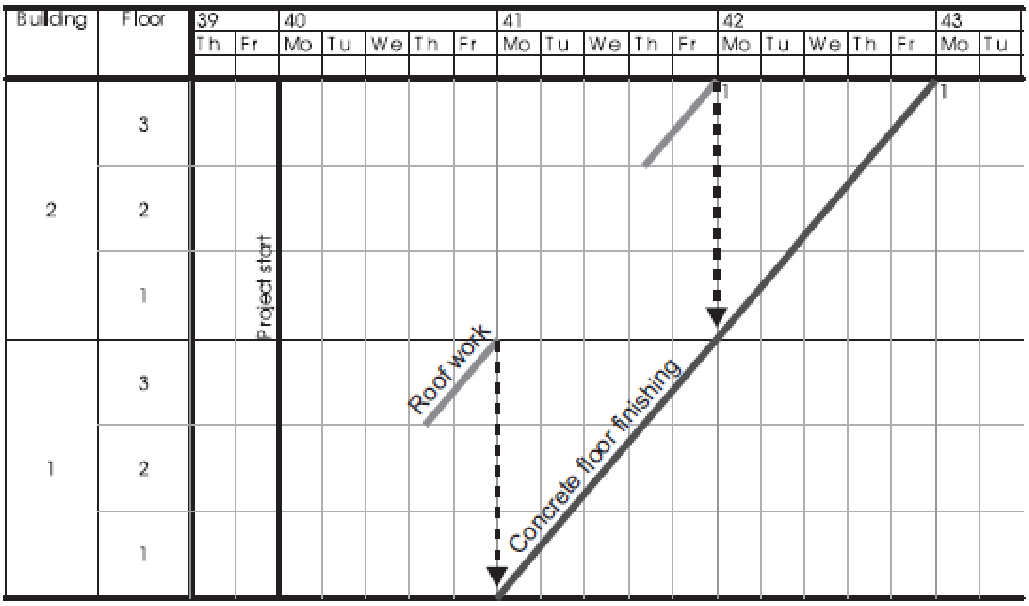


Figure 5: Layer 2 logic (Kenley, Seppänen, 2009)

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. The third logic layer is critical to the achievement of flow of resources and uninterrupted work, and thus may be considered flow logic. 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.

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 6)

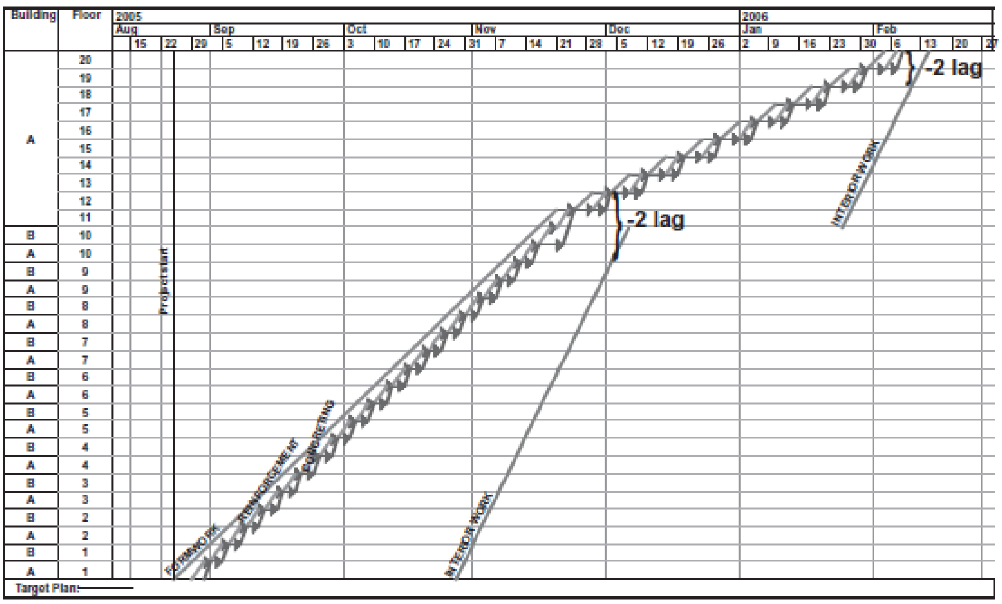


Figure 6: Layer 4 logic (Kenley, Seppänen, 2009)

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. Layered logic reduces the complexity of schedules because the same project can be modeled with much fewer links. Figure 7 shows how multiple layers of logic could be active simultaneously.

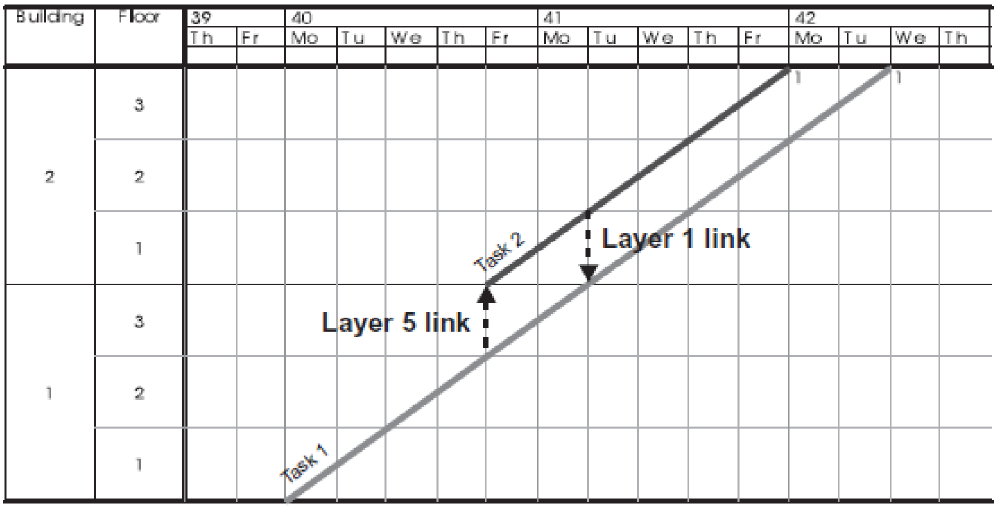


Figure 7: Layer 5 logic (Kenley, Seppänen, 2009)

2.3.1.5 LBMS Algorithm

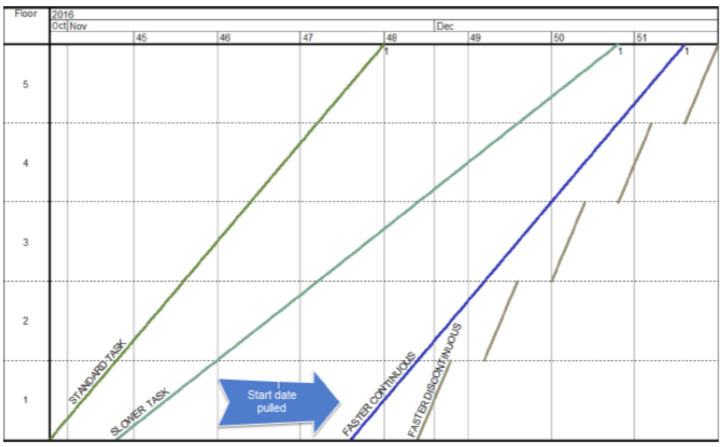


Figure 8: LBMS continuous and discontinuous tasks (Seppänen, Lecture at Aalto University 2020)

LBMS algorithm is not presented in detail in this thesis because the mathematics and the computational basis which lie behind are very complicated and needless for the dissertation. However, few information is worth mentioning. 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 8 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.

2.3.1.6 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. 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. This risk can be minimized by planning continuous work and protecting the continuous workflow from variability by adding buffers. Buffers are inserted to protect the continuous flow of critical tasks.

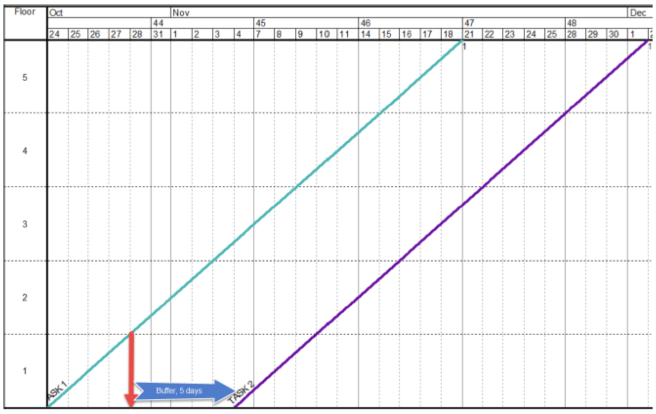


Figure 9: Buffer addition (Seppänen, Lecture at Aalto University 2020)

2.3.1.7 Schedule Optimization

The starting point for schedule optimization in LBMS is a schedule where resources have been determined for each task separately (for example by discussing with subcontractors or by using one crew for all tasks). In the initial schedule, all tasks are continuous. This will result in some trades flowing through the building slower than others. The optimization process focuses on aligning the schedule in such a way that the empty spaces are eliminated. Empty spaces can be eliminated by changing resources, changing scope, changing location sequence, splitting tasks or switching to discontinuous work. In location-based planning, improving the alignment of schedules will shorten project durations. The practical application of this theoretical paragraph will be shown in Chapter six where, through a real case study, the optimization process will lead to a substantial reduction of the project duration without compromising the constructive logic of the various construction phases. The ability to complete the building earlier by decreasing manpower is called *the location-based planning paradox.*

2.3.2 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. 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.

2.3.2.1 Status Monitoring

The basic progress monitored in LBMS focuses on four aspects:

1. Actual start and finish dates and interruptions
   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.
2. Actual quantities
   Tracking actual quantities 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. 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.

3. Actual resources

   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.

4. Actual shift length and days off

   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.

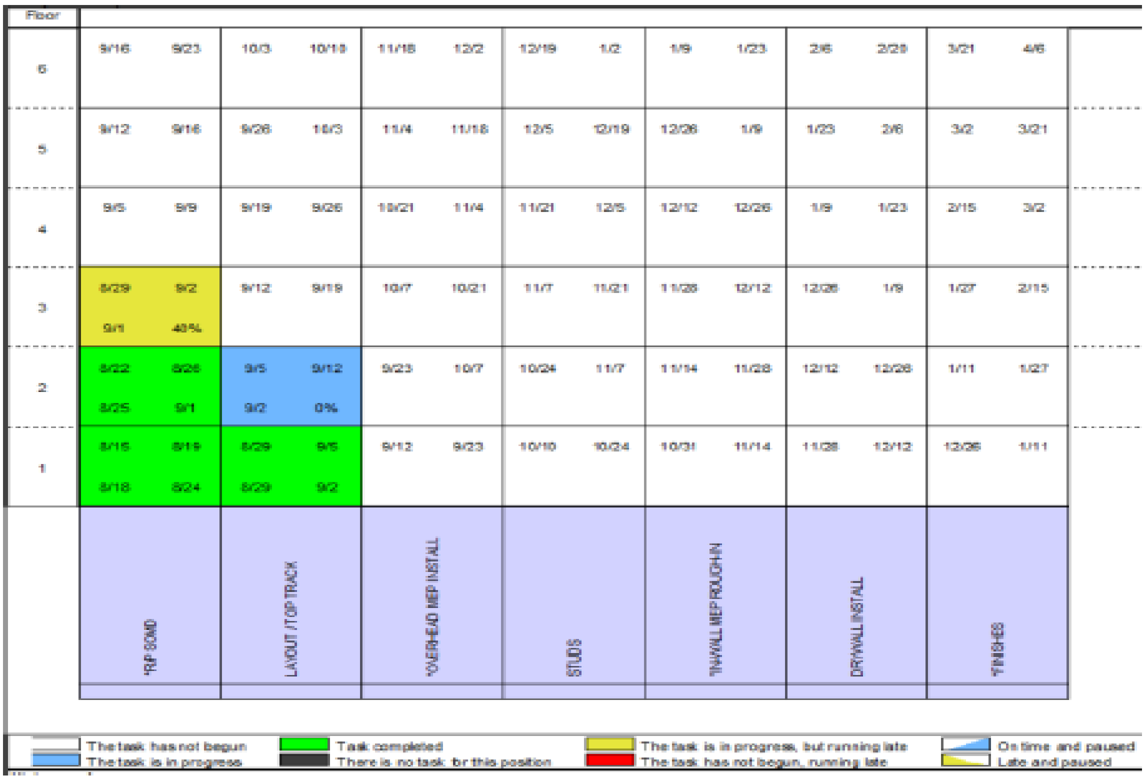


Figure 10: Control chart (Seppänen, Lecture at Aalto University 2020)

2.3.2.2 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. Alarms appear as red dots in figure 11.

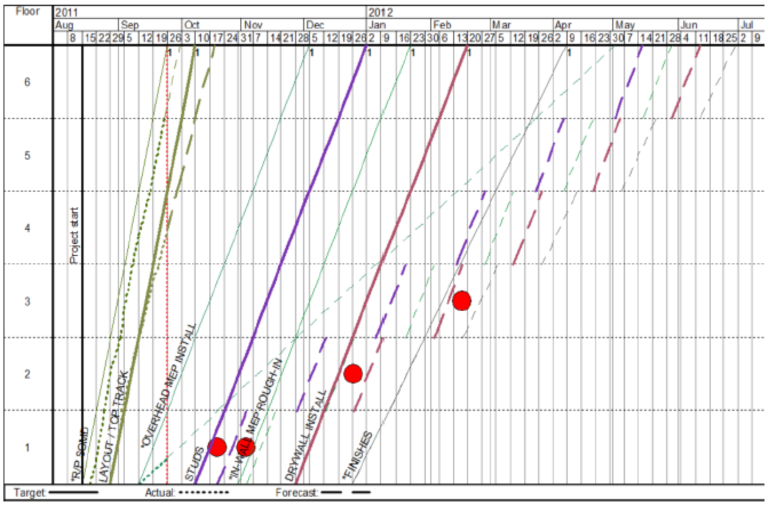


Figure 11: Forecasting and alarms (Seppänen, Lecture at Aalto University 2020)

The importance of forecasting in LBMS method will be deeply discussed in paragraph 2.4.

2.3.2.3 Planning control action

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. Figure 12 shows the three different types of lines.

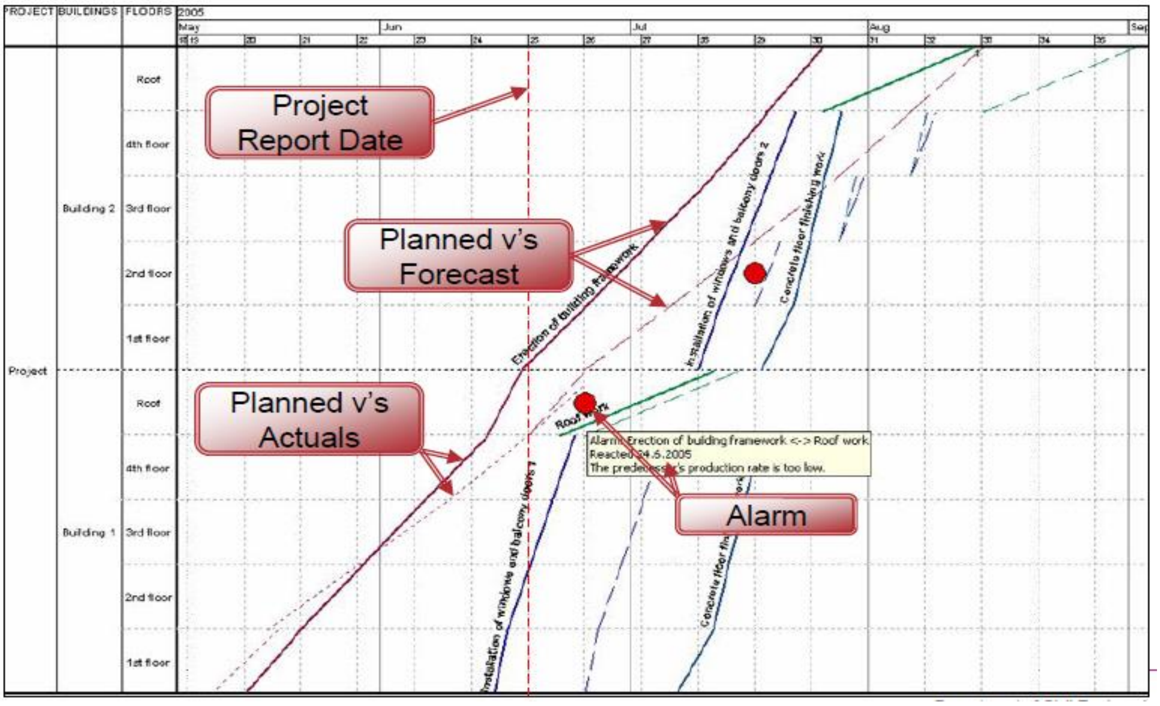


Figure 12: Planned, actuals and forecasted lines (Seppänen, Ballard, Pesonen, 2010)

2.3.2.4 Cascading Delays

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.

2.4 Forecast

As anticipated in paragraph 2.3.2.2, this section of the thesis is dedicated to the importance of the schedule forecast in the LBMS method. LBMS forecasts are used primarily to predict upcoming problems and to allow management to take early action when actual production rates do not meet the target rate. Forecasts do not become the new plan or the new target. Instead, production managers should take control actions to beat the forecasts and prevent them from becoming reality. LBMS forecasts are based on actual resource consumption (manhours / unit) achieved close to the time of calculating the forecast (recent events are given more weight). This resource consumption is combined with forecasted resource information (either from the plan or from the control plan if one has been used). The duration of all upcoming locations of the same type of work is calculated by using this resource consumption value. Impacts to other tasks are calculated using the logic network.

This paragraph of the thesis is based on Seppänen, O., Evinger, J., & Mouflard, C. (2013) in which authors evaluated the accuracy of LBMS forecasts by analyzing two hospital construction projects and comparing forecasts to actual progress. Their hypothesis was that the forecasts would be more accurate in the short term for continuous production of similar work. They expected the forecasts to fail if there were a lot of problems with starting constraints, lot of starts and stops, if work was performed out of sequence or if work was not fully completed before moving to the next location. Forecasts were evaluated in terms of total quantity completed, manhours consumed and sequence of work.

The two case study projects analyzed by the authors followed a different management philosophy. Project 1 tried to use LBMS, forecasts and the Last Planner System (the method will be widely descripted in Chapter 3 and the integration between LBMS and LPS will be presented in paragraph 5.1). Project 2, instead, used LBMS for owner-reporting only and did not utilize the forecasts for decision making managing the project conventionally without the use of lean tools. Both projects were hospital construction projects in California and the number and scope of tasks was similar between the projects. The schedule forecasts were evaluated for tasks at four time points looking forward one, two, three and four weeks. These forecasts were compared to actuals of the same time intervals. The tasks were selected based on a series of specific requirements and, after the collection of actual data at the same time steps, data was compared to the forecast actual labor consumption, actual production rate, actual resources, number of location completed, percentage of correct location completed and percentage of correct location worked. The following list shows the conclusion achieved:

1. Tasks with continuous workflow were best forecasted by LBMS forecasting method: LBMS forecast had difficulties with tasks that happened out-of-sequence, had starts and stops or that started ahead or after forecast;
2. Forecasts are inaccurate if labor consumption is highly variable, resources are not mobilized according to plan, or work happens out of sequence;
3. Technical forecast of LBMS worked better in longer term (cumulative 4 weeks) than in short term: this finding is important because the Last Planner System aims to improve the reliability of weekly work plans, targeting the next week in particular. The combination of these two methods will be proven in Chapter 5 to be proven able to improve both short-term and longer-term forecasting on projects;
4. Forecasts were too optimistic in the conventionally managed Project 2 where the focus was on starting as early as possible instead of focusing on finishing work: It can be argued that Project 2 had reached a chaotic, unpredictable state where continuous workflow could not be recovered without radical re-planning;
5. Forecasts can be used by Last Planners as a tool for lookahead and weekly planning purposes in projects where workflow is still predictable and work is mainly continuous.

2.5 Social Aspects

Up to now, the discussion has analyzed only the technical part of the LBMS method, trying to explain the key components, processes and mechanisms that distinguish the method itself. This section of the thesis, on the other hand, will no longer focus on the methodological and operational aspect of the Location Based Management System, but wants to focus on the behavior of the main actors in the realization of a project: specifically, this paragraph will be focused on explaining what happens in daily project management (traditional work management behavior) in relation to what should happen (expected LBMS behavior). The key to comprehend the social aspects of implementation of a new method is to understand the behaviors of key stakeholders: subcontractors and superintendents.

To better understand this relationship, the paragraph will take inspiration from Freeman, Seppanen (2014).

2.5.1 Traditional Subcontractor Behaviours

The interest of subcontractor in a generic traditional project can be explained by a legitimate desire to focus resources on profitable and predictable project. However, fulfilling this desire often comes at the expense of other subcontractor's productivity and damages the project as a whole. In particular, the authors have identified three main subcontractor behaviors:

- Starting work and ramping up of resources: general preference to start work slowly to minimize costs while identifying problems and learning the project. Subcontractors prefer to send a small number of resources to learn the project, identify problems which could block efficient workflow and prove whether work can be efficiently performed. Subcontractors prefer to increase project resources only when the initial crew has prover work can be done efficiently.
- Developing excuse backlogs for potential claims: subcontractors start building an "excuse backlog" as early as possible. They look for problems that can be used as an excuse for delay and store them until needed. The probability of claim is increased when the targeted profitability is at risk. Subcontractors will more aggressively use the excuse backlog or look for additional problems when their targeted profit is damaged due to delays for poor estimating.
- Maximize cash flow: in order to optimize cash flow, subcontractors like to complete the easiest and most valuable work in multiple location first. To achieve this goal, multiple crews can simultaneously start multiple locations. Although this behavior does increase the value of work put in place, it results in multiple unfinished locations. Moreover, this behavior creates a ripple effect causing cascading delays to the project and greatly decreasing the ability of downstream subcontractors to work efficiently because the critical path is often impacted when overall efficiency continues to devolve.

2.5.2 Traditional Superintendent Behaviors

The primary interest of a superintendent is to minimize the risk on the project he is responsible for. Superintendents combine a focus on high-level planning and a focus on problems as they arrive. Their actions are based on a combination of intuition and experience fed by direct observation with limited trust in planning tools. In particular, the authors have identified four main superintendent behaviors:

- Start as soon as possible with large labor force: superintendents prefer for subcontractors to start work on the first day predecessors could reasonably be expected to finish even if the early start is likely to prevent continuous labor flow and to start with as many resources as possible. Superintendents prefer for subcontractors to start with a large labor force and only reduce resources when it is proven they are not required.
- Focus controlling on dates: superintendents are focused on making dates, not on achieving efficient production. Productivity is a secondary consideration that is the primary responsibility of the subcontractors. Superintendents focus the majority of their time on activities that are critical or near critical with less focus on making sure other activities are moving along.
- Intuition and experience: superintendents make most decisions based on intuition fed by experience. At the beginning of their career, when they lacked experience, they would have preferred to have good data to inform their decision making, but it was rarely available. Over time, they gained experience and could make a reasonable decision based on intuition with increasing frequency. As a direct consequence of this superb behavior, superintendents do not have faith in planning tools. Decision making is based on direct observation of the state of the site. All of these results in a large percentage of time is spent on reactionary behavior preventing a focus on future problem prevention.
- Omniscience and omnipotence: this behavior is strictly linked with the previous one. Superintendents must convey omniscience and omnipresence to the owner because he wants a superintendent that has always complete control over the project. Due to this constant reminder, superintendents have adopted

overconfidence as an everyday attitude and they have falsely come to believe they actually do hold knowledge of all project aspects.

2.5.3 Impact of both parties behaving traditionally

The following table 1 shows the cause-effect chain in a traditional project: it is shown how actions taken both by superintendents (SI) and subcontractors (SC), if they behave traditionally, impact on the whole project:

N°	Causes	Effects on the project
1	SI forces SC to use max resources SC wants to start with small crews	Initial contrast
2	SC wants to maximize billing by working on easiest activities	Downstream subcontractors cannot complete work in locations where their predecessors are partially complete
3	SI looks for available works in order to keep SC on site SC works in location other in which they were scheduled to work	SC interfere with other trades scheduled to work in those locations
4	SC bounces people between sites in attempts to increase enterprise wide billings	Resource levels fluctuate frequently
5	Resource levels fluctuate frequently	New resources brought on site have low efficiency
6	Presence of more subcontractors on site Increasing site management difficulty	Labor efficiency diminish
7	Labor efficiency diminish	Project completion date slip
8	Project completion date slip	Accelleration charges and expansion of working hours, more shifts, more days or more resources
9	Increasing inefficiency Erosion of contractor profitability	Claims requesting more money

Table 1: Superintendents and subcontractors behave traditionally (elaboration of the author)

Throughout years, both superintendents and subcontractors have developed a way of working that best suits their specific interests while defending against the interest of the other party. Each party has developed an optimized process based on the management tools they have available and their expectations of the degree of cooperation they will receive from the other party.

2.5.4 Desired LBMS Subcontractor Behaviors

In the planning phase, subcontractors in LBMS projects should participate collaboratively in planning and optimizing the schedule. Participation means agreeing on a common Location Breakdown Structure, pull planning to get a list of tasks and their relationship and providing quantities, production rates and labor consumption rates for each identified task. During construction, subcontractors are expected to self-report their actual progress by location in daily reports, giving f.i. information on the percentage of work completed, actual resources on site or any suspension of work. Operationally, subcontractors are expected to complete one location completely prior to moving to the next scheduled location. The ultimate goal is to perform work as productively as possible without interfering with other subcontractors.

2.5.5 Desired LBMS Superintendent Behaviors

A good LBMS implementation requires data-driven decisions for starting new tasks and for taking control actions regarding currently ongoing tasks: in general, a new work should start only if the project is ready to accommodate additional resources, not just because it had been planned to start on a specific date. It is required a continuous and proactive control by the superintendent in order to identify any potential issue and solve it ahead of production. Production rates should be actively monitored and any deviation which results in a production alarm should trigger an immediate control action collaboratively with the subcontractor. Another important superintendent behavior include not allowing subcontractors to interfere with each other, planning meticulously the work flow in a logical sequence to minimize confusion.

2.5.6 Impact of both parties implementing desired LBMS Behaviors

Freeman, Seppanen, (2014) has supported the implementation of LBMS approach listing results achieved and data from various projects reported by other authors. Seppanen (2009) reported an opportunity to compress project duration by 10% by eliminating cascading delays. Evinger et al. (2013) found that, comparing two different floors on the same project managed in two different ways (CPM and LBMS), the floor managed with the LBMS approach had 18% higher productivity. Seppanen at al. (2014) reported that control actions were able to prevent production alarms from turning into problems 50%

of the time and the control actions resulted in an average increase of 37% of production rates.

Among the benefits associated with the LBMS implementation in a project in which all stakeholders have open-minded and collaborative behaviors, there is also an increase in the reliability of schedules, a materialization of fewer production problems and a general improvement in productivity.

The benefits of LBMS can only be fully achieved in the context of superintendents and all subcontractors simultaneously changing their behavior. In order to make all parties more open to learn how a different approach could work, it is absolutely necessary to create a climate of trust and confidence in the others. The real challenge consists in educating all parties on how the new system and a new set of behaviors could better protect their own interests and improve the project as a whole.

.

Chapter Three: Last Planner System

3.1 Definition

The Last Planner System is a comprehensive “pull” system for the optimization of the planning and the execution of construction work. It includes a cooperative planning process as well as an analysis of incorrect planning. This achieves excellent cooperation in the production process and establishes a sound basis of trust, which is a necessity for the on-time completion of the project. The project planning of the LPS is divided into two different stages, the long-term planning stage and the short-term planning stage. The long-term planning phase consists of the Master Schedule and the Phase Schedule, which are adjusted as needed to specify what should be done. The Lookahead Plan bridges the gap between long-term project planning and short-term execution planning. The goal of the Lookahead planning is to make plans more realistic as construction tasks approach execution, exposing as many problems as possible, as early as possible. The Lookahead Plan is used to decompose activities from phase level to operations level. The Commitment Plan, also known as the Weekly Work Plan (WWP), specifies the individual work steps that will be done, as well as the interdependences between the various contracting parties. To ensure the reliability of the Commitment Plan, the tasks must meet the following four quality criteria: definition, soundness, sequence, and size. Finally, the phase of Learning describes the completed work. It is considered as a tool for future planning optimization by tracking the performance of the short-term planning process to improve the productivity and efficiency of the project.

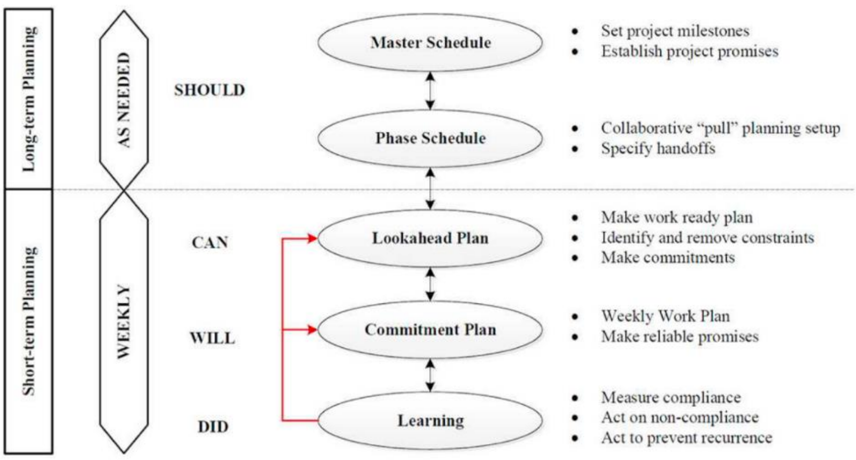


Figure 13: Last Planner System structure (Heigermoser et al. 2019)

3.2 History

The following figure 14 shows the synthetic but extremely effective timeline of Last Planner System development throughout years. The development process started in early '90s with the research made by Glenn Ballard and Gregory Howell on industrial construction sector and production management systems. The LPS method was first fully presented in 2000 in Ballard's doctoral thesis for the University of Birmingham's Faculty of Engineering. Since then, Ballard himself and numerous other authors have focused their attention on LPS' applications and integrations.

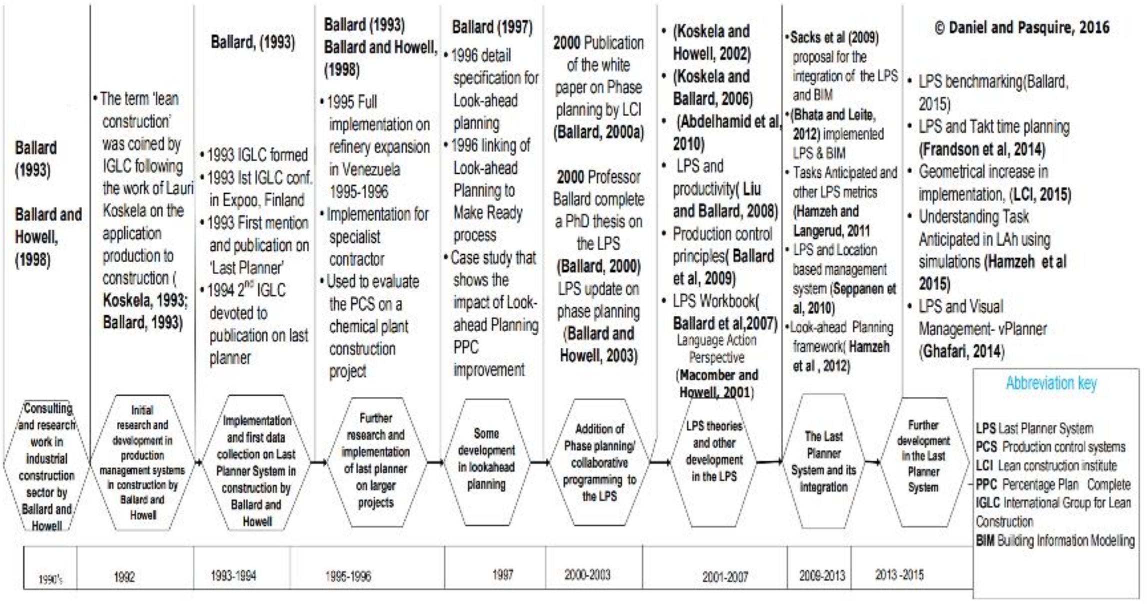


Figure 14: LPS historical development (source https://s3-us-west-2.amazonaws.com/leanconstructionblog.com/Last-Planner-Timeline.pdf, Daniel and Pasquire, 2016)

3.3 Operational steps

3.3.1 Assignments

Before starting with the explanation of the various phases of the LPS, it is important to explain the fundamental unit of the system developed by Glenn Ballard. Aside from the simplest and smallest jobs, design and construction require planning and control done by different people, at different places within the organization, and at different times during the life of a project. Planning high in the organization tends to focus on global objectives and constraints, governing the entire project. These objectives drive lower level planning processes that specify means for achieving those ends. Ultimately, someone (individual or group) decides what physical, specific work will be done tomorrow. That type of plans has been called "assignments". They are unique because they drive direct work rather than the production of other plans. The person or group that produces assignments is called the "*Last Planner*". The term "assignments" stresses the communication of requirements from Last Planner to design squad or construction crew. But these products of planning at the production unit level are also commitments to the rest of the organization. They say what WILL be done, and (hopefully) are the result of a planning process that best matches WILL with SHOULD within the constraints of CAN

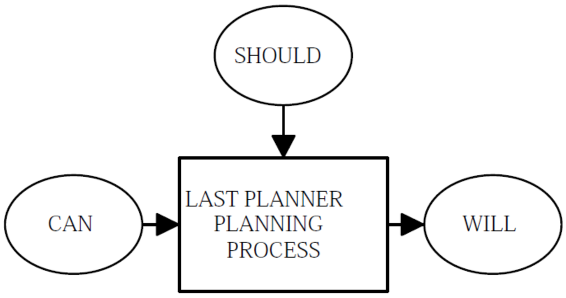


Figure 15: Can, Should, Will relationship (Ballard 1994)

3.3.2 Master Schedule

Master scheduling is the first process in front-end planning and it translates the owner's value proposition into a master schedule describing work over the entire duration of a project. It involves project-level activities mostly in relation to contract documents. These high-level activities describe milestones, which in turn define project phases. Master scheduling starts by translating the owner's values and purposes (value preposition) into work plans and execution strategies which are expressed in project level activities. The dialogue between the owner's values and work strategies produces the foundation for setting project milestones. After identifying major milestone dates, Critical Path Method (CPM) logic is used to determine overall project duration. CPM logic can be represented in different forms including Gantt, PERT (Program Evaluation Review Technique), and line of balance diagrams. The

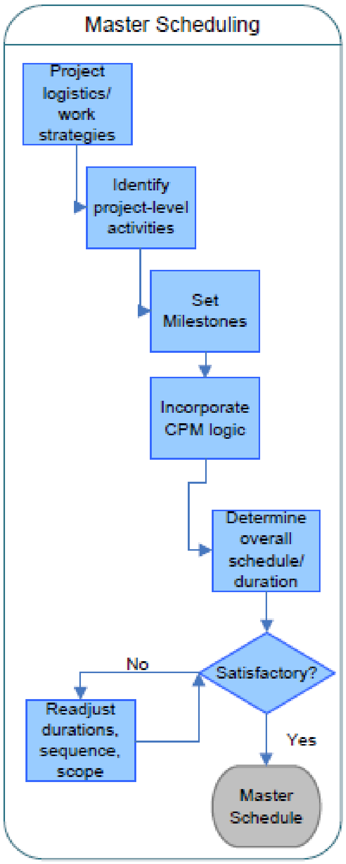


Figure 16: Master Scheduling structure (Hamzeh 2009)

calculated project duration and the timing of milestones are checked against the owner's expectations. If found unsatisfactory, alternatives or adjustments to the original schedule in terms of duration, sequence, or scope are introduced and re-planning performed until a satisfactory schedule is developed. When project stakeholders are engaged early in the project, as when employing integrated project delivery, it the master schedule can be developed collaboratively incorporating feedback from project parties who have already been engaged in the project at that stage.

3.3.3 Phase Schedule

The purpose of phase scheduling (also called pull scheduling) is to produce a plan for meeting a milestone or completing a phase while maximizing value generation and establishing support from project stakeholders. Scheduled activities are then drawn from the phase schedule into the lookahead process, broken down into operations, and made ready for execution in weekly work plans.

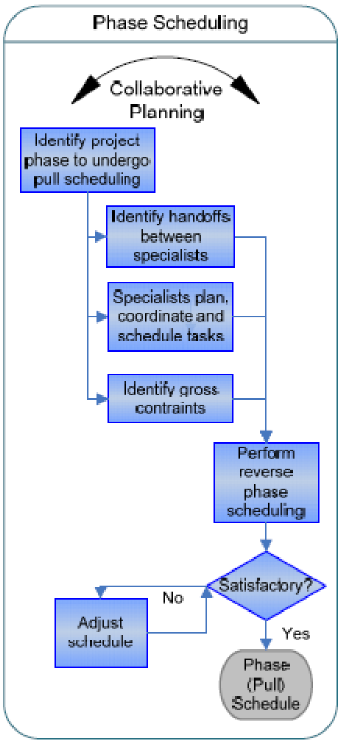


Figure 17: Phase Scheduling structure (Hamzeh 2009)

Linking work structuring to production control, phase scheduling produces a phase schedule communicating handoffs and goals to which to steer production. In a collaborative planning setup, the phase schedule identifies handoffs between project parties and employs reverse phase scheduling to find the best way to meet milestones shown on the master schedule. Phase scheduling often results in introducing adjustments to original CPM logic as needed to meet project goals. On large and complex projects, the master schedule includes many milestones and high-level tasks that express project phases. Figure 17 shows that the first step in master scheduling is identifying milestones delimiting phases that must undergo collaborative pull scheduling. Phase or pull scheduling is a collaborative process that a team can use to plan the delivery of a phase of work (to plan the accomplishment of a schedule milestone) according to customer pull or value expectations.

Pull scheduling works backwards from a target completion date. Tasks are defined and sequenced to release work to downstream tasks when they are requested/pulled, thus achieving a handoff. Pull scheduling works backwards from a target completion date to eliminate work that may not add value and reducing the waste of overproduction.

When identifying phases to undergo phase scheduling, it is essential to align the perspectives of various project partners unifying the team’s expectations to what value needs to be delivered when executing this milestone. This step, called milestone alignment, starts by identifying deliverables or outcomes of value to downstream customers, followed by expressing and communicating the conditions of satisfaction for the outcome to be delivered by a partner upstream to another project partner downstream. Conditions of satisfaction result from negotiations/discussions between the parties. Setting tough time-targets often encourages such negotiations/discussions. Milestone alignment results in a better understanding of the milestone to be pulled, a date to pull to, and a set of handoffs between various specialists.

Collaborative or team planning engages representatives of all project stakeholders involved in a project phase. With handoffs or deliverables identified, team members begin team planning by writing on sheets of paper:

1. Brief description of work they must perform;
2. Expected duration;
3. Resources employed;
4. Previous work to be completed by others to release work to them.

It is recommended that the meeting participants prepare for the meeting by reviewing their work scopes and developing a preliminary work plan. The team then arranges the sheets on a wall in their expected sequence of execution. This exercise encourages team coordination as planning breaks out in the room and team members start developing new network paths, devising new methods, negotiating sequence, and considering different batch sizes.

The next step is reverse phase scheduling, starting from the milestone and moving backwards towards the start. Backward scheduling is helpful in uncovering constraints when team members have to think of prerequisites required to start an activity. It is crucial at this stage to start uncovering gross constraints that impact a phase or a process within a phase.

While the phase schedule is developing, network logic is often readjusted, and task durations altered to find the best way to meet the milestone or phase undergoing phase scheduling. A phase may be decomposed into interim milestones that can be used in pull scheduling (e.g. structure as a phase can be broken down into many interim milestones such as ‘first floor’, ‘second floor’, etc.).

The resulting reverse phase schedule may take one of three possible forms:

1. a schedule that does not meet the allotted time frame
2. a schedule that fits the time frame tight
3. a schedule that contains some float.

The schedule that results from backward pass process is satisfactory only when the scheduled tasks fit within the available time, with sufficient float to buffer critical and variable tasks. First attempts often do not meet time limits, as in the example shown in Figure 18 much less provide a schedule buffer; so, re-planning is required.

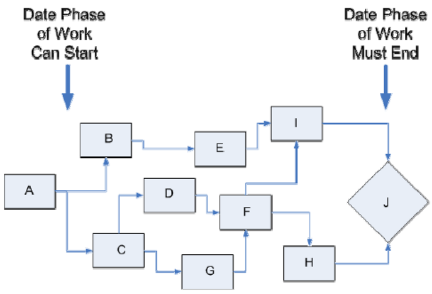


Figure 18: Reverse phase scheduling (Hamzeh 2009)

To create an acceptable buffered schedule, the project team analyzes the network for possible changes in logic or task duration. The team may generate several ways to shorten time including:

1. starting more tasks in parallel (a matter of reducing the handoff batch size)
2. allocating resources differently
3. applying new methods or technologies.

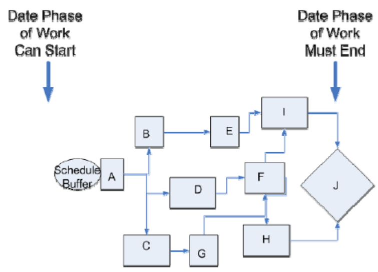


Figure 19: Adjusted reverse phase scheduling (Hamzeh 2009)

Figure 19 shows an example of an adjusted reverse phase schedule creating a schedule buffer.

Once an acceptable schedule is created, the team then has to decide how to allocate this time. Many options are available for the team to explore including:

1. allocating buffer to certain activities, usually activities with high uncertainty (as shown in Figure 20);
2. using the buffer in the beginning (delaying the start);
3. bringing the phase completion date forward.

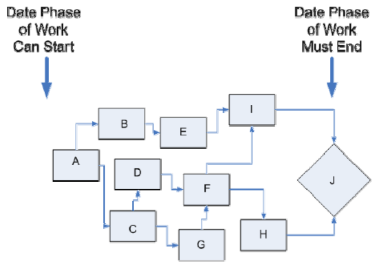


Figure 20: Reverse phase schedule after schedule buffer (Hamzeh 2009)

Although the goal of phase scheduling is to find the best way to meet a milestone or accomplish a phase, sometimes this is not possible and in this case the phase completion date can slip out. The goal of phase scheduling is to generate a schedule that all project stakeholders buy into, define handoffs between specialists for control without going into too much detail, introduce required adjustments to CPM logic, and produce an executable schedule agreed on before the start of phase.

3.3.4 Lookahead Plan

Lookahead planning is the first step in production planning and provides a link between the project schedule and short-term commitments. It starts with generating a lookahead view from phase schedule and continues to weekly work planning. However, as Figure 21 shows, lookahead planning means not just viewing near-term tasks from the master or phase schedule and possibly detailing them; rather, it is a process that involves:

1. breaking down tasks into the level of processes/operations;
2. identifying and removing constraints to make tasks ready for execution;
3. designing operations through first run studies.

Lookahead planning is an essential process in production planning and control. It:

1. shapes the sequence and rate of workflow;
2. links master and phase schedules to weekly work plans;
3. shields downstream tasks from uncertainty in upstream tasks;
4. sizes workflow to match capacity and constraints;
5. produces a backlog of workable activities by screening and pulling.

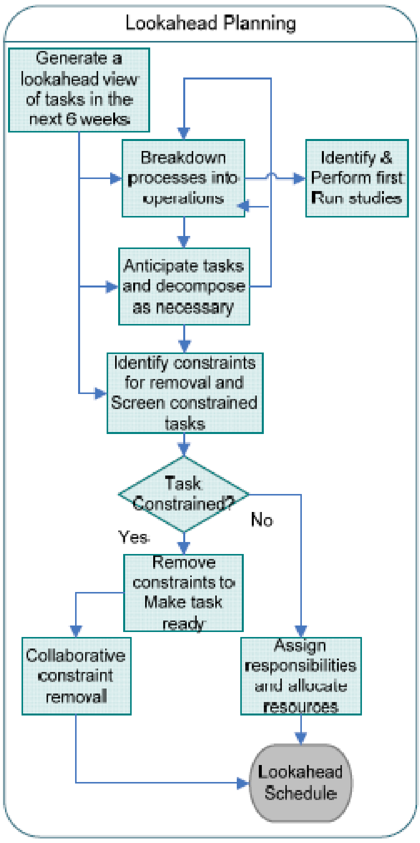


Figure 21: Lookahead Planning structure (Hamzeh 2009)

Screening submits tasks to constraint analysis to identify actions needed now to make scheduled tasks ready, so that they can be performed when scheduled, and to prevent commitment to tasks that cannot be made ready. Typical constraints are contracts, change orders, requests for information, design instructions, materials, predecessor tasks, labor, equipment, and space.

Pulling dictates which tasks to make ready by removing constraints and ensuring the availability of prerequisites as per actual site demand. While pulling is built into the schedule that lookahead planning should start with, it is also present in the LPS rule that no tasks are to be imposed on work groups unless they are ready to perform them.

Lookahead planning starts by filtering a schedule that looks several weeks, most commonly six, into the future.

1. Six weeks ahead of execution. Tasks enter the six week lookahead plan from the phase schedule. At this stage, gross constraints are evaluated and a plan for removal is devised. Gross constraints are those that impact all instances of phase-level tasks and processes, i.e. to every operation that belongs to that type of process.

An example is the production of fabricated items such as precast concrete panels. This process involves several operations: detailing, fabrication, and delivery. Fabrication is one operation in this process and will recur many times. For construction, typical gross constraints are materials and design information. Phase scheduling can act as a catalyst for identifying handoffs and gross constraints early on. Although removing constraints can take place anywhere within the six weeks on the lookahead plan, it is desirable to remove constraints two to three weeks prior to executing a task.

2. Between five weeks and four weeks ahead of execution. Activity break down starts by decomposing tasks into their elements, moving from processes to operations (projects consist of phases, phases of processes, processes of operations, operations of steps, and steps of elemental motions). Elemental motions are not represented in current forms of the LPS, although they may be appropriate analytical units for design of highly repetitive tasks executed under controlled conditions. Steps are defined in the design of operations and assigned to individuals or sub-teams within work groups.

Activity breakdown goes in parallel with defining operations, sequencing work in the most optimal way, coordinating tasks among project stakeholders, loading operations with resources, sizing load to match capacity, and analyzing tasks for soundness so that prerequisite inputs are ready such as previous work, information, material, labor, and space.

3. Three weeks ahead of execution. By this time the team should have designed operations through first run studies, developed detailed plans for work execution, and screened out those tasks they are not confident can be made ready in time. A first run study is an actual performance of an operation for the first time in order to try out, study, learn, and improve the method to execute an operation. It involves understanding the work involved, the skills and resources needed, and the interactions with other operations. The process involves evaluating the devised plan, launching refinements, and establishing standardized work. Potential operations requiring first run studies are those that are new, critical, or repetitive.

4. Two weeks ahead of execution. Lookahead plan activities are broken down and detailed as they move closer to execution. Accordingly, when activities are two weeks away from execution, they will match the detail required for production at the weekly work plan level. The level of detail in planning is time driven. It may be planning to the day, to the shift, or to the hour (e.g. planning of shutdown operations). Tasks that are constraint-free join the workable backlog (backlog of workable or ready tasks). Tasks on the workable backlog may be selected to join the weekly work plan if they meet the quality criteria as discussed next.
5. One week ahead of execution. At this stage, a provisional weekly work plan is prepared according to quality criteria of definition, soundness, sequence, size, and learning. Tasks that are critical, made ready, or can be made ready in the upcoming week are incorporated in the weekly work plan within available capacity. Made ready and non-critical tasks are placed on the fall back / follow on work list to be performed in case of extra capacity, either from completing critical tasks sooner than expected.

3.3.5 Commitment Plan (Weekly Work Planning)

Commitment Plan (most commonly known as Weekly Work Planning) is an extension of lookahead planning into the execution week. It represents the most detailed plan in the LPS and directly drives production. It is the level at which promises and commitments are made. In phase scheduling, team members are committing to do their best. In lookahead planning, team members are doing all they can to remove constraints. In weekly work planning, team members are committing to doing their tasks. Plan reliability at the weekly work planning level is promoted by making quality assignments and reliable promises to shield production units from uncertainty in

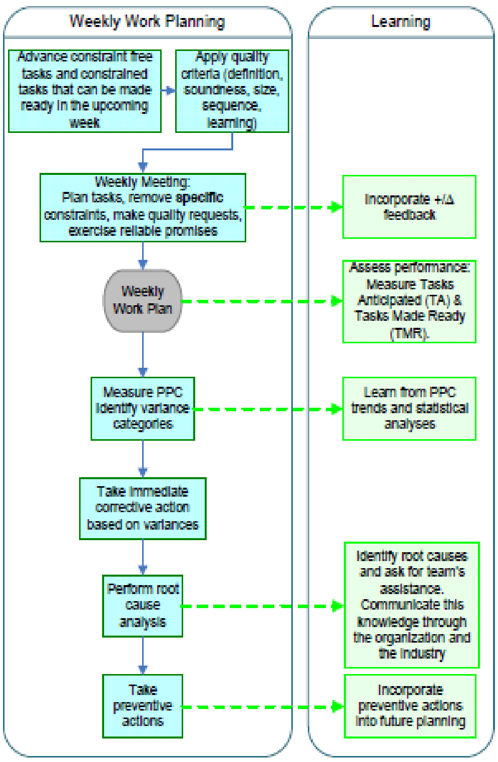


Figure 22: Weekly Work Planning and Learning (Hamzeh 2009)

upstream tasks. At the end of each week, reliability is assessed by measuring the number of assignments completed relative to the number of assignments planned. For tasks that are not accomplished, analyzing the reasons for plan failure and acting on these reasons is used as a basis for learning and continuous improvement.

Weekly work planning involves:

1. advancing tasks that are well defined, constraint-free, in proper sequence, well sized (in terms of load and capacity);
2. performing collaborative weekly work planning to remove constraints for constrained tasks;
3. exercising reliable promising;
4. learning from plan failures.

As figure 22 shows, weekly work planning starts by advancing both tasks that are ready (constraint-free) and tasks that can be made ready during the course of the week. Capacity permitting, constraint-free critical tasks are given the first priority followed by critical tasks that are constrained but can be made ready during the week. Critical tasks that cannot be made ready are screened out of weekly work plans to shield production from executing tasks that are not ready. These tasks will be evaluated in the upcoming weeks and are given priority in removing their constraints. At this stage noncritical tasks that are not ready are also screened out while constraint-free critical tasks are incorporated on the fallback / follow-on list to be executed when having extra capacity.

It is desirable to advance to the weekly work plan only tasks that make quality assignments. Quality assignments are measured against five main quality criteria:

- definition: a task should have a clear scope and desired outcomes;
- soundness: planned tasks should be constraint-free or can be made constraint-free during the plan period;
- sequence: arrange tasks in the proper sequence and avoid out-of-sequence work;
- size: match load and capacity (e.g. match the workload placed on individuals, sub-teams, or work groups with their actual capacity);
- learning: use root cause analysis to continuously improve the quality of assignments.

Then, next week's work plan is discussed, coordinated and finalized during a collaborative weekly work plan meeting involving project stakeholders. This meeting enables last planners (i.e. team leaders responsible for production teams) to discuss constrained tasks, make requests to remove constraints, and make activities ready by removing constraints. Last planners make quality requests to remove constraints and quality commitments to next week's work tasks.

3.3.6 Learning

Learning takes place during various steps of the process:

- attending collaborative meetings;
- analyzing performance metrics;
- monitoring trends in weekly work planning;
- identifying root causes for plan failures and incorporating actions to prevent the repetition of plan failures.

Learning and continuous improvement can be captured during collaborative meeting by using the '+/Δ' method where last planners share with the team what steps they consider add value to the process (+) and what steps need to be improved (Δ). '+/Δ' sessions can be very helpful in uncovering deficiencies, surfacing hidden issues, and generating improvement ideas.

Monitoring and analyzing performance metrics such as PPC (Percent Plan Complete), Task Anticipated (TA) and Task Make Ready (TMR) can provide important insights into the team's performance in terms of communication, coordination, collaboration and commitments.

$$PPC = \frac{Completed\ tasks}{Planned\ tasks} * 100\% \qquad TMR = \frac{Tasks\ ready\ for\ next\ week}{Total\ tasks\ for\ next\ week} * 100\%$$

$$TA = \frac{Tasks\ planned\ for\ next\ week\ on\ previous\ plan}{Total\ tasks\ for\ next\ week} * 100\%$$

Monitoring trends in weekly work plans such as percentage of repeated tasks, percentage of work executed but not planned, and number of constraints, can indicate areas that need further improvement. While PPC reports the team's performance and plan failures, it does not necessarily give indications to actions that the team needs to take to prevent the recurrence of failures.

In order to uncover these preventive actions root cause analysis is used and understanding the root causes behind plan failures means using the ‘five why’s’ method. It involves asking “why” many times in succession until a root cause(s) is found where an action can be taken to prevent the failure from happening again. An example of the ‘five why’s’ method is used and documented graphically in the following figure 23:

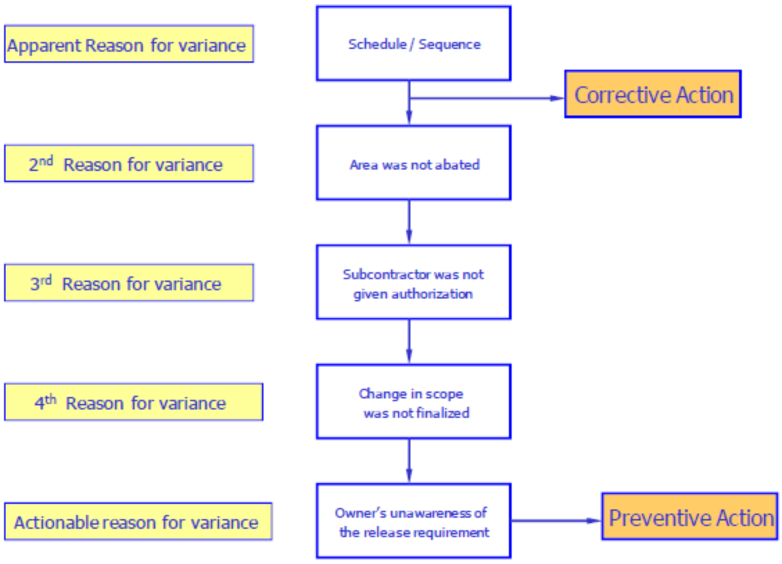


Figure 23: Five why's method (Hamzeh 2009)

Asking the question “Why did the sequence / schedule variance occur?” uncovers area abatement as a prerequisite work required to take place prior to commencing lay out. Posing the question “Why was abatement not completed?” directs us into looking at the work of the subcontractor responsible for this activity. Again asking “Why didn’t the subcontractor receive authorization?” exposes the process of releasing a change order covering the abatement works. Once more asking “Why wasn’t the change order finalized” reveals the owner’s unawareness of the importance of this release especially that the release does not show as a constraint in schedule. A corrective and a preventive action can be taken at this level. Root cause analysis should be accompanied by corrective and preventive actions. The corrective action entails devising a quick recovery plan to mitigate the failure or variance. The preventive action which comes after performing root cause analysis should be incorporated into "lessons learned" to make sure the same type of failure does not recur.

3.4 Last Planner System as linking mechanism

Last Planner adds a production control component to the traditional project management system. As shown in Figure 24, Last Planner can be understood as a mechanism for transforming what SHOULD be done into what CAN be done, thus forming an inventory of ready work, from which Weekly Work Plans can be formed. Including assignments on Weekly Work Plans is a commitment by the Last Planners (foremen, squad bosses) to what they actually WILL do.

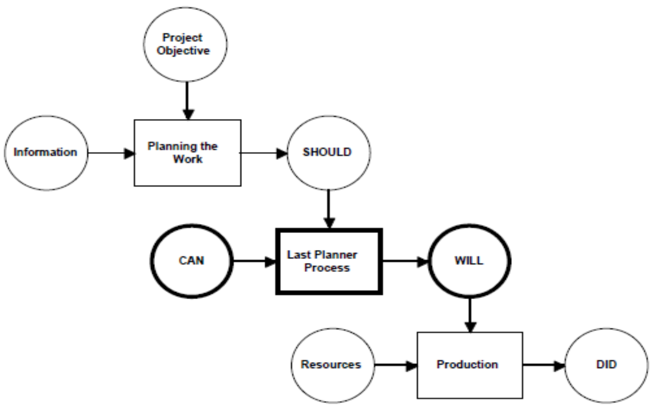


Figure 24: Last Planner as a linking mechanism
(Ballard 2000)

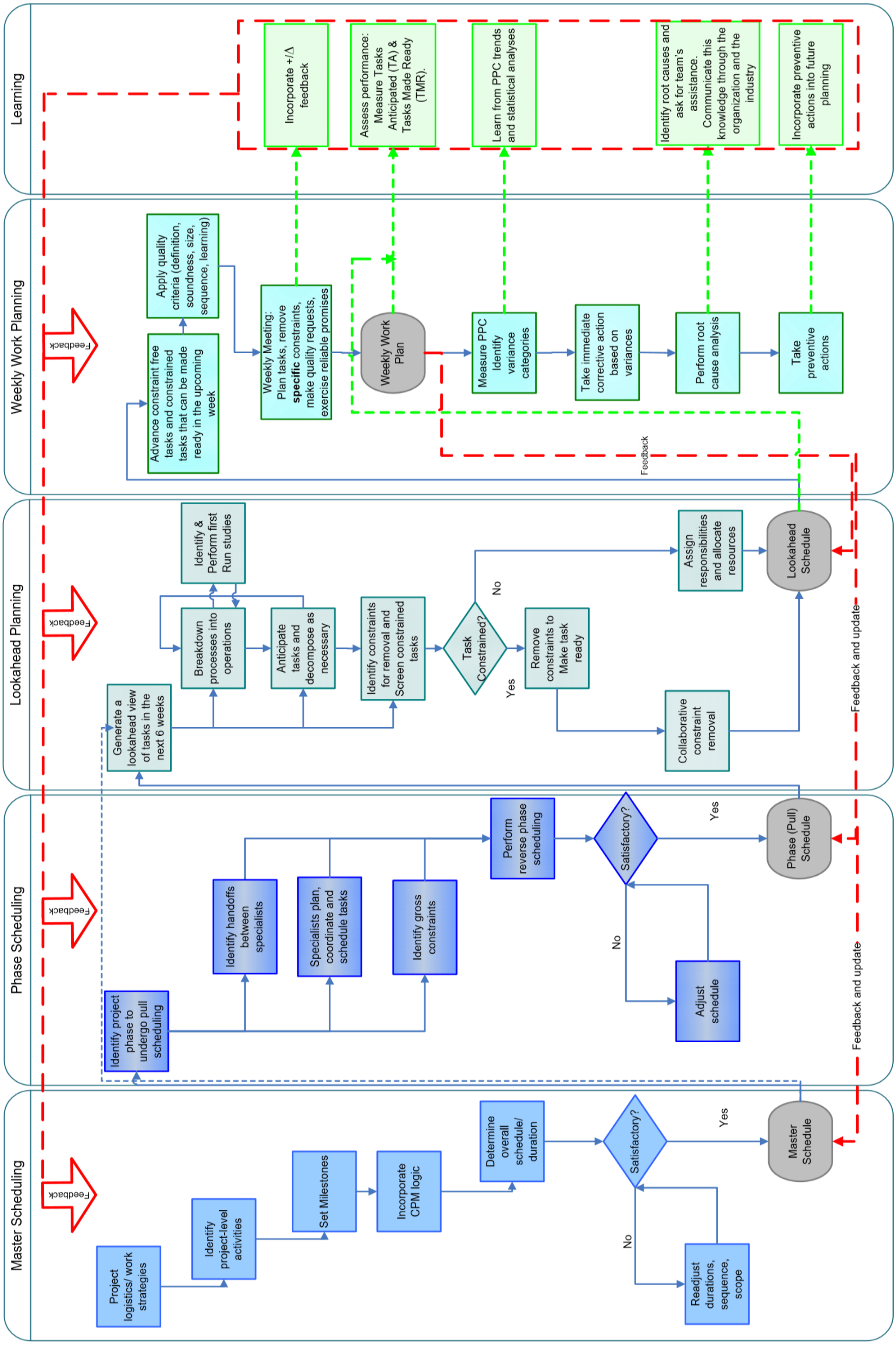


Figure 25: The Last Planner System as a whole (Hamzeh 2009)

Chapter Four: Critical Path Method

4.1 Definition

CPM (Critical Path Method) is a mathematical algorithm that helps the project teams to analyze, plan, and schedule complex projects. By determining the critical path, it will be defined which activities are critical in completing the project, and which ones will not have any serious impact on the project development and can be delayed. The name was selected because of the central position that critical activities in a project play in the method. Each project consists of a number of tasks and activities that are interconnected and essential for project's success. The more complex the project gets, the more demanding the project management is. At its core, CPM is a powerful tool that allows to identify the longest path of planned tasks necessary to meet the deadlines and identify the early start and finish dates

4.2 History

The Critical Path Method was developed by Morgan R. Walker from DuPont and James E. Kelley from Remington Rand in the late 1950's. Around the same time other similar applications of the CPM were developed. The Operational Research Section of the Central Electricity Generating Board in UK was also working on a similar idea. This group had an idea called "longest irreducible sequence of events", which they applied on a Keadby Power Station in 1957 for managing the shutdown and maintenance process. The precedence methodology was developed by Dr. John Fondahl when the U.S. Navy's Bureau of Yard and Docks contracted with Stanford in the late 1950s to report on "The Application of Operations Research and Other Cost Reduction Techniques to Construction".

Kelley and Walker explained that large construction projects involve vast number of stakeholders with different skillsets and knowledge focusing on their specific problems, i.e. coordination of these interrelating activities is the very work of management. For addressing these issues, CPM was devised to manage variety of coordination and resource intensive projects by forming a topological network of discrete activities representing the overall project scope. CPM was intended to help to plan project resources, duration and optimize the cost in a systematic way. CPM was first tested in 1958 in a project to construct a new chemical plant and, ever since, has been one of the most frequently used techniques of project management.

4.3 Operational Steps

4.3.1 Network diagram of CPM

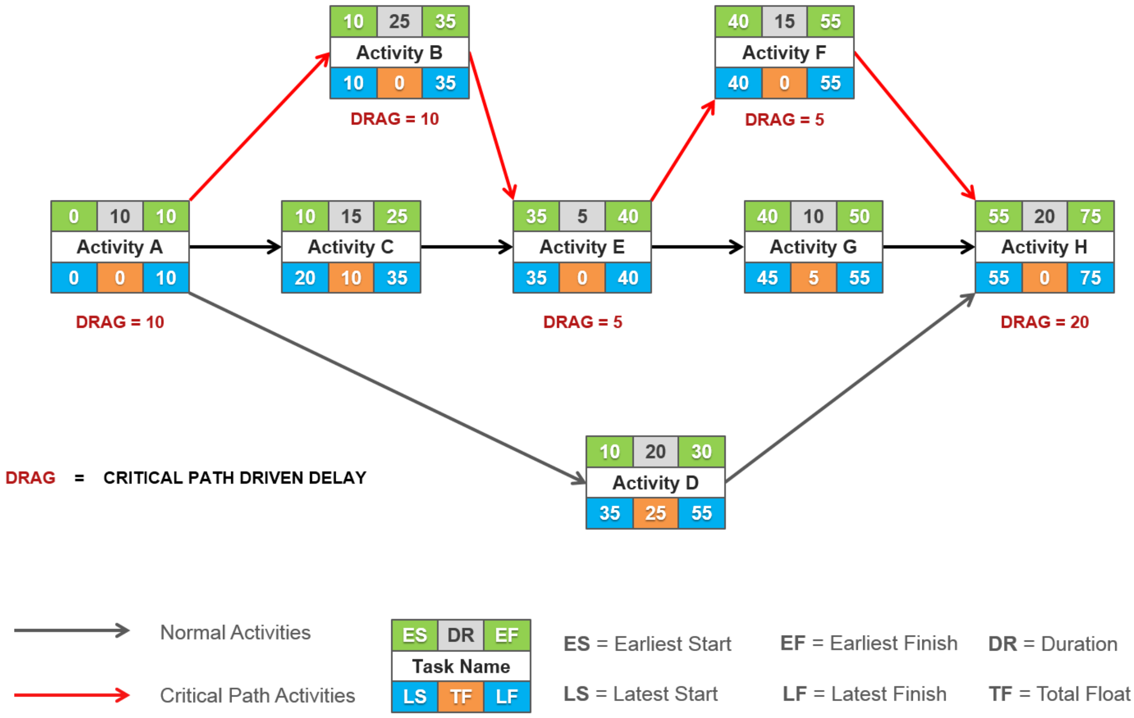


Figure 26: Network diagram of CPM (source: www.project-risk-manager.com)

4.3.2 Main steps of Critical Path Method

A critical path method includes the following steps:

1. Identifying activities

   By using the project scope, you can break the work structure into a list of activities and identify them by name and coding; all activities must have duration and target date.

2. Determining sequence of activities

   This is the most important step as it gives a clear view of the connection between the activities and helps you establish dependencies as some activities will depend on the completion of others.

3. Creating a network of activities

   Once you determined how activities depend on each other you can create the network diagram, or critical path analysis chart; it allows you to use arrows to connect the activities based on their dependence. (Figure 26)
4. Determining completion time for each activity

   By estimating how much time each activity will take will help you determine the time needed to complete the entire project. (While with smaller projects you can make estimates in days, more complex ones require making estimates in weeks).
5. Finding the critical path

   A network of activities will help you create the longest sequence of activities on the path or the critical path using these parameters:

   - Early Start ES - earliest time to start a certain activity providing that the preceding one is completed;
   - Early Finish EF - earliest time necessary to finish activity;
   - Late Finish LF - latest time necessary to finish the project without delays;
   - Late Start LS - latest start date when the project can start without project delays.

If there is a delay in any task on the critical path, the whole project will have to be delayed. The critical path is the path where there can be no delays (TF = 0). Naturally, not all the project activities are equally important. While some have a huge impact on the critical path and are therefore critical, others don't make much difference to the project if they are delayed. The critical path method helps us determine which activities are "critical" and which have "total float". However, if any of the floating activities get seriously delayed, they can become critical and delay the entire project.

4.3.3 Resource limitations

In every execution of a project, there are still certain limitations that affect it and create new dependencies. For example, if the number of team members suddenly drops from 10 to 7, it is easy to run into resource limitations (i.e. resource constraint). As consequence, the basic assumption that underlies the Critical Path Method is that adequate resources are available to implement any computed schedule. Apparently, there are two extremes that need to be considered:

- Available resources are invested in one project.
- Available resources are shared by many projects.

In the first case experience has shown that there is usually no difficulty in implementing any computed schedule. Any difficulty that does arise seems to be easily resolved. The Critical-Path Method applies very well in this case. It may be called *intra-project scheduling*.

In the second case, however, there could be difficulties in trying to share men and equipment among several projects which are running concurrently. It may be called *inter-project scheduling*.

The fundamental problem involved here is to find some way to define an objective for all projects which takes the many independent and combinatorial restraints involved into account: priorities, leveling manpower by crafts, shop capacity, material and equipment deliveries, etc. For any reasonable objective, it also is required to develop techniques for handling the problem. In such scenario, the critical path changes into *Resource Critical Path* where resources related to each activity become an integral part of the process. This means that some of the tasks will have to be performed in a different order which may cause delays, and, consequently, make the project longer than expected.

4.4 CPM Scheduling

4.4.1 Objective

As already happened for paragraph 2.5 "*Social aspects*", this section of chapter 4 aims to analyze CPM Scheduling from the point of view of two fundamental stakeholders in the building process such as owners and contractors because, while Critical Path Method scheduling has been around since the 1950s, its application in the construction industry has still not received full acceptance or consistency in how it is used. In particular, this paragraph is aimed at addressing the following three key areas:

- Establish the views from both owners and contractors as to the use of CPM scheduling and its applicability in today's constructed projects;
- Determine whether standards, certifications and/or best practice guidelines are being sought by the industry;

- Determine whether CPM scheduling can assist in the risk management assessment process.

In order to determine how the industry views its applicability and usage, a survey (made by Galloway 2006) has been developed for these stakeholders above cited. Taking the author's work as a starting point, the paragraph will be articulated with an initial overview on the point of view of owners and contractors, and then continue with the detailed explanation of CPM standards and risk management. Finally, the last section will try to summarize the results obtained from this analysis.

The author has developed an online survey opened for six months and has received 430 responses composed of owners (private and government), contractors, engineers and construction managers. The survey concerned on various topics and, among the most important, there were:

1. Contract requirements for CPM scheduling;
2. Scheduling techniques employed;
3. Applications and primary use of CPM scheduling;
4. Management decision making based on CPM schedules;
5. Advantages and disadvantages of CPM scheduling;
6. Success of CPM scheduling usage;
7. Opinions relative to CPM scheduling standards and best practices.

4.4.2 Owner's viewpoint

Of the owners that responded, almost 50% indicated that CPM scheduling is always required on their projects. Relative to the CPM specification requirements, nearly all respondents indicated that schedule updates were required and over 84% required schedule revisions. Regarding advantages of CPM Scheduling, owners that preferred merely bar charts explained that they were easy to understand, they provided near-term lookaheads and were appropriate on bigger projects as budget allow the cost of CPM scheduling only in that kind of projects. Moreover, CPM scheduling was indicated as being advantageous in that "what if" scenarios, namely when submitted in electronic format to determine impacts on changes and delays to the project. CPM also allowed summarization into a bar chart format for ease of understanding by management.

Throughout the survey, owners have identified three main disadvantages in the use of CPM scheduling:

- The construction managers and project managers do not use the software enough to be knowledgeable in its use and what it is portraying;
- The contractor is more informed about CPM and can more easily manipulate the schedule and use it for claims;
- Owners feel that CPM is overkill for small projects with little cost justification.

4.4.3 Contractor's viewpoint

Of the contractors that responded, over 50% noted that their contracts require CPM scheduling and, in case of absence, 67% indicate that they still prepare a CPM for purposes of planning and monitoring their work. Figure 27 on the right lists the primary reasons by contractors for using CPM.

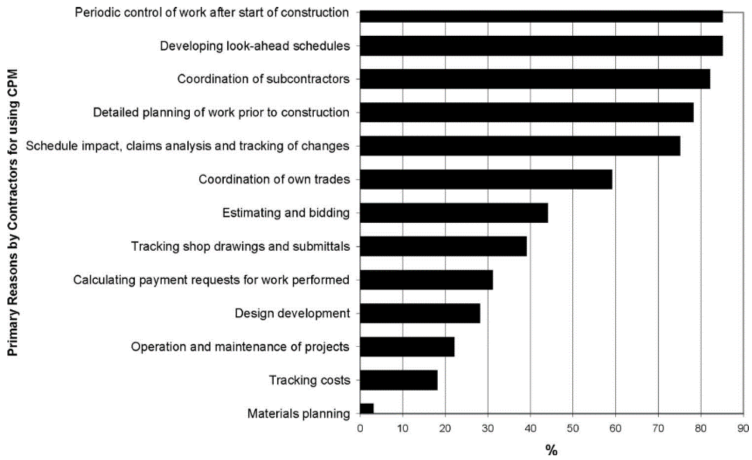


Figure 27: Reasons for using CPM from contractor's viewpoint (Galloway 2006)

Regarding advantages of CPM scheduling from the contractor's point of view, the survey unearths improvements in planning before work starts, improved scheduling, better understanding of the project, improved project control after work starts, improvement in communications among the workforce, increased control over risk and uncertainty, reduction of delays, minimization of disputes between the contractor and owner, time savings, faster response to problems and cost savings. Other comments that were specifically noted included a sense of control for the management team and owner's possibility to react more quickly.

The following figure 28 summarized the reasons listed above, also indicating the specific percentage of each of them:

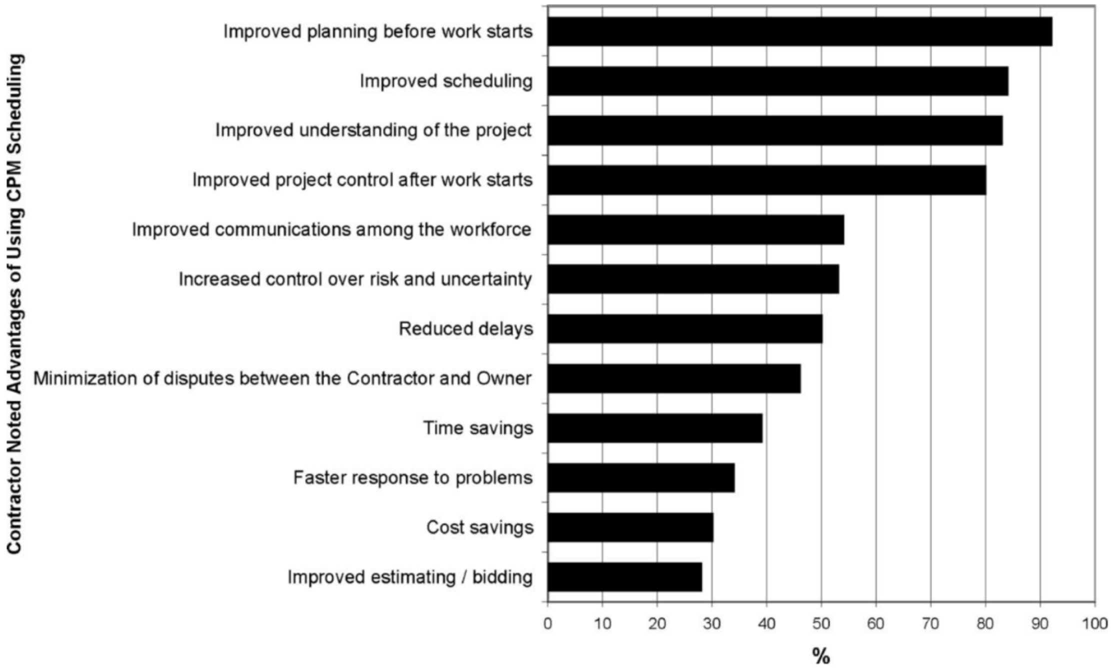


Figure 238: CPM advantages from contractors' viewpoint (Galloway 2006)

Regarding disadvantages of CPM scheduling from the contractor's point of view, nearly 40% of the contractors indicated that the primary disadvantage was logic abuse, followed by the excessive work to be implemented, the overly dependence on specialists and the inability to respond to the needs of field personnel. Other comments noted by contractors included the difficult comprehension by laborers and superintendents, difficulties in interpretation and the excessive training in CPM scheduling required from users.

The following figure 29 summarized the reasons listed above, also indicating the specific percentage of each of them:

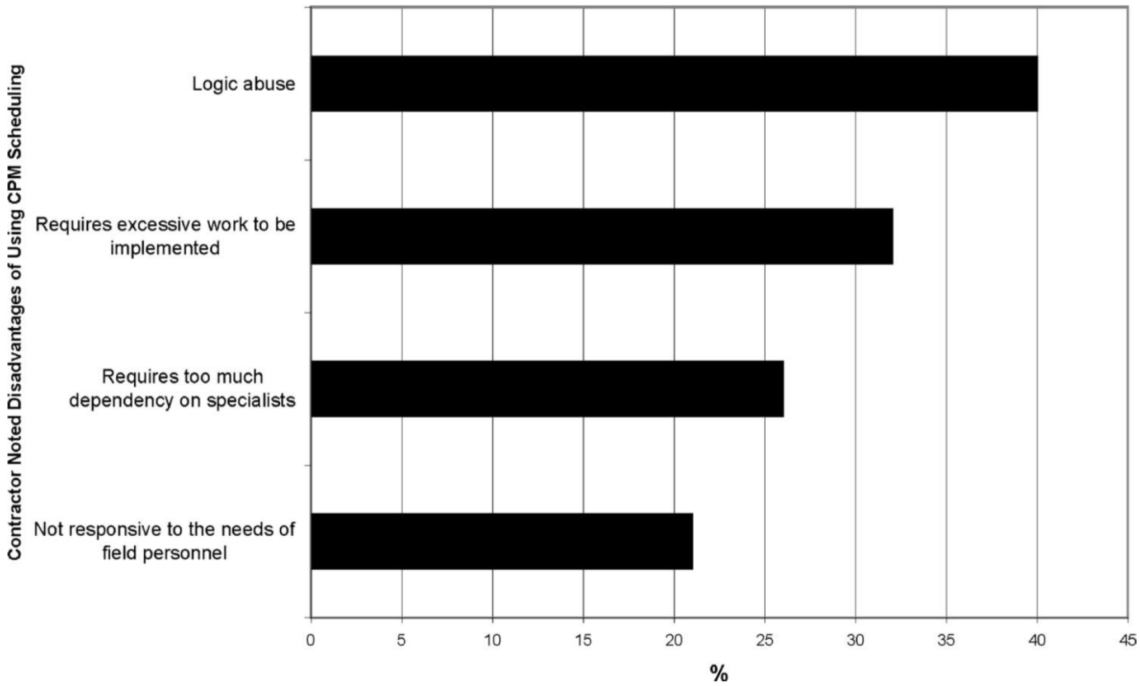


Figure 29: CPM Disadvantages from contractors' viewpoint (Galloway 2006)

4.4.4 CPM and CPM Standards

When asked for the reasons why CPM scheduling was used, over 82% of the respondents have indicated that it was a beneficial planning tool that makes projects more efficient and cost effective, followed by contract requirement (63%), claims after the fact (53%) and change management (47%).

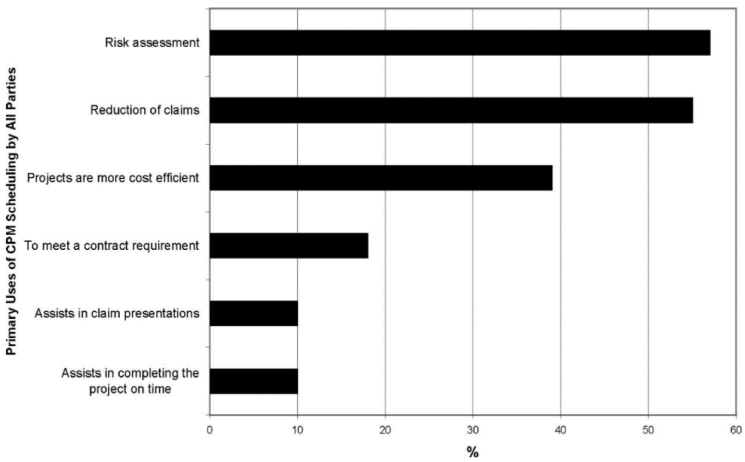


Figure 30: Primary uses of CPM Scheduling (Galloway 2006)

Other responses minorly noted were coordination of multiple construction projects and identification of delay issues. Considering all parties involved in the construction industry, the primary uses of CPM scheduling are listed in figure 30.

One of the crucial aspect investigated in the survey was with respect to the need for standards in CPM scheduling. Seventy nine percent indicated that standards should be defined in the area of CPM scheduling. However, there was no consensus as to who should develop these standards among multiple organizations proposed in the survey and half of those responding indicating that they did not know. While the majority of respondents were not familiar with the cited organizations (PMICOS and AACEI), over 58% indicated that certification of schedulers could have improved the industry and 92% of those responding indicated that best practices guidelines should have been developed and made available to owners and contractors.

4.4.5 Risk Management

Galloway (2006) deeply investigates on the relationship between CPM scheduling and risk management assessment process, asking the interviewees whether and how risk management helped their projects. Over 83% of respondents have indicated to believing that risk management assessments are able to save money on projects and, in particular, figure 31 shows how much.

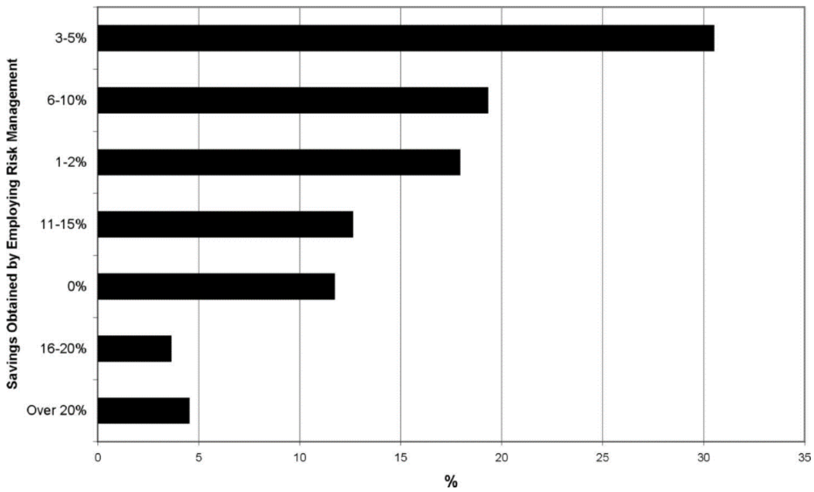


Figure 31: Savings obtained by risk management (Galloway 2006)

4.4.6 Concluding remarks

The effectiveness of the author's work lies in having considered (as a study poll) a broad representation of the construction world and, due to this wide variety, this work provides an excellent image of what really happens. The survey has identified owners, contractors, engineers and construction managers as crucial stakeholders in a project and, in particular, parties who have to live with the decisions based on the CPM scheduling information. In order to summarize the results obtained in this CPM scheduling “social” analysis, it is possible to recognize and list the following common opinions:

- CPM scheduling has become a standard project control tool and both owners and contractors use the tool whether it is or is not required by contract;

- CPM scheduling has become very sophisticated year by year and a broader knowledge on the topic is requested;
- CPM schedules are easily manipulated, especially with respect to logic abuse;
- The majority of the respondents felt that CPM scheduling was beneficial in risk management applications;
- Best practice guidelines should be developed sooner than later by certifying organizations and made available for all the stakeholders.

4.5 Benefits of Critical Path Method

The Critical Path Method allows to stay focused on the big picture by giving a clear view of all project activities and its potential outcome. The best thing about CPM is that less important tasks can be rescheduled and focus the efforts on optimizing the work in order to avoid delays.

Although Critical Path Method may have become an outdated technique due to fast-paced technological advances, it still offers several advantages:

- It defines the most important tasks and prioritizes them;
- It makes dependencies clear and transparent;
- The method visualizes projects in a clear graphical form;
- It identifies all critical activities that need attention and helps team to stay focus;
- CPM scheduling helps define the project duration accurately and adhere to this schedule;
- CPM facilitates control: control of the total construction process not only involves the control of the actual performance of the crews on site, but also items such as provision for materials, owner-furnished equipment or materials, shop drawings, sample approvals and a host of other interrelated activities;
- CPM helps prevent delays, wasted time, or time lost juggling a series of necessary tasks. It is helpful in scheduling time wisely to prevent waste and stay on schedule with the support of software;
- It makes comparison between planned vs actual progress: project management teams can refer to CPM scheduling to evaluate their progress, including the

progress of certain teams and subcontractor work, and take steps to expedite delayed or late projects;

- CPM helps to allocate contractual responsibilities: as the network is an interrelated time-event model of the project, it is the best means of allocating, communicating, and controlling contractual responsibilities between stakeholders within the engineering phase of a project;
- It permits to do easy and efficient risk assessment.

4.6 Criticisms of Critical Path Method

Concluding remarks listed in section 4.4.6 provide evidence on the key shortcomings of the CPM from the stakeholders' viewpoint. Furthermore, over the years several other authors have identified further criticalities of the method. However, it is important to underline that, despite the identification of critical insights, CPM method has maintained a dominant position in the construction world. The following discussion will bring to light the criticalities ascertained by literature and, for clearness and logicality in the discussion, they will be listed in chronological order, from the oldest to the most recent:

- The CPM method focuses on the technological dependencies only, meaning that it does not support achieving the stable continues workflow and handovers between project stakeholders on the operational level (Peer 1974).
- Jaafari (1984) identifies three main criticisms of CPM for project planning analysis:
    1. The basic assumptions of project activities having fixed time and discrete nature are unrealistic, especially when repetitive units or linear projects are to be constructed;
    2. Resource allocation, smoothing or leveling procedures are incapable of ensuring full continuity for a production crew or process which is the backbone of operational planning in construction processes, especially in repetitive cases;
    3. CPM scheduling is expensive to run. Status reports take time to reach managers and decision makers, and, by the time they receive these the information contained in them, tend to be out of date.

- Goldratt (1997) argues that the main problem with traditional project management method and, in particular, CPM is its misuse of safety times or buffers in activities. Buffers are added to each individual activity for accommodating the potential uncertainty, causing the effect that preparations for the next stage are not made because it is not clear when the previous activity will finish. As a result, activities are not ready to start when the previous activity actually does finish.
- All projects always face a residual uncertainty and randomness that cause productivity variances, waste of capacity, schedule deviations and workflow instability. It has been argued that the CPM can be used to identify major critical disturbances. However, Seppänen & Aalto (2005) stated that identification of deviations is not clearly visualized and often occurs too late in CPM with respect of other methods.

Chapter Five: Integrations

The dissertation of this thesis has so far focused on the formal and theoretical explanation of the three main planning and control methods existing in the construction world. However, as already mentioned in paragraph 1.4, the goal that this paper has set is to go beyond the single method. In fact, there is a long series of elements (already partially highlighted during the discussion) which, if properly adapted and declined correctly, make it possible to integrate the various methods described so far. The goal of this chapter is therefore to explain to the reader how, through careful bibliographic analysis, these methods can be combined, how one supports the other and what results their combination arrives at.

The dissertation of the chapter will take place in three different parts: the first part will be dedicated to the combination of Location-Based Management System and Last Planner System, the second part to the analysis of Location-Based Management System and Critical Path Method and finally Last Planner System with Critical Path Method.

5.1 Combination LBMS – LPS

5.1.1 Introduction

The objective of this paragraph is to explain the development of a process and best practice to combine the benefits of LBMS and LPS.

LBMS is a technical data-driven system which transforms quantities in locations and productivity information to reliable durations, it makes buffers explicit and forecasts future performance based on historical trends and alarms of future production problems. LBMS mainly provide information to decision making.

LPS is primarily a control system more concentrated on the social process of continuous improvement, it aims at making planning a collaborative effort and focuses on improving the reliability of commitments of team members, rather than providing explicit tools to implement actions.

The narrative of this paragraph will try to respond to three driving questions that are:

- How to best link LBMS and LPS in order to achieve better project performance?

- Can the LBMS control mechanism be integrated with LPS?
- Can phase pull scheduling be integrated with LBMS?

Based on Seppänen, Ballard and Pesonen (2010), Seppanen et al. (2015) and Dave, Seppanen, Modrich (2016), the following section will be devoted on the explanation of the proposed combined process developed by the authors above listed.

5.1.2 Proposed combined process

5.1.2.1 Master scheduling

The proposed process is to define the overall Location Breakdown Structure for the project during master scheduling (on building and floor level of detail), and to use available productivity rates and quantities to evaluate the required production rates. Master schedules are recommended to have 20-30 tasks, using available quantities and resource information where possible (even though in master scheduling phase there is generally limited availability of information about design). The focus should be on tasks with mandatory technical hand-offs to other trades and on tasks which require a lot of space for laydown areas and work. This will help to identify any subcontractors with high resource needs who may become bottlenecks if a reliable subcontractor is not selected. The actual dates of this master schedule are used only for long lead time items and to establish realistic phase milestones. The master schedule will be gradually replaced by the phase schedules which will be used as control standards for execution.

5.1.2.2 Phase scheduling

In LPS, a big part of scheduling happens in phase scheduling meetings. The planning is done by starting from the milestone and working backwards so that each task releases work to the next task. Typically phase scheduling meetings have been carried out by using sticky notes where task names and durations are written. Phase scheduling produces better schedules because of the knowledge the specialists bring and because the participants have power over resources and knowledge regarding availability and capability.

In the proposed process, with the aim of collecting all the data for a collaborative planning session, the phase scheduling has to be broken into two different meetings.

The first meeting defines the detailed Location Breakdown Structure for the phase as a collaborative effort. One of the key decisions at this stage is the location size. Large locations mean implicit buffers because if locations are large, it typically would be possible to have several subcontractors work in the same area. Very small locations can be hard to define so that they work for all or most of the subcontractors and it may not be possible to place all the materials within the location.

In practice, defining the Location Breakdown Structure is easier when floor plans are printed. The facilitator of the meeting needs to make sure that each participant understands that a location must be able to be fully completed before moving to the next location. Subcontractors often request their own custom locations to locally optimize productivity but can be persuaded to adopt a common location breakdown structure when they understand that they will be able to own the location.

After that, the normal sticky note exercise has to be done to identify task types and their logical relationship. However, durations were not yet defined.

After the identification of tasks and locations and between the workshops, quantities, productivity rates and labor consumption (manhours / unit) for each task in each location are collected through a homework assignment.

In the preparation of the second optimization meeting, the tasks should be formed so that all the hand-offs between subcontractors are accurately modeled. Any internal hand-offs can be simplified and lumped to the same task. Non-location-based tasks do not need to be shown during flowline optimization but should constrain the start dates of tasks through CPM logic. All tasks are scheduled with one optimal crew. This will typically result in unaligned production rates.

All these steps give all the information required creating a location-based plan before the second meeting.

Production rates are aligned in the second workshop as a team exercise. Each change in production rate is recorded as a commitment. The ultimate result is an aligned schedule with parallel flowlines. Finally, buffers are planned between tasks. The proposed process suggests also to ask the participants what time buffer is needed to absorb the variation. In this way, schedules can also be compressed during phase scheduling.

The following figures 32 summarized the proposed phase scheduling process.

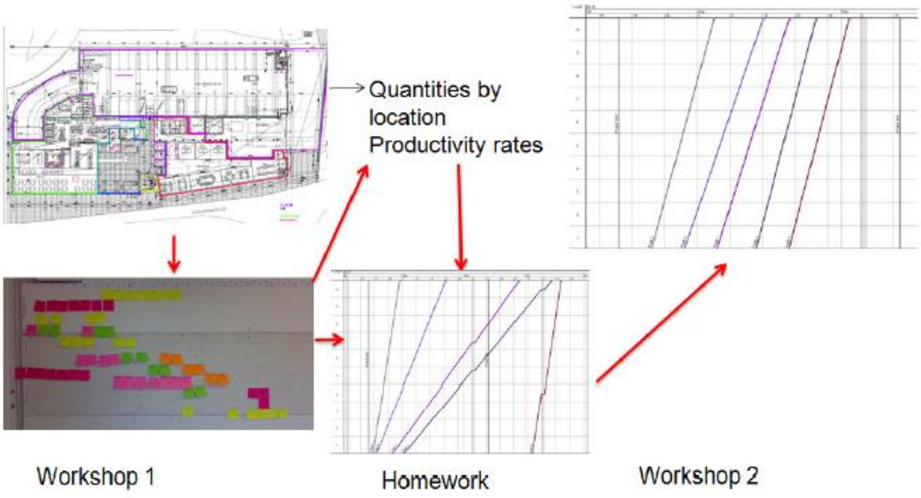


Figure 32: Proposed phase scheduling process (Seppänen, Ballard, Pesonen, 2010)

After Phase Scheduling has been completed, the Phase schedule data from LBMS would be imported in LPS system. The information can then be shown in a simple Gantt view and subsequently in the timeline view (figure 33) once the resources (workers) are allocated to tasks. Figure 34 shows the imported Phase schedule from LBMS system, with activity-location handover date shown as a milestone (red diamond).

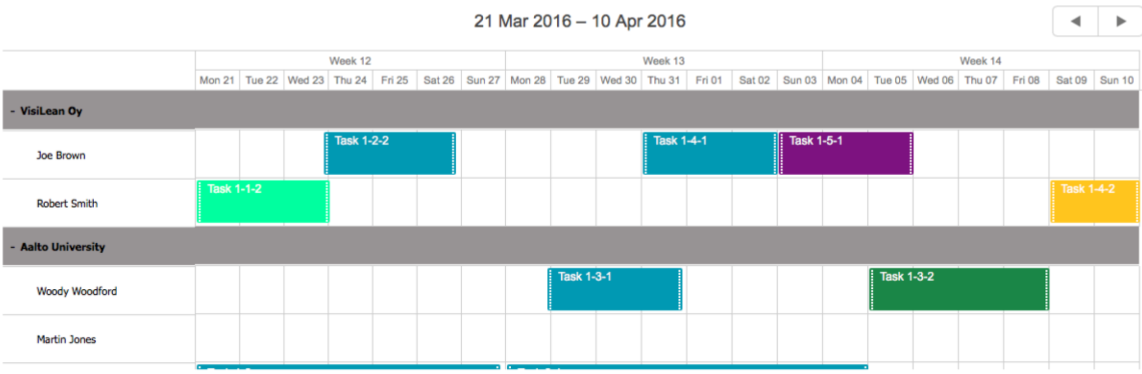


Figure 33: Task allocation (Dave, Seppänen, Modrich 2016)

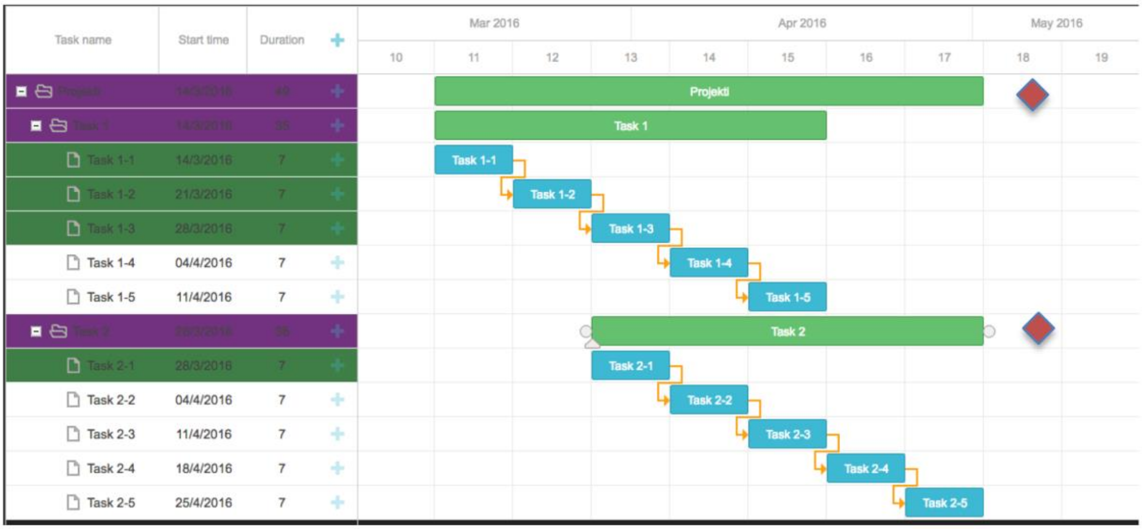


Figure 34: Imported phase schedule (Dave, Seppänen, Modrich 2016)

5.1.2.3 Lookahead planning

In the Last Planner System, lookahead planning consists of constraints identification and removal, replanning when necessary, task breakdown to the level of operations, and collaborative design of new operations.

LBMS is concerned with cascading delays caused by interference between trades. The main control tools include systematic collection of progress data, forecasting future production based on actual production and alarming of upcoming interference. Constraints or operations level are typically not incorporated to the LBMS schedule because they could lead to cluttering and decrease of visual effectiveness of flowline diagrams.

LPS and LBMS are very complementary with regard to look-ahead planning because they raise different problems for discussion. The LPS process exposes constraints which must be removed for production to continue according to the plan without interruptions. LBMS highlights problems related to capacity and production rates.

All of these problems can be analyzed through root cause analysis and solved collaboratively. Seppänen, Ballard and Pesonen (2010) proposed that the combined look-ahead process works by updating LBMS forecasts for discussion in a superintendent meeting devoted to lookahead planning. The complete weekly look-ahead process would thus include the following steps:

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

These steps are elaborated below.

- Identify Tasks and Locations in the Look-ahead Window

Tasks and locations in the look-ahead window are identified based on the LBMS phase schedule. This can be done graphically on production wall by drawing a line through the flowline diagram and listing all tasks and locations where flowlines are to the left, or intersecting with the look-ahead period line.

- Break down tasks and locations to operations

Tasks in locations are broken down to operations level in a pull scheduling session with the team responsible for the task. The team needs to come up with the answer of what steps are required for the task to be finished in a location. This should be reviewed for both the task in general (what is common in all locations?) and by location (specific operations related to that location). Different circumstances and their impact on operations should also be considered. For example, the attachment of top track depends on whether it is attached to concrete, metal deck or joists and any special circumstances may include different operations.

- Identify, assign and remove constraints

Any missing constraints related to operations, tasks or locations are identified in meetings with the team responsible for doing the work and in weekly superintendent look-ahead meetings. A constraint can apply to the whole operation (for example, material not delivered) or a certain location (for example, open Request for Information (RFI) on the fifth floor related to Drywall Framing). Identified constraints are assigned to team members who commit to their removal by a certain date. Currently active constraints are reviewed weekly and their status is updated. If a constraint cannot be removed before the LBMS forecast date, the constraint will be elevated into a problem.

- Review actual production and forecasts to identify ongoing production problems

Progress data is collected and analyzed with LBMS to identify start-up delays, production rate deviations and work interruptions. Forecast is calculated based on actual labor consumption rate and current resources on site. Any alarms caused by current or future interference between trades are elevated to problems.

- Root cause analysis and resolution for problems

Any problems identified through constraint identification, constraint removal or actual production are analyzed for root causes. LBMS will provide numerical support - such as actual production rate and actual labor consumption - for any discussions related to production deviations. Actions are agreed with the team to target these root causes. If the agreed-on actions impact the crew size or anticipated future productivity of an operation, the forecasts are recalculated with these values to see if the actions are enough to prevent the problem.

- Re-Plan to address current and upcoming problems

Re-planning can be initiated to address current or upcoming issues which cannot be dealt with by productivity improvements or crew adjustments, or if a better way to finish the phase has been proposed. Re-Planning can change any aspect of the phase schedule and can be organized in the same way.

- Release constraint-free tasks and locations to workable backlog

When all constraints related to all operation of a task in a location have been removed, the location is released to workable backlog. The control chart is a good visual way to keep track of workable backlog. In control chart, the location-breakdown structure is shown on vertical axis and phase schedule tasks on horizontal axis. Tasks in a location are color-coded based on constraints and status. Any tasks with constraints in a location can be shown in grey color. Although operations belonging to a task can also be constraint-free, they should generally not be started until all operations can be performed before handing off the location to the next trade. Starting individual operations would result in work-in-progress of no value to the downstream operation.

- Designing upcoming operations

Before the start of an operation in the first location, the operation should be explicitly designed by those who are to execute the operation. The design of operations can be done using virtual prototyping, physical prototyping or first run studies. Standardization is appropriate for new, critical, and repetitive operations. Critical operations, such as heavy lifts, are those whose failure cannot be tolerated, and so warrant extensive planning and preparation. Planning and preparing for new operations, such as assembly and installation of light fixtures, helps avoid rework and work flow interruptions. Repetitive operations may benefit from virtual or physical prototyping (mockups), but can also be refined over multiple iterations. That starts with a design session involving the craft workers who will do the first run (the first instance of the repetitive operation), documentation (videotaping, process maps, etc.) of the work as actually performed, and review with the craft workers to develop further improvements.

5.1.2.4 Weekly Planning

The proposed integration with LBMS on weekly planning level is to compare commitments to LBMS forecasts to highlight problems earlier. If commitments do not match or exceed the LBMS forecast, it is possible to know a week earlier that there will be issues. In the combined system, weekly planning highlights problems in the commitment phase through LBMS comparison and after execution through plan failures. Both the upcoming and actual problems should be subjected to root cause analysis and learning process.

5.1.3 Proposed combined data model

Figure 35 shows the proposed combined data model. The master and phase schedules are prepared in LBMS and milestones are imported in LPS. The reverse phase scheduling (in a collaborative way) is carried out in LPS and information is updated in LBMS. Subsequently, the constraints analysis and operational level planning is carried out in LPS, while the forecasts are updated in LBMS for potential delays or low-productivity. Weekly planning with resource allocations is taken care in LPS, and actuals are tracked from the field. Both the LPS and LBMS systems are updated with field updates and control actions are initiated from respective systems.

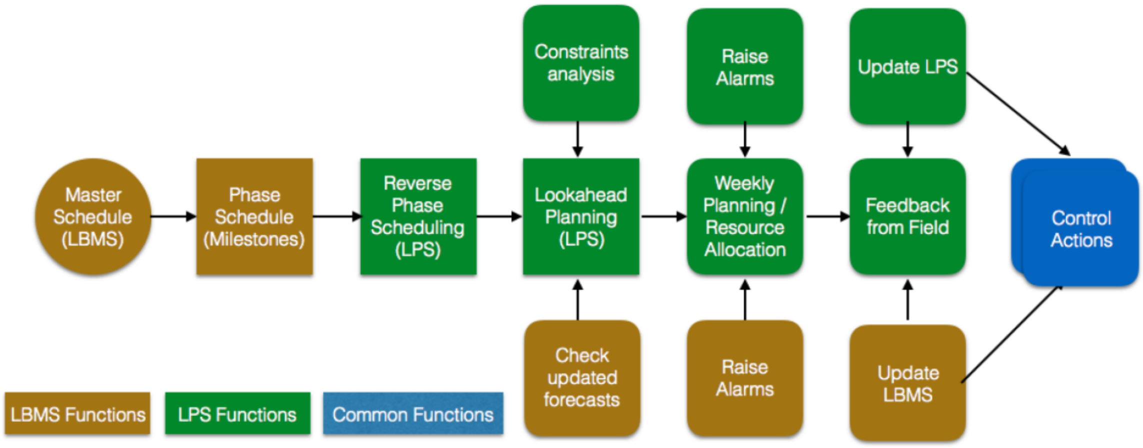


Figure 35: Proposed combined data model (Dave, Seppänen, Modrich 2016)

By integrating Location-Based Management System and Last Planner System, the workers would have access to the short-medium term production planning and scheduling information (through LPS) and the impact of the current decisions and statuses on long-term project plan (through LBMS).

5.2 Combination LBMS-CPM

5.2.1 Introduction

The objective of this paragraph is to explain whether and how LBMS, throughout its tools, is able to improve schedules and project performance, addressing CPM's main shortcomings, already listed and widely discussed in chapter three.

As previously observed, LBMS is a method of construction planning and production control that is based on the movement of resources through the jobsite, aiming to maximize continuous use of labor and productivity, reduce waste and risk, increase transparency and improve predictability and flow.

The Critical Path Method (CPM) is a powerful scheduling and progress control tool for managing projects. In the construction industry, CPM has grown in importance over the last several decades to manage complicated projects. However, CPM has been criticized regarding repetitive and linear projects, which have lengthy and detailed schedules.

Moreover, CPM's main shortcomings in relation to generating workflow, crew balancing and resource continuity have been already discussed and proved.

The core of this paragraph is validating the assumption that LBMS could resolve key shortcomings relating to planning construction projects, especially concerning the lack of workflow, the inability to provide the continuous use of resources and complicated scheduling processes.

Based on the identified shortcomings of the CPM method and the main characteristics of LBMS, the following two hypotheses will be tested:

- Hypothesis 1: LBMS optimization enables more continuous workflow without increasing the total duration of a project, resources or subcontractors;
- Hypothesis 2: LBMS schedules include significantly fewer planning elements (activities and logic) making the scheduling process less complicated

Based on Olivieri, Seppanen, Granja (2018), the following section will be devoted to the presentation of the research method developed by the authors and to the explanation of the results obtained regarding the differences of CPM and LBMS in the schedule planning phase.

5.2.2 Research method

Five Brazilian contractors were contacted to provide project schedules for analysis regarding three different case studies. For each project, authors accessed the following documents: the baseline CPM schedules (developed using Microsoft Project), a logical relationship document that contained the logical links of the project tasks, the executive forecasted budget that included resources (materials, labour and equipment), quantities and cost and a document containing the general overview of the project, including blue prints and photos. Quantities, resources and production rates were collected from executive budgets and baseline schedules.

Between 20 and 25 repetitive tasks were selected for analysis from each project and the subcontractors responsible for each task were identified.

The first step in each case study was to analyze the Gantt chart of the original CPM schedule, in particular the tasks selected for analysis. The original schedules did not contain filters to facilitate the analysis. The logic links were compared with the logical relationship document.

The second step was to analyze the CPM schedule by visualizing it in a flowline graph. Tasks, locations, subcontractors, calendars, durations, lags, dates and logic links were manually inserted in Schedule Planner, developed by Vico Office.

The third step was to simulate resource smoothing in Schedule Planner. Resource smoothing is an approach that levels the resource graph even when resource constraints are not violated by moving start dates to achieve a more continuous workflow. The resource smoothing simulation started from the CPM flowline. Tasks which did not have a workflow were made continuous if the adjustment would not impact the project end date.

The fourth step was to improve the flowline using LBMS principles, generating a new LBMS schedule for comparison. The optimization process was constrained by limiting the amount of resources available for each subcontractor to the same amount as the maximum used by the CPM schedule. The durations were calculated based on quantities and production rates. During optimization, the first step was to make all the tasks continuous and this extended project durations. Then, the production rates were synchronized by adding resources to tasks with slow production rates until the bottleneck contractor was identified as resource limits were reached. Then, the resources of faster tasks were decreased to match the production rate of the bottleneck. Finally, any tasks which could not be slowed down by decreasing resources (i.e. only one crew), were made discontinuous.

The same metrics were calculated for the CPM and resource smoothing schedules and the results were compared for all CPM, resource smoothing and LBMS schedules. Metrics used for the comparison were:

- Total duration
- Peak resource usage
- Number of mobilizations and demobilizations
- Percentage of time the work proceeded continuously
- Number of activities and logic links

5.2.3 Results

The following three tables show the results obtained from the research. These results will then be discussed and interpreted from the point of view of the workflow, the number of planning elements and from the point of view of visualization.

Case study	Schedule	Total duration (months)	Peak resource use	Number of mobilizations and demobilizations
A	CPM	18	121	4422
	Resource smoothing	18	118	4056
	LBMS	18	111	3790
	Reduction (CPM vs. LBMS)	–	**8%**	**14%**
B	CPM	20	180	7050
	Resource Smoothing	20	135	6270
	LBMS	20	176	5649
	Reduction (CPM vs. LBMS)	–	**2%**	**20%**
C	CPM	13	186	4564
	Resource Smoothing	13	161	3350
	LBMS	13	163	2864
	Reduction (CPM vs. LBMS)	–	**12%**	**37%**

Table 2: Duration, peaks and number of mobilizations and demobilizations (Olivieri, Seppänen 2018)

Case study	Schedule	Number of activities (CPM)/tasks (LBMS)	Number of logic links	Number of operations to improve the CPM schedules
A	CPM	912	1426	
	LBMS	34	795	10
	Reduction	**878 (96%)**	**631 (44%)**	
B	CPM	1748	2244	
	LBMS	68	1502	23
	Reduction	**1680 (96%)**	**742 (33%)**	
C	CPM	936	1599	
	LBMS	46	904	9
	Reduction	**890 (95%)**	**695 (43%)**	

Table 3: Number of activities (Olivieri, Seppänen 2018)

	Case A (%)			Case B (%)			Case C (%)		
Tasks	CPM	Res. smooth.	LBMS	CPM	Res. smooth.	LBMS	CPM	Res. smooth.	LBMS
(1) Concrete structure	0	0	0	0	0	0	0	0	0
(2) Drywall lines and profiles	100	100	100	90.9	100	100	48.7	48.7	100
(3) Drywall boards	100	100	100	90.9	100	100	48.7	100	100
(4) Waterproofing	100	100	100	100	100	100	38.5	38.5	100
(5) Plaster treatment	0	0	100	0	0	100	–	–	–
(6) Complete plaster	100	100	100	95.5	100	100	64.1	100	100
(7) Floor tiles	33.3	100	100	32.6	100	100	64.1	100	100
(8) Walls tiles	100	100	100	100	100	100	0	100	100
(9) Floor levelling	100	100	100	100	100	100	51.3	100	100
(10) Gypsum ceiling	100	100	100	97.7	100	100	87.2	87.2	100
(11) Windows	26	26	100	0	100	100	38.5	100	100
(12) Doors	100	100	100	100	100	100	0	100	100
(13) Electrical infrastructure	100	100	100	0	100	100	0	0	100
(14) Electrical finishes	69.6	100	100	0	0	100	0	33.3	100
(15) Hydraulic columns	78.3	100	100	95.5	100	100	15.4	15.4	100
(16) Water plumbing	100	100	100	90.9	100	100	38.5	38.5	100
(17) Sewer plumbing	78.3	100	100	90.9	100	100	38.5	38.5	100
(18) Sanitary ware	100	100	100	0	0	100	100	100	100
(19) Painting first layer	100	100	100	100	100	100	100	100	100
(20) Painting second layer	100	100	100	0	0	100	100	100	100
(21) Hard cleaning	100	100	100	100	100	100	46.2	100	100
(22) Final cleaning	0	100	100	81.8	100	100	100	100	100
(23) Structural masonry	–	–	–	–	–	–	0	0	0
(24) Internal masonry	–	–	–	–	–	–	0	0	0
Average (%)	**76.6**	**87.5**	**95.5**	**65.1**	**77.3**	**95.5**	**42.6**	**65.2**	**87**
Increased LBMS vs. CPM (%)		**25**			**47**			**104**	

Table 4: Workflow LBMS vs CPM (Olivieri, Seppänen 2018)

5.2.3.1 Workflow

The lack of workflow in CPM schedules, highlighted in the three case studies, was caused mainly by the varying production rates of activities. In addition, the lack of workflow and the inability of the CPM algorithm to force work continuity caused unnecessary mobilizations and demobilizations. Table 2 clearly shows the reduction in percentage between the number of mobilizations and demobilizations in LBMS with respect of CPM schedule. LBMS increases productivity and improves task workflows by forcing tasks to be continuous by default.

5.2.3.2 Number of planning elements

CPM usually requires multiple activities to represent a repetitive or linear project as demonstrated in the three case studies. CPM schedules include activities and each activity is a planning entity. LBMS combines the activities to tasks of the same type, representing a total reduction in planning elements (between 95 and 96%, as shown in table 3). Most of the planning decisions were made at the task level, rather than at the activity level. Thus, since the number of elements in the plan was smaller, adjustments were easily made and different scenarios could be simulated and analyzed. The number of logic links required to model a schedule is much lower in LBMS due to its layered logic: in fact, LBMS models the same schedule with fewer links. The number of links was based on the number of tasks and not the number of floors. Therefore, the benefit of LBMS over CPM increases with the number of locations.

5.2.3.3 Visualization

Using specific filters, CPM schedules can be visualized in several ways. However, due to the large number of lines and pages the complete CPM schedule demands, it was difficult analyzing wasted time or checking task sequences on a specific floor. The problem of visualizing the sequence of tasks on a floor can be solved through a simple filter, making it possible to analyze the wasted time in a location. However, in this view, it is not possible to visualize the floors together, making workflow analysis difficult.

5.2.4 Conclusion

This paragraph summarizes the differences of CPM and LBMS in the schedule planning phase. Better workflows were achieved using LBMS without affecting the total duration. The evidence of this sentence is shown, respectively, in table 2 and table 4 where the percentage of time the work could proceed continuously to the next location of the same type is calculated. This percentage was calculated based on the number of interruptions for each task. Thus, 100% indicates the task was performed without interruptions, while any number less than 100%, and more than 0%, represents at least one interruption. The number 0% represents a task that was performed with interruptions on each floor. The percentage of continuous work in LBMS schedules was higher than in CPM schedules for all case studies.

Moreover, table 2 supports the first hypothesis – LBMS-based workflows did not increase a project's total duration. The main causes of poor workflow in CPM schedules were identified as starting tasks as soon as possible, variability of durations and the inability of CPM algorithms to schedule continuous work.

The second hypothesis dealt with the number of planning elements in LBMS and CPM. This hypothesis was strongly supported by the evidence shown in table 3. The number of tasks was significantly lower than the number of CPM activities in all case studies. The number of logic links required to model a schedule was a fraction of those found in CPM schedules.

In conclusion, the argumentation of this paragraph addressed the three key shortcomings of CPM, namely lack of workflow, inability to schedule continuous resource usage and number of planning elements which have been successfully resolved by LBMS without apparent disadvantages in construction projects that demonstrate location repetition.

5.3 Combination LPS - CPM

5.3.1 Introduction

The objective of this paragraph is to demonstrate how CPM Scheduling and Last Planner System can work complementarily in a process that improve crew flow and work flow in a Lean based project management approach. Based on Huber, Reiser (2003), the following section of the dissertation will be devoted to the definition of the assumptions used and to the presentation of the combined process.

In order to clarify the concept of Lean Production, a short section of this paragraph will also be devoted to a theoretical hint about this topic.

5.3.2 Assumptions

During the dissertation of this thesis, speaking of the role of the CPM in the construction process (also in relation to the opinion and uses of the main stakeholders), we have repeatedly referred to the wide versatility of the method. It is precisely this versatility that has contributed to the maintenance in use even today of a system conceived at the end of the 1950s. It has already been written in Chapter 4 of the importance of the CPM from a contractual point of view in regulating the relationships between owners and contractors. However, in this paragraph it is necessary to underline that the fundamental premise that will accompany the whole discussion is that the primary function of scheduling and planning is to optimize production through the management of crew flow and work flow, not as a contract claim or claim defense documentary.

The second fundamental assumption is that the explosive growth in the capability and sophistication of computer based project management software over the last few decades has not been closely matched by a parallel interest for the data and analysis that they provide. In order to survive in this fast and chaotic environment, the CPM schedule must necessarily deliver its value quickly and efficiently or it faces the distinct possibility of losing out to other persistent demands on the manager's time and attention. For this reason, the integration between CPM and LPS becomes almost a necessity.

5.3.3 Lean Production

Lean Production was coined by Womack et al (1990) to describe the implementation of the ideas inherent in the Toyota Production System. It was based upon their studies of the car manufacturing industry in Japan and other countries. Womack and Jones (1996) moved from the automotive industry to look at manufacturing in general and established the five principles for Lean:

1. Value: value can only be defined by the ultimate customer, where the customer can be considered as all downstream operations. This is the first step to waste recognition, defined as everything that adds no value from the clients' perspective. It can be applied in the construction context in which end customers are multiple and the construction client can rarely be considered as the single ultimate customer.

2. Value stream: value stream analyses three types of actions along with the value stream: first, activity creating value; second, activity creating no value but is unavoidable with current technologies and production assets; third, activities creating no value and are determined to be avoidable;
3. Flow: The concept of flow is one of the core elements of Lean Thinking philosophy to achieve complete removal of waste. Once a company has reduced or eliminated waste and variation from a single process and streamlined the value stream, the next step is to make the remaining process steps flow. It is the opposite of batch and queue. The goal of this principle is to have a product move from concept to customer without interruption or delay;
4. Pull: this principle is closely related to the "pull" system which the Toyota Production System firstly created. The end users pull the production such that it is only produced to suit their requirements;
5. Pursue perfection: this principle indicates "the complete elimination of *muda* (Japanese term for "non-value activities") so that all activities along a value-stream create value". The lean concept associated with perfection is kaizen, a Japanese word which is interpreted as continuous improvement in the West. By applying the previous four principles each time, the organization gains more and finds more hidden wastes that can be eliminated.

5.3.4 Combined Process

Standing alone, the CPM is disinterested in the elbow-to elbow coordination of the individual crews out on the site. It knows what the crews are doing and where but not how. On the other side, the Last Planner System is disinterested in the measurable contribution to overall project success caused by the completion of an individual crew assignment. It knows the who, where, and how but not the why.

Current Lean Construction thinking divides work into categories based on the task's readiness for assignment to a crew. Crew assignments are pulled into the weekly work plan by the responsible supervisor's acceptance of an assignment from an available pool of ready tasks. There exists another set of tasks that the master plan suggests must be done but are not as yet ready for assignment to a crew. Typically represented as distinct subsets of the total pool of uncompleted work, an alternative view presents itself using float calculation to measure pull intensity across the project matrix. In this view the individual tasks are ranked using total float so that make ready efforts and weekly crew assignments are brought to bear where they will do the overall project the best. In this scenario the CPM and the Last Planner System inform each other of the pull intensity (total float) and planning reliability (PPC) as the project is planned and re-planned in a periodic cycle as the project progresses.

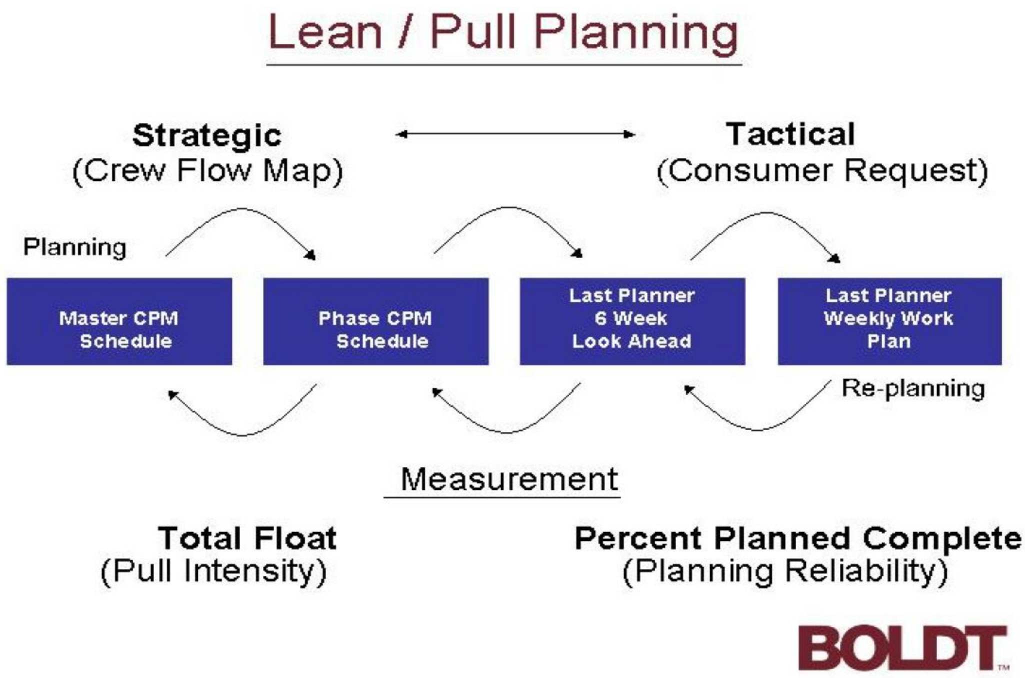


Figure 36: Combined process LPS-CPM (Huber, Reiser 2003)

In this case the planning is crew-centric and focuses on smoothing and stabilizing crew flow through the available made ready space. Making downstream space ready for future crew assignment requires not only the completion of work by other trades but also removal of all constraints including design, material deliveries, safety, access, shared resources, etc.

Chapter Six: Production Planning Case Study

6.1 Case study introduction

The case study presented in this chapter was proposed, in the months of January and February 2020, to the students of the Operation Management in Construction course by Professor Olli Seppänen, lecturer at Aalto University in Espoo (Finland). The task of this assignment is to prepare the schedule, using the guidelines provided by the LBMS method, for the interior and MEP work in a real project. This chapter has been inserted in the thesis to show the reader how the theoretical foundations concerning the Location-Based Planning System, discussed in paragraph 2.3.1, are applicable in reality and to what results they lead.

The case study was settled with the help of the Schedule Planner software developed by Vico Office.

The case study was developed on part of the original project for the construction of a three-story medical office building for Camino Medical Group (CMG), a division of the Palo Alto Medical Foundation, in Mountain View, California, US. The medical facility houses has more than 130 physician offices for primary and specialty care, nearly 260 exam rooms, 34 procedure rooms, a 2000 m² outpatient surgery center, a 2800 m² laboratory and diagnostics radiology center, a comprehensive infusion services department, a 560 m² urgent care center, and a 600 m² pharmacy. The campus also features a 40000 m² of parking structure.

Figure 37: Office building for Camino Medical Group (source https://www.dpr.com/projects/camino-medical-group-medical-office-building)

The teacher divided the students of the course into groups of three components and, to each group, provided the following material:

- Schedule Planner (Vico Office) software license which is a location-based scheduling program;
- PDF file containing the instructions and project specification for the development of the assignment and the evaluation matrix of the final paper;
- Excel file containing the list of activities to be considered, the related subcontractors, the maximum number of resources available for each subcontractor and the correct (and unchangeable) sequence of activities to be carried out in the project.

The main targets of this assignment are to maximize the flow, finish the project on time and follow resource constraints via schedule.

Before starting with the explanation of the case study, I would like to thank my group mates Aman Oli (from Nepal) and Luca Beretta (from Italy). I had the pleasure of working side by side with them in this project for six weeks and thanks to them I was able to expand my wealth of technical knowledge and human skills.

6.2 Main goals and challenges

The project specifications contained in the PDF file sent to us upon delivery by prof. Seppänen, which were mandatory for the correct execution of the project, are listed below:

- To complete the task within the given deadline i.e. 65432 hours;
- One task flowline should not intersect the flow line of another task;
- The project should not use maximum resources more than allowed;
- Changes and modification should not be done in Structure or Roofing task;
- Dependencies should be followed as instructed;
- Change in production factors is forbidden;
- Gaps is allowed only 1 or 2 in order to prepare a standard schedule;
- Major fluctuations are not allowed;

- Risk analysis should be conducted, and buffers are allowed to utilize in appropriate locations.

6.3 Process

6.3.1 Uploading excel and bill of quantities

First, we have checked the given assignment in order to obtain a better understanding of the requests. Then, the bill of quantities has been extracted from the Excel file and imported into the Schedule Planner Standard software.

Camino Medical Group - Mountain View Medical Office Building
MEP/FP Systems Installation

	Areas		Southeast				Southwest				Northeast				Northwest				Center						
	Floor	Consumption Rate (man hours per unit)	1	2	3	Roof	1	2	3	Roof	1	2	3	Roof	1	2	3	Roof	1	2	3	Roof	Units	Optimal Crew Size	Subcontractor
	Item																								
1	Branch conduit	0,064	3000	3000	3000	3000	2500	2500	2500	2500	3000	3000	3000	3000	2500	2500	2500	2500	1000	1000	1000	1000	(lf)	1	Electrical
2	Cable Tray	0,053	250	250	250	250	160	160	160	160	250	250	250	250	160	160	160	160	50	50	50	50	(lf)	1	Electrical
3	Casework, Millwork	0,2	2000	2000	2000		1300	1300	1300		2000	2000	2000		1300	1300	1300		1075	1075	1075		lf	2	Casework
4	Ceiling tile	0,007	30000	30000	30000		20000	20000	20000		30000	30000	30000		20000	20000	20000						sq.ft.	1	Ceiling Tile
5	Dom Water	0,07	2000	2000	2000		1400	1400	1400		2000	2000	2000		1400	1400	1400						(lf)	1	Plumbing
6	Doors & Hardware	0,9	75	100	100	5	75	100	100	5	75	100	100	5	50	75	75	5	5	5	5	0	No.	2	Doors, Frames Hardware
7	Drywall	0,013	36000	36000	36000	0	24000	24000	24000		36000	36000	36000	0	24000	24000	24000	0	8000	8000	8000	8000	sq.ft.	2	Drywall
8	Feeder conduit	0,1	2000	2000	2000	2000	1500	1500	1500	1500	2000	2000	2000	2000	1500	1500	1500	1500	750	750	750	750	(lf)	1	Electrical
9	Fireproofing	0,02	35000	35000	35000		24000	24000	24000		35000	35000	35000		24000	24000	24000		8000				sq.ft.	2	Fireproofing
10	Floor coverings	0,018	30000	30000	30000		20000	20000	20000		30000	30000	30000		20000	20000	20000		5000	5000	5000	0	sq.ft.	2	Flooring
11	Frame priority fullheight walls etc.	0,25	1000	1000	1000	0	650	650	650	0	1000	1000	1000	0	650	650	650						(lf)	2	Drywall
12	Light Fixtures, Diffusers, Ceiling Mounted Trim	0,5	464	464	464	450	354	354	354	350	464	464	464	450	354	354	354	350	100	100	100	100	No.	1	Electrical
13	Mechanical Rough	0,1	1500	1500	1500		1000	1000	1000		1500	1500	1500		1000	1000	1000						(lf)	1	Mechanical
14	MED GAS	0,07	0	0	0	0	0	0	0	0	0	0	0	0	2000	0	0	0	0	0	0	0	(lf)	1	Plumbing
15	Medium pressure duct	0,1	500	500	500		350	350	350		500	500	500		350	350	350						(lf)	1	Mechanical
16	MEP Trim	0,5	75	75	75	0	50	50	50	0	75	75	75	0	50	50	50	0	25	25	25	25	No.	1	Mechanical
17	Paint	0,008	36000	36000	36000	0	24000	24000	24000		36000	36000	36000	0	24000	24000	24000	0	8000	8000	8000	8000	sq.ft.	1	Painting
18	Rain Water Leaders, Waste and Vent	0,04	2500	2500	2500		1700	1700	1700		2500	2500	2500		1700	1700	1700						(lf)	1	Plumbing
19	Specialties and accessories	0,2	75	100	100	5	75	100	100	5	75	100	100	5	50	75	75	5	5	5	5	0	No.	1	Specialties
20	Sprinkler Rough	0,07	2120	2120	2120		1400	1400	1400		2120	2120	2120		1400	1400	1400						(lf)	1	Fire Sprinkler
21	Tape and Finish	0,007	36000	36000	36000	0	24000	24000	24000		36000	36000	36000	0	24000	24000	24000	0	8000	8000	8000	8000	sq.ft.	2	Drywall
22	T-Bar	0,014	30000	30000	30000	0	20000	20000	20000	0	30000	30000	30000	0	20000	20000	20000	0	5000	5000	5000	0	sq.ft.	2	Ceiling Tile
23	Tele/data, Nurse Call, Security, AV, and Fire Alarm	0,008	3000	3000	3000		2500	2500	2500	0	3000	3000	3000	0	2500	2500	2500	0	1000	1000	1000	0	(lf)	1	Electrical
24	TOP TRACK, BEAM CLAMPS ETC.	0,25	1000	1000	1000	0	650	650	650	0	1000	1000	1000	0	650	650	650	0				1500	(lf)	2	Drywall
25	VAV and Low Pressure Ducts	0,1	4000	4000	4000		2650	2650	2650		4000	4000	4000		2650	2650	2650						(lf)	1	Mechanical
26	Wall, Hard Ceiling, and Soffit Framing	0,04	1900	1900	1900	0	1300	1300	1300	0	1900	1900	1900	0	1300	1300	1300	0				3000	sq.ft.	2	Drywall
27	Wall, Hard Ceiling, and soffit MEP Roughins	0,3	25	25	25	0	15	15	15	0	25	25	25	0	15	15	15	0	0	0	0	40	No.	1	Mechanical

Figure 38: Excel datasheet (elaboration of the authors)

6.3.2 Add dependency to all tasks

We have distributed the subcontractors to the activities and we have arranged the correct sequence of tasks. At this point, we were conscious because one of the challenges was to prepare the schedule with correct dependencies.

	Sequence of activities
	Item
1	TOP TRACK, BEAM CLAMPS ETC. (After structure completed in an area)
2	Fireproofing (NOTE: Fireproofing on the third level can only start after roof has been completed in the same quadrant)
3	Frame priority fullheight walls etc.
4	Sprinkler Rough
5	Medium pressure duct
6	Mechanical Rough
7	VAV and Low Pressure Ducts
8	Dom Water
9	Rain Water Leaders, Waste and Vent
11	Branch conduit
12	Feeder conduit
13	Wall, Hard Ceiling, and Soffit Framing
14	Wall, Hard Ceiling, and soffit MEP Roughins
15	MED GAS
16	Cable Tray
17	Tele/data, Nurse Call, Security, AV, and Fire Alarm
18	Drywall
19	Tape and Finish
20	Paint
21	T-Bar
22	Light Fixtures, Diffusers, Ceiling Mounted Trim
23	Ceiling tile
24	Casework, Millwork
25	MEP Trim
26	Floor coverings
27	Specialties and accessories
28	Doors & Hardware

Figure 40: Sequence of activities (elaboration of the authors)

The maximum resources for each trade are as follows:

Subcontractor	Maximum Resources
Casework	12
Ceiling	12
Doors, Frames and Hardware	4
Drywall	20
Electrical	12
Fire Sprinkler	3
Fireproofing	10
Floor Coverings	12
Mechanical	16
Painting	8
Plumbing	8
Specialties	1

Figure 39: Number of maximum resources for each subcontractor (elaboration of the authors)

Here it is presented an example of the way in which we have assigned the dependency and the same process has been carried out for all other activities:

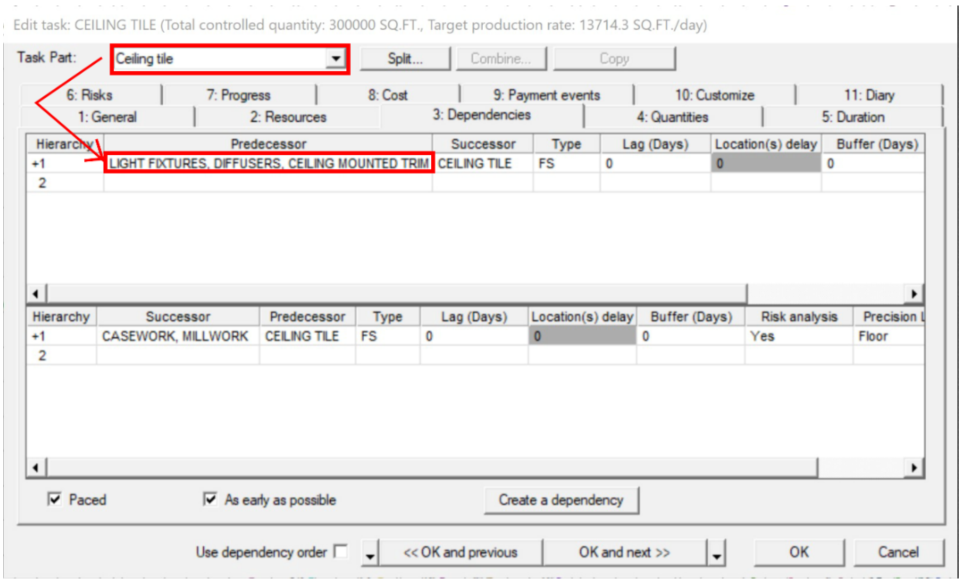
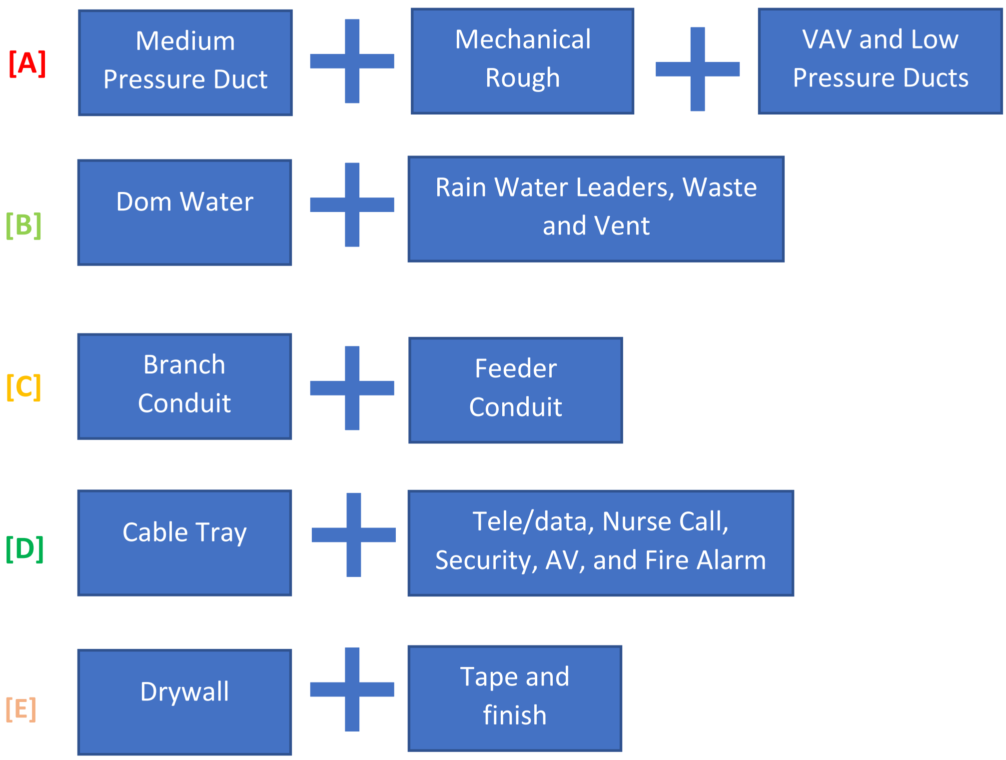


Figure 41: Assign dependency (elaboration of the authors)

6.4 Schedule adjustment

6.4.1 Combine tasks

We have deeply analyzed the slopes of consequent activities and we have decided to combine them if they were provided by the same supplier. We have done this operation with these tasks:



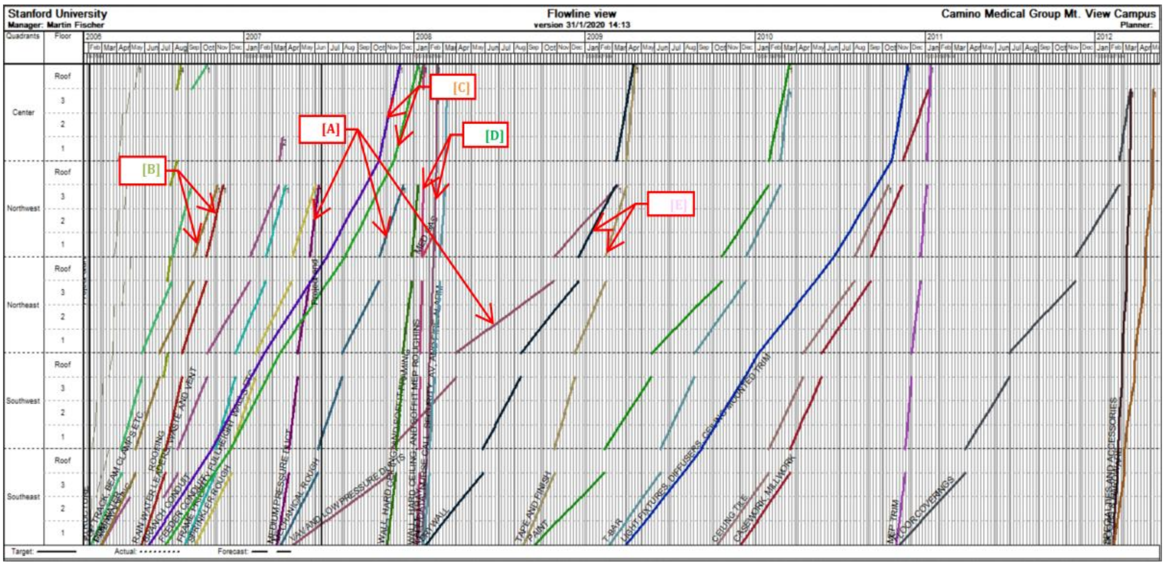


Figure 42: Before combination (elaboration of the authors)

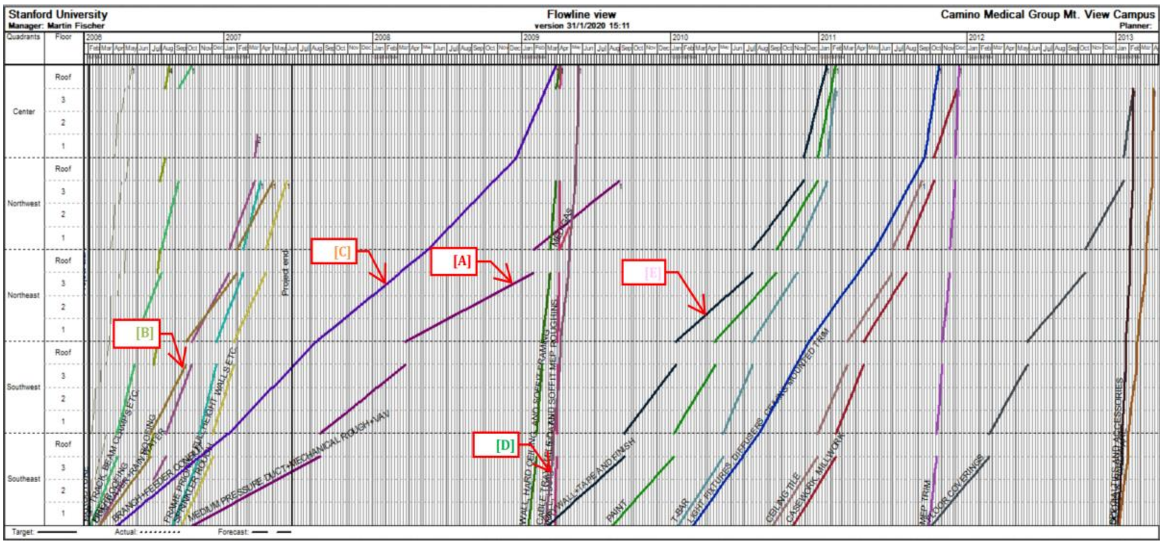


Figure 43: After combination (elaboration of the authors)

6.5 Interceptions removal and optimization

As mentioned before, one of our main goals was removing all the interceptions between different tasks. Due to this and due to a preliminary optimization of the slopes and the resources number, we were able to anticipate the project end from April 2013 to July 2007.

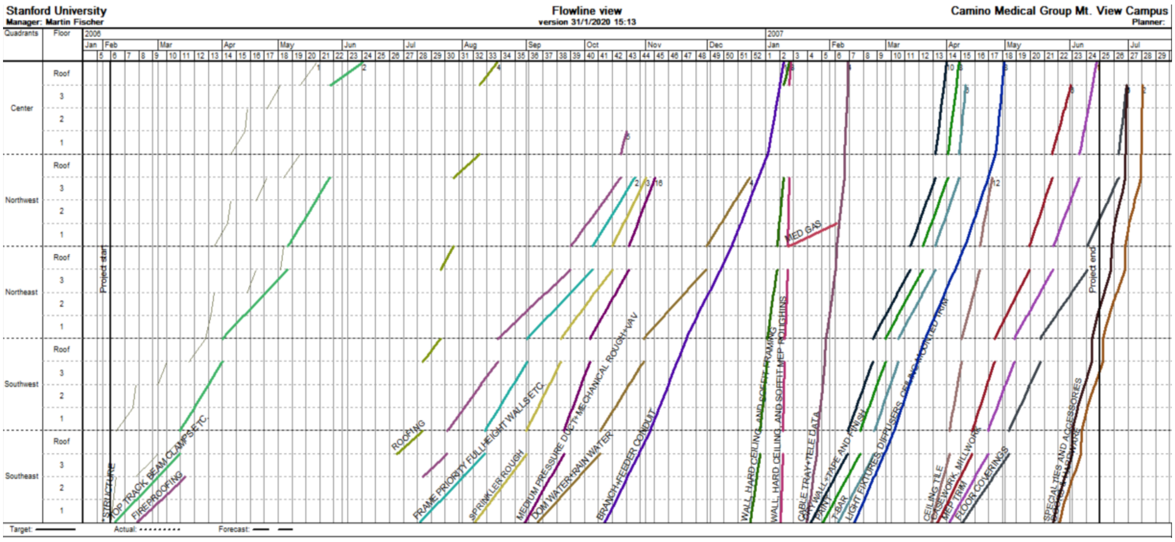


Figure 44: Preliminary optimization (elaboration of the authors)

6.5.1 Further optimization

In order to complete the project before the deadline, we have proceeded with a further optimization focusing our attention on Fireproofing, T-Bar, Dom Water and MED Gas tasks. Due to this operation, we were able to minimize the completion time by 2 months.

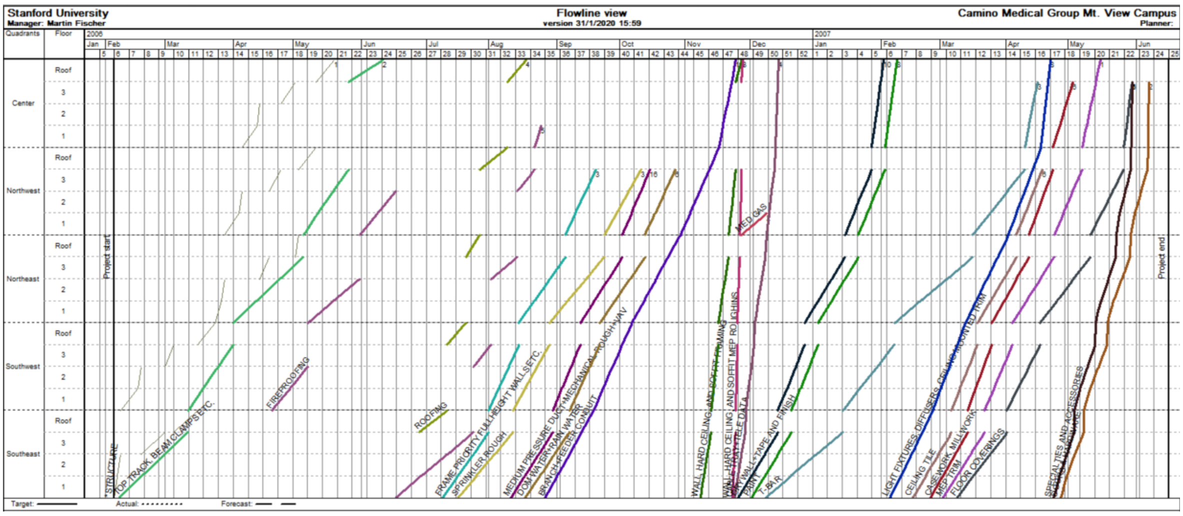


Figure 45: Further optimization (elaboration of the authors)

6.6 Buffer addition in critical tasks

Adding buffers is a way of managing activities when unforeseen events occur. It helps to continue the work without major fluctuations. Time buffers are added between the tasks to protect hand-offs. The following table shows how decided to add buffers in the case study.

Activities	Buffers [days]
TOP TRACK, BEAM CLAMPS ETC.	5
Fireproofing	0
Frame priority fullheight walls etc.	1
Sprinkler Rough	3
Medium pressure duct + Mechanical Rough + VAV	5
Dom Water + Rain Water Leaders, Waste and Vent	5
Branch conduit + Feeder conduit	3
Wall, Hard Ceiling, and Soffit Framing	3
Wall, Hard Ceiling, and soffit MEP Roughins	7
MED GAS	3
Cable Tray + Tele/data	0
Drywall + Tape and Finish	2
Paint	2
T-Bar	2
Light Fixtures, Diffusers, Ceiling Mounted Trim	0
Ceiling tile	6
Casework, Millwork	0
MEP Trim	1
Floor coverings	2
Specialties and accessories	5
Doors & Hardware	0
Total	**54**

Table 5: Time buffer addition (elaboration of the authors)

After the buffer addition, our final version of the schedule is shown in the following figure:

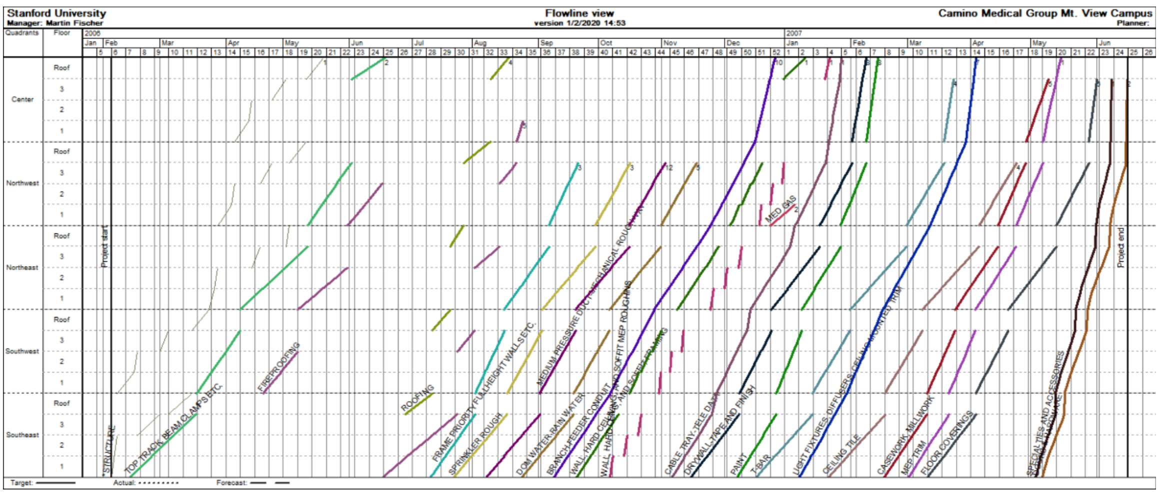


Figure 46: Schedule after buffer addition (elaboration of the authors)

Table 6 on the right is the Resource Registry taken from the software and it shows how we have respected the maximum number of resources for each trade during our optimization process.

Name	No	Maximum usage
casework	10	
casework	10	12
ceiling tile	12	
ceiling tile	12	12
doors, frames hardwar	4	
doors and frames hard	4	4
drywall	18	
drywall	18	20
electrical	11	
electrical	11	12
fire sprinkler	3	
fire sprinkler	3	3
fireproofing	10	
fireproofing	10	10
flooring	12	
flooring	12	12
mechanical	13	
mechanical	13	16
painting	8	
painting	8	8
plumping	5	
plumping	5	8
specialities	1	
specialities	1	1
t resources	8	
Roofing	8	

Table 6: Resource Registry (elaboration of the authors)

6.7 Risk Analysis

Risk analysis has been carried out inserting the **intermediate risk level** on every task. The simulation process has been conducted with 1000 iterations using the Monte Carlo Method's function provided by the software. The results of our risk analysis is shown in the following picture. We have been able to identify the major sources of risks which are Wall, Hard Ceiling, and soffit MEP Roughins, MED Gas and Cable Tray + Tele Data tasks. Critical activities are displayed through red dots.

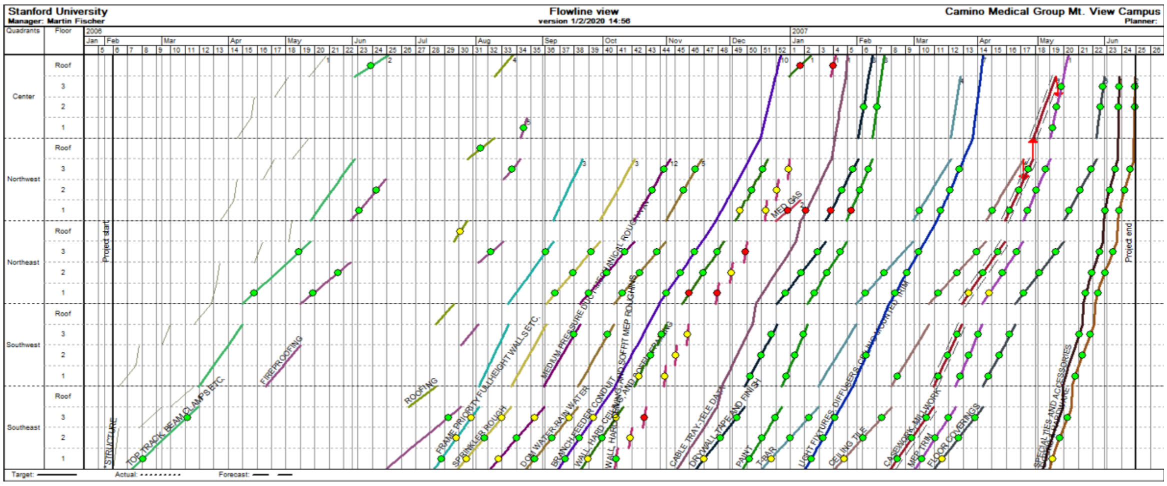


Figure 47: Risk analysis (elaboration of the authors)

6.8 Fluctuation analysis

Our optimization process has been made following the goal of reducing the majority of fluctuations during tasks of the same contractor. Obviously, it has not always been possible due to the variety of the trades and the wide temporal distance in some of them. The following figures shows our results:

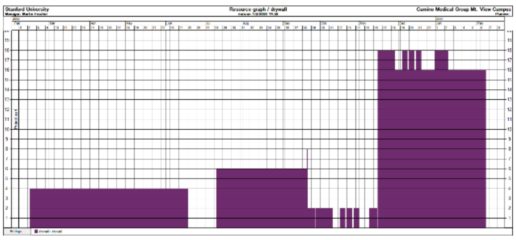


Figure 48: Drywall subcontractors fluctuation

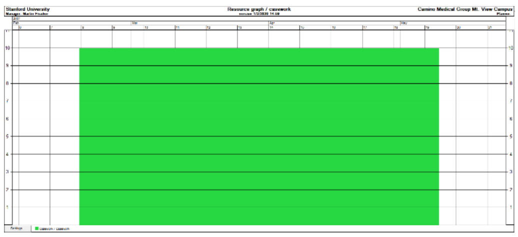


Figure 49: Casework subcontractors fluctuation

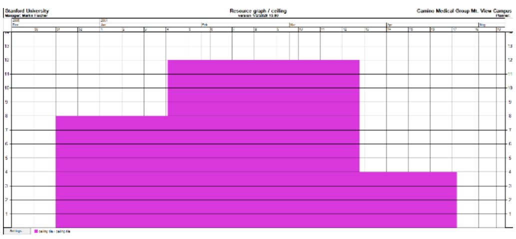


Figure 50: Ceiling subcontractors fluctuation

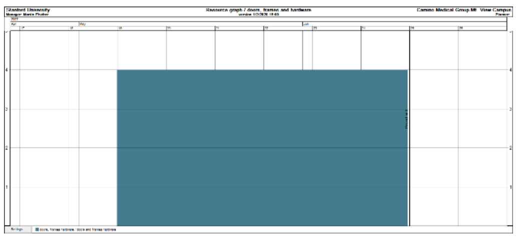


Figure 51: Doors subcontractors fluctuation

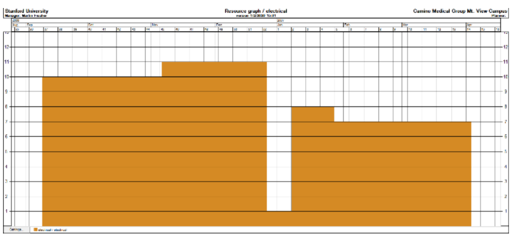


Figure 52: Electrical subcontractors fluctuation

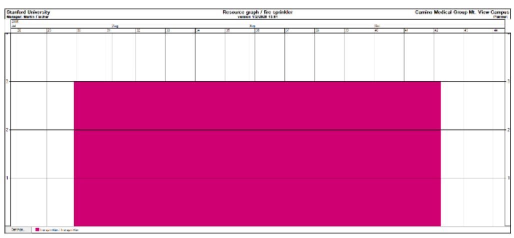


Figure 53: Fire Sprinkler subcontractors fluctuation

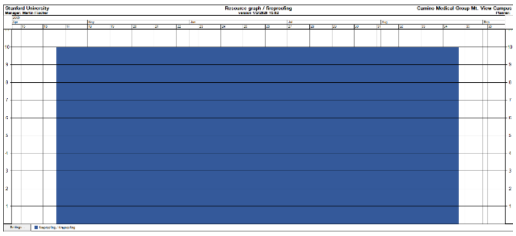


Figure 54: Fireproofing subcontractors fluctuation

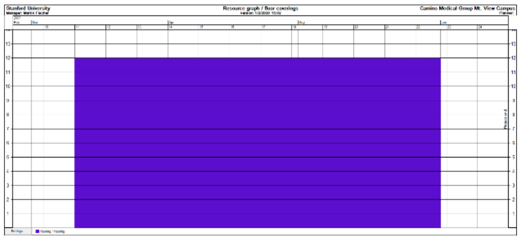


Figure 55: Floor Coverings subcontractors fluctuation

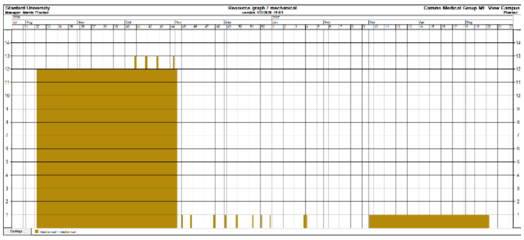


Figure 56: Mechanical subcontractors fluctuation

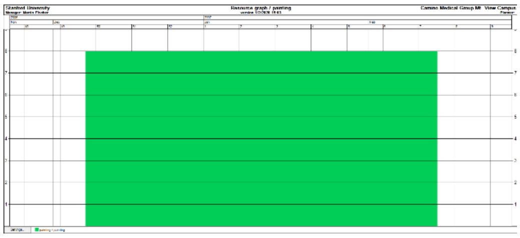


Figure 57: Painting subcontractors fluctuation

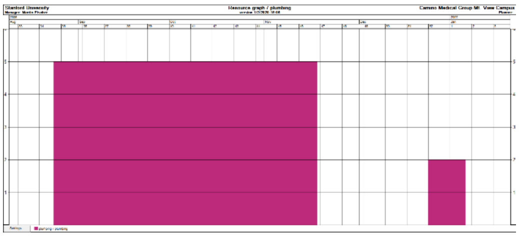


Figure 58: Plumbing subcontractors fluctuation

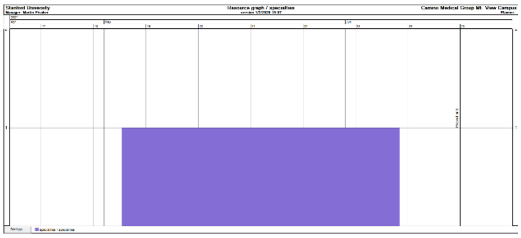


Figure 59: Specialties subcontractors fluctuation

6.9 Results and conclusion

The optimization process that we have used in this case study leads to very satisfactory results. Applying theoretical foundations provided by LBMS, we have been able to complete all the activities within the proposed deadline, we have been able to guarantee a good continuity in the work flow and we have guaranteed a very similar slope among the various tasks, leaving just 2 important time gaps (between weeks 41 and 44 in 2006 and between weeks 11 and 17 in 2007).

Moreover, we have demonstrated in practice the location-based planning paradox, that is, as LBMS leads to substantial reduction of the project duration, decreasing the number of resources and without compromising the constructive logic of the various construction phases.

Chapter seven: Controlling Case Study

7.1 Case Study introduction

The case study presented in this chapter was proposed in February 2020 to the students of the Operation Management in Construction course held by Professor Olli Seppänen, lecturer at Aalto University in Espoo (Finland). This chapter has been inserted in the thesis to show the reader how the theoretical foundations concerning the Location-Based Controlling System, discussed in paragraph 2.3.2, are applicable in reality and to what results they lead.

The objective of the proposed case study is to create a simulation, as realistic as possible, of the daily difficulties, complexity and unpredictability that can occur in a construction project and, consequently, show how certain actions and decisions taken in real-time influence the carrying out the project itself.

The case study was established with the help of the Schedule Planner software developed by Vico Office.

7.2 Instructions

This case study was individually assigned by Professor Seppänen to the students.

Through the university's teaching platform, the professor provided two daily updates (approximately 8.30 - 9 AM and 4.30-5 PM) in which information on the progress of work in a hypothetical project was communicated from time to time. The students' task was, following the guidelines explained in paragraph 2.3.2, to upload this information on the Schedule Planner software, to verify and analyze what kind of impact they had on the progress of the project, to discuss with classmates on the reactive solutions to be adopted, to take an unambiguous decision on what to do and communicate corrective actions to the teacher always through the platform. Actions could be for example:

- Ask contractor X to increase the number of resources for activity Y;
- Postpone the start of activity X;
- Start the X activity on the Y floor instead of the Z floor.

The simulated "return" decisions and the new scenarios were communicated to the students through the subsequent update together with the explanation of the new scenario developed.

The assignment lasted 12 days for a total of 23 updates.

The case study takes into consideration a simplified scenario with only seven tasks:

- R / P SOMD (concrete pouring over slab on metal deck);
- LAYOUT / TOP TRACK (section of a non-load bearing wall framing assembly that is fastened to the primary structure, left unconnected to the vertical stud member);
- OVERHEAD MEP INSTALL (installation of MEP cables on the ceiling);
- STUDS (vertical framing members which form part of a wall or partition);
- IN-WALL MEP ROUGH-IN (all electrical cables have been pulled through studs and inserted into wall);
- DRYWALL INSTALL (application of walls without mortar or plaster);
- FINISHES (used in final part of construction, forming the final surface of an element).

7.3 Scenario Updates

The starting point of the Production Control Assignment has been **the week 4** (red dotted vertical line is on week 5 because Figure 48 is the result of having already entered the input in Schedule Planner software, Figure 48 shows what is going to happen the following week) because the previous three updates have been developed during class under the professor's supervision:

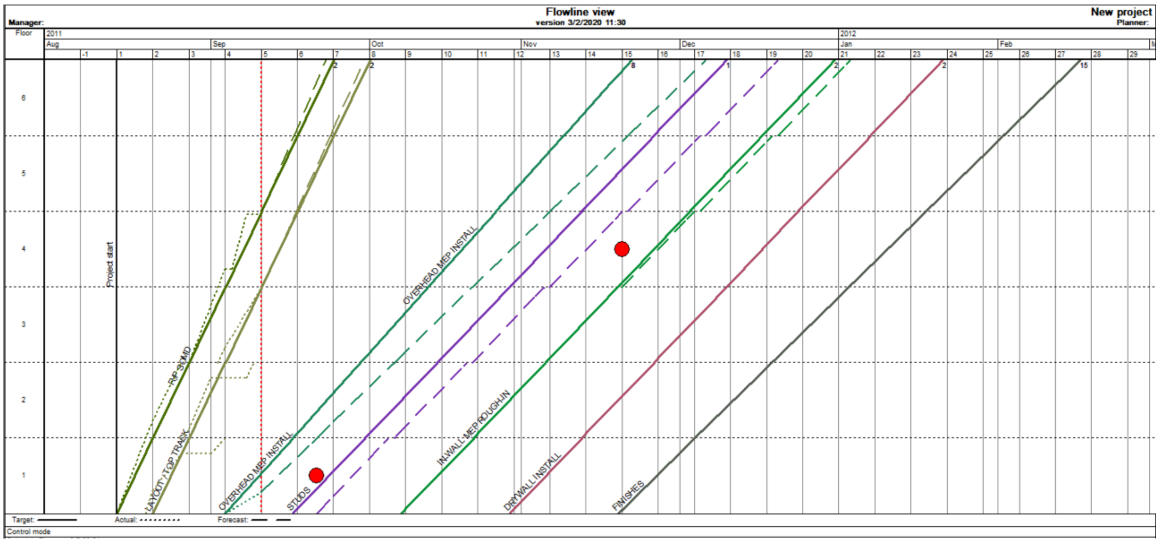


Figure 60: Week 4 update (elaboration of the author)

Due to the fact that the forecast on MEP Install behavior would have influenced the following tasks causing delays (red dot in location one), we have proposed an increase in the number of his resources. The following image shows **the week 5 update**:

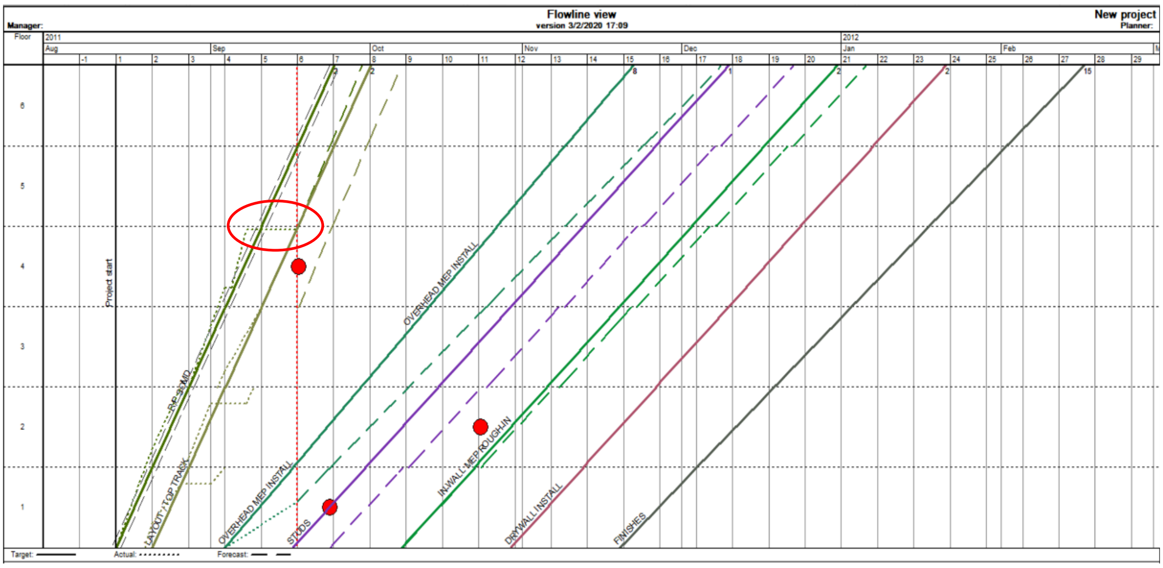


Figure 61: Week 5 update (elaboration of the author)

This week we have experienced a simulated bad weather scenario, so R/P SOMD team on the fourth floor had to stop working (horizontal dotted line). MEP installers had not arrived yet, so we proposed to start working on Saturdays (until that moment the working week was Monday-Friday). The following image shows **the week 6 update**:

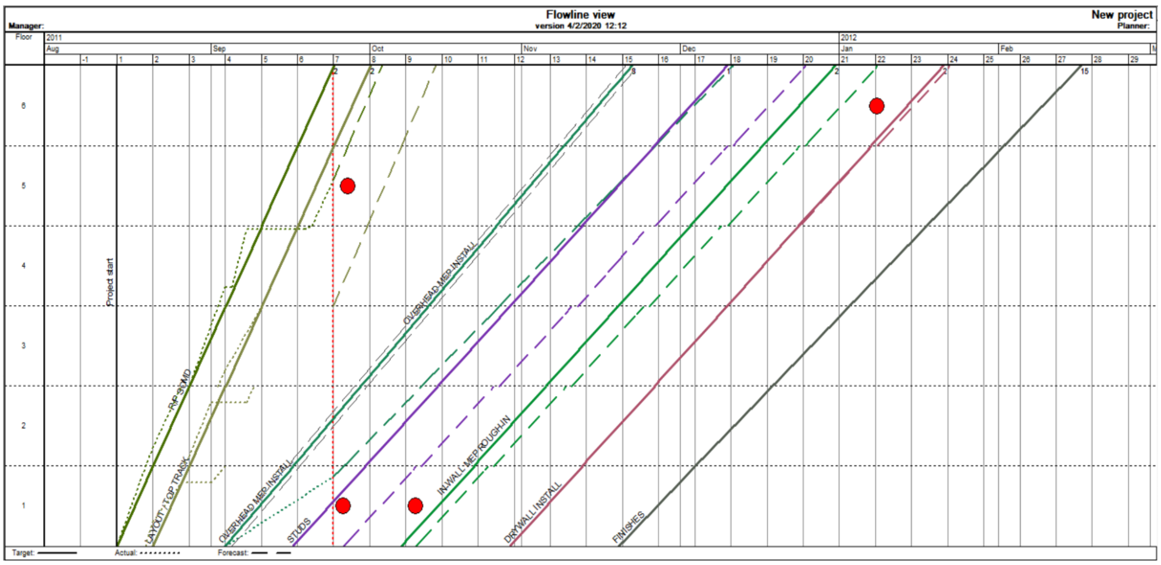


Figure 62: Week 6 update (elaboration of the author)

We had reached the maximum amount of resources in MEP tasks so, basically, we couldn't have speeded up the process. Our proposal was to add a time buffer in order to give flexibility to the schedule and starting the Studs task on week 8. The following image shows **the week 7 update**:

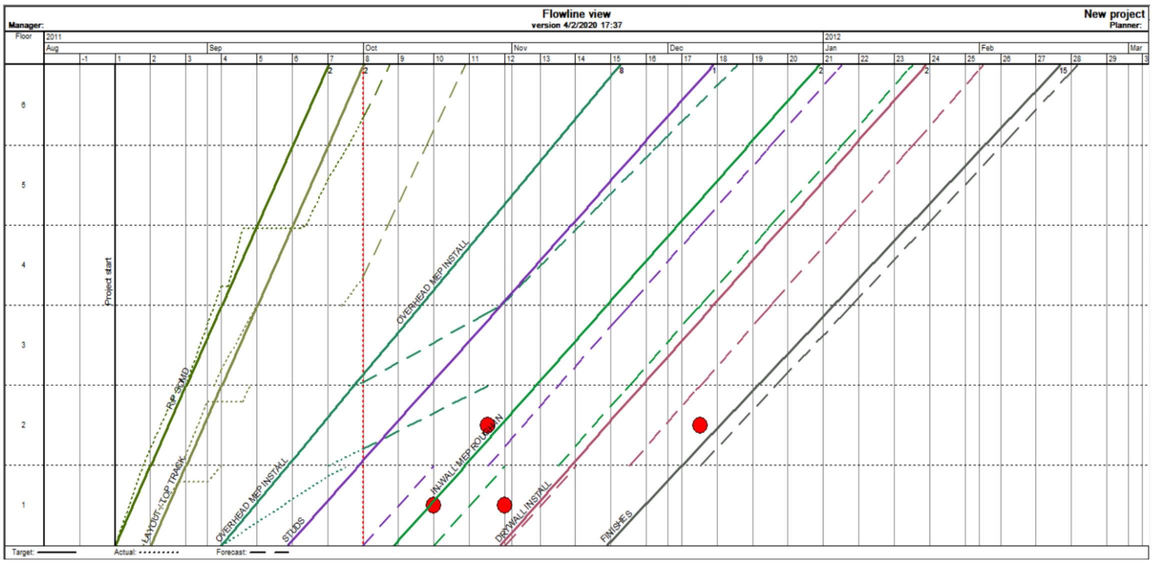


Figure 63: Week 7 update (elaboration of the author)

We have decided to prioritize the MEP task completion on the second floor. The following image shows **the week 8 update**:

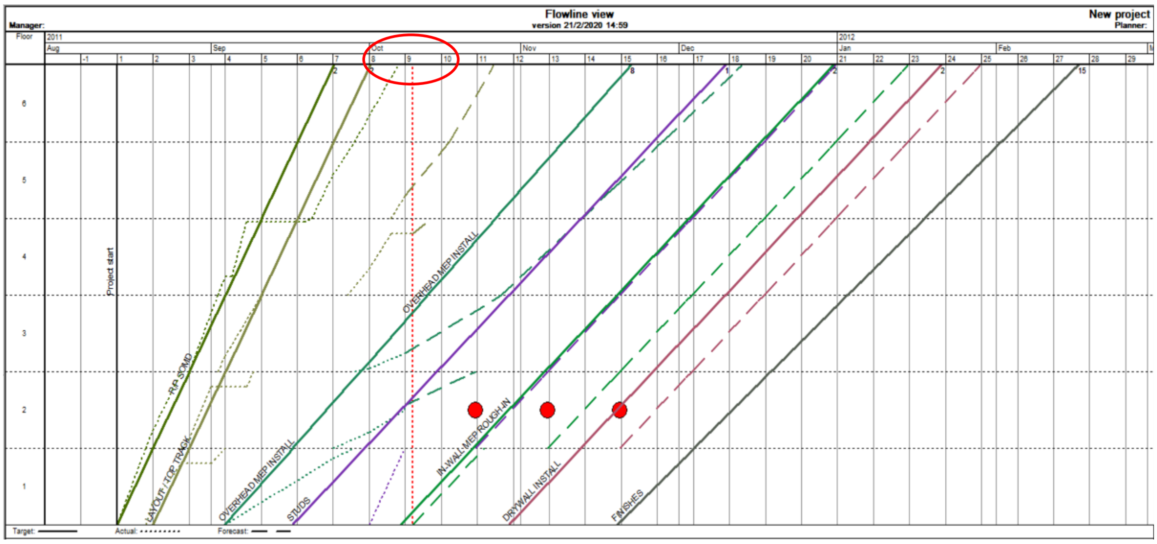


Figure 64: Week 8 update (elaboration of the author)

Until now, the work week was Monday-Friday and the software defaulted to Saturday and Sunday as days off. For this reason, each week was counted from Sunday to Sunday.

From this update onwards, we were able to get the work teams to work in overtime even on Saturdays but, due to an unchangeable setting of the software that requires two days off to record the data, the new reference day for all subsequent updates will be on Monday. The proposed control action was to prioritize the Layout/Top Track in floor 4 before going to the fifth floor. Studs crew ran out of work and decided to help the Layout/Top Track crew to finish the fourth floor. The following image shows **the week 9 update**:

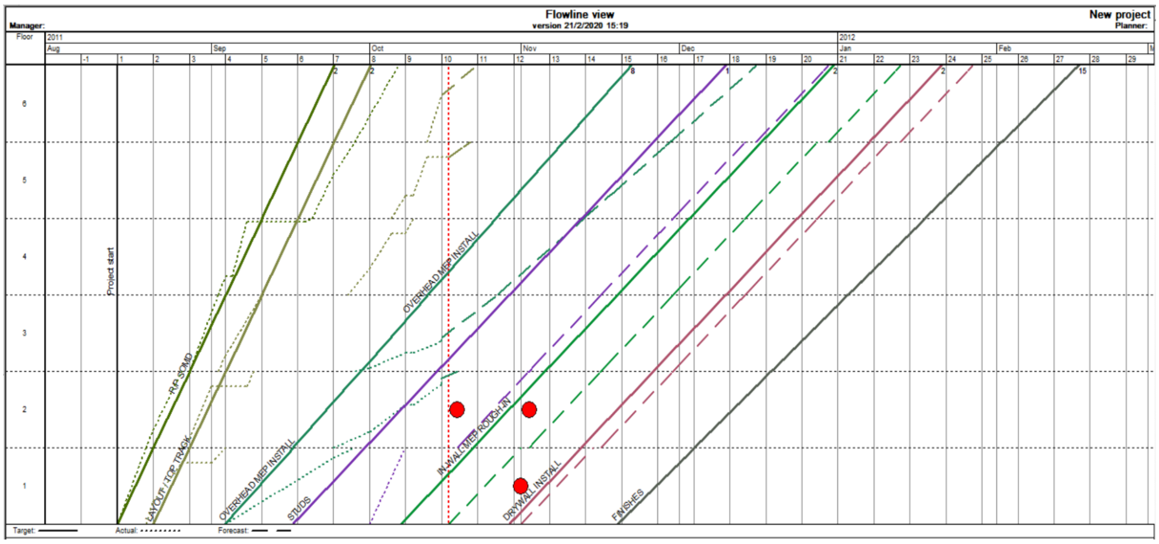


Figure 65: Week 9 update (elaboration of the author)

MEP delay was badly influencing the following task, so we have tried to focus the attention on continuing the work with the same crew size on the second floor. The following image shows **the week 10 update**:

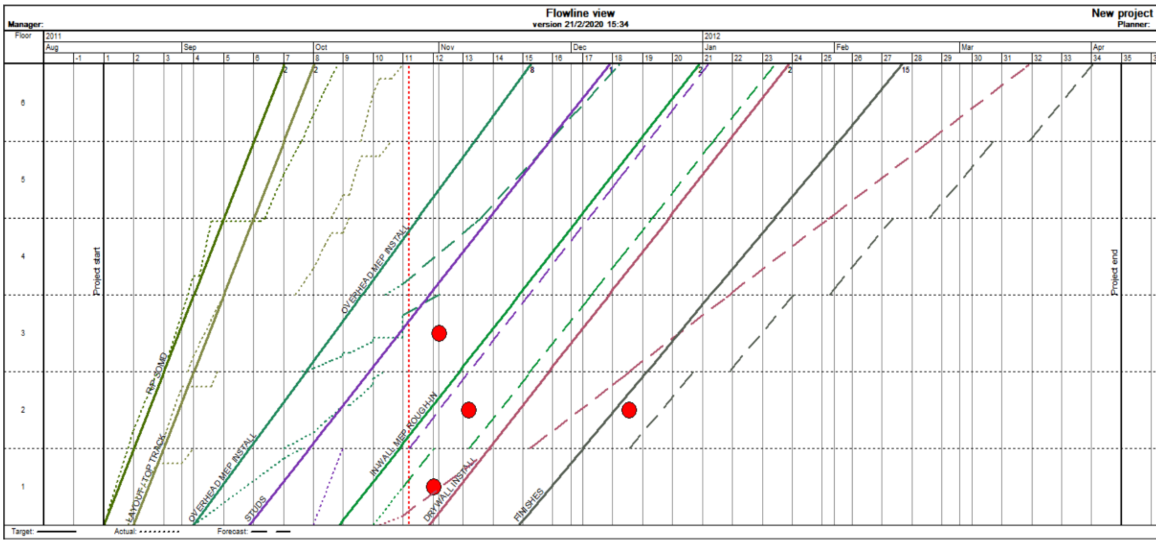


Figure 66: Week 10 update (elaboration of the author)

With the actual resource, Drywall Install would have been too slow so we have proposed to add 2 more resources to the contractor and again 2 more resources to studs work. The following image shows **the week 11 update**:

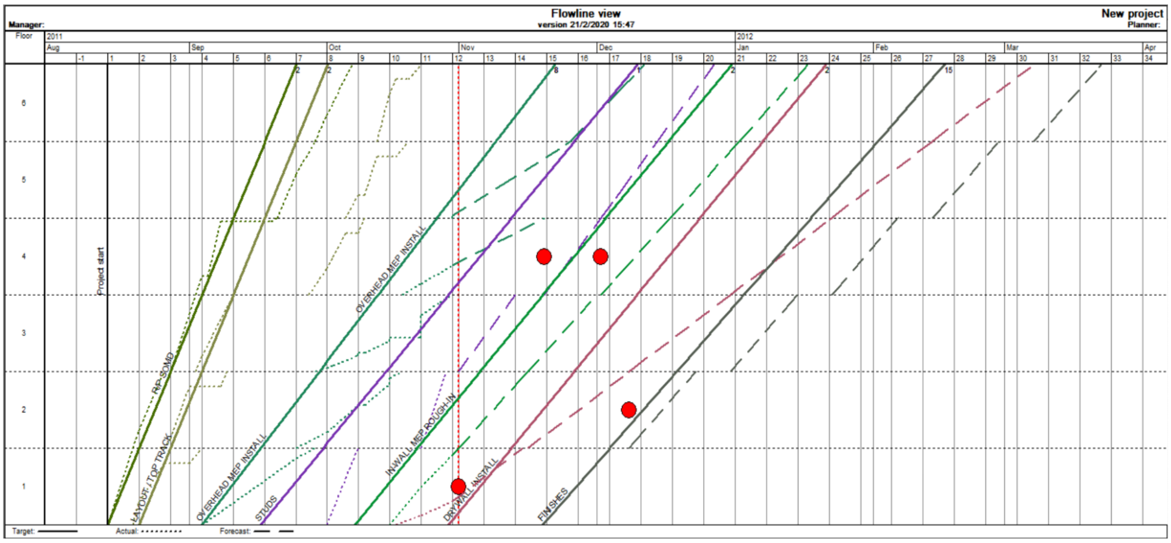


Figure 67: Week 11 update (elaboration of the author)

More Drywall workers were coming so basically we hadn't proposed any control actions, but we had discussed about the future scenario regarding drywall and finishes tasks. The following image shows **the week 12 update**:

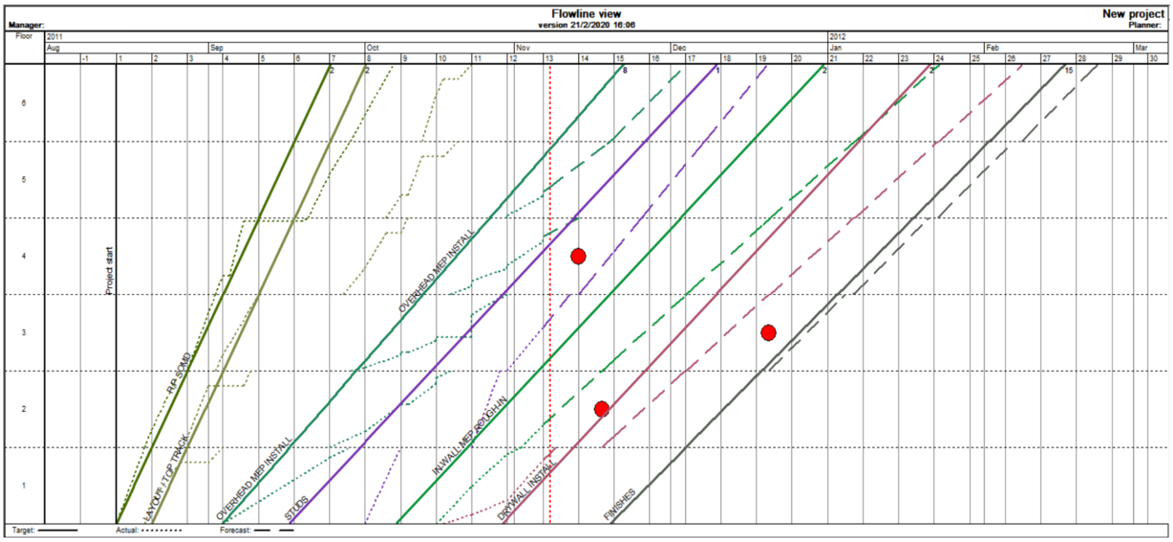


Figure 68: Week 12 update (elaboration of the author)

One member of the team has tried to add one resource in the MEP task and, after showing us the advantageous result of this solution, we have required one more electrician in MEP. The following image shows **the week 13 update**:

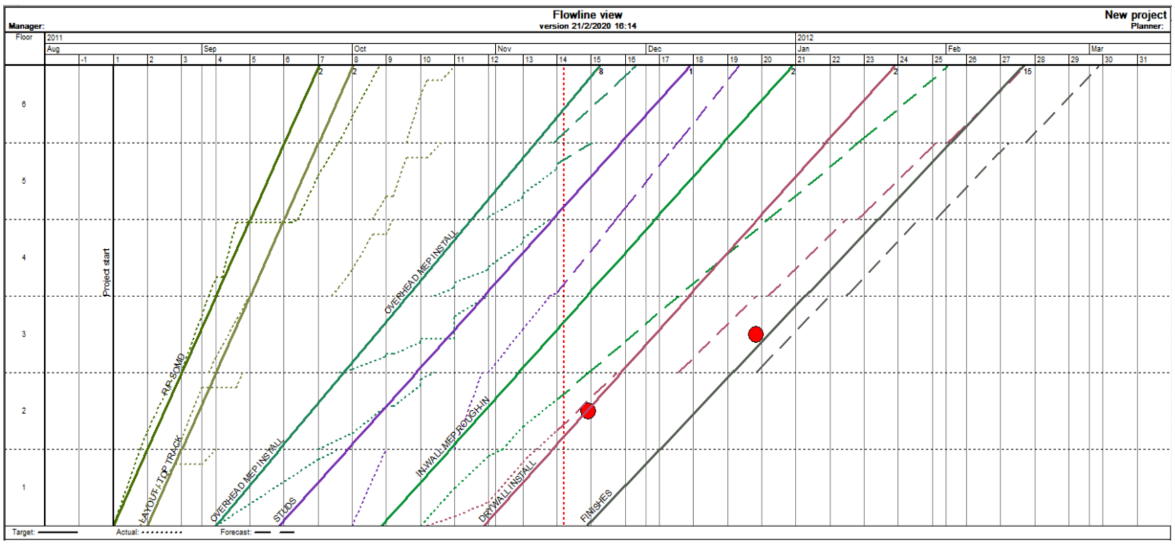


Figure 69: Week 13 update (elaboration of the author)

The proposed control action was to prioritize the Overhead MEP in floor 5 before going to the sixth floor. Moreover, we have decided to work on Saturdays in the In-Wall MEP activity. The following image shows **the week 14 update**:

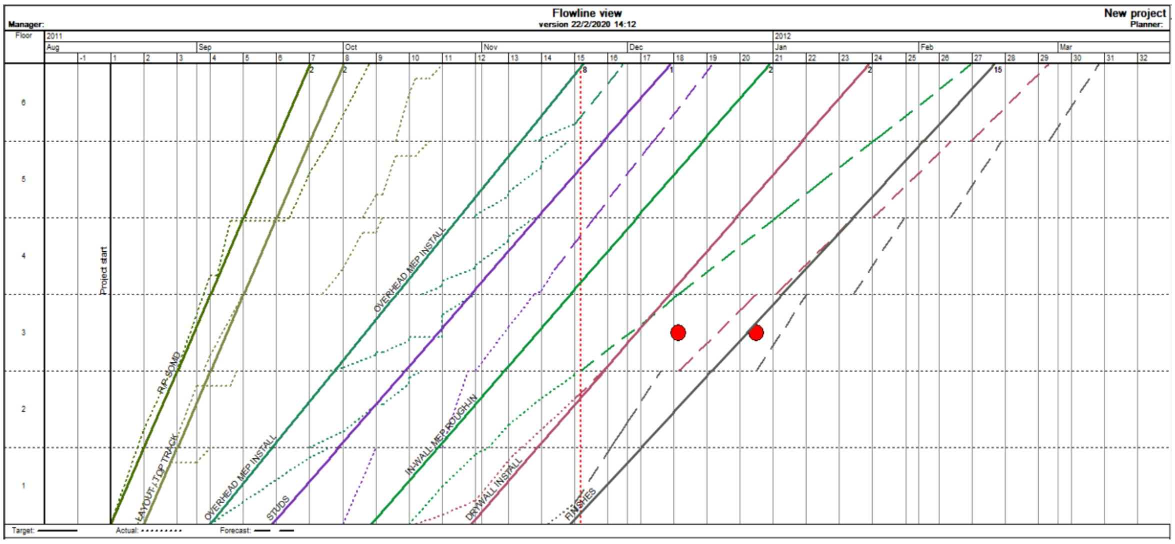


Figure 70: Week 14 update (elaboration of the author)

We were waiting for new electrician who was supposed to arrive the following week, so we haven’t proposed anything. The following image shows **the week 15 update**:

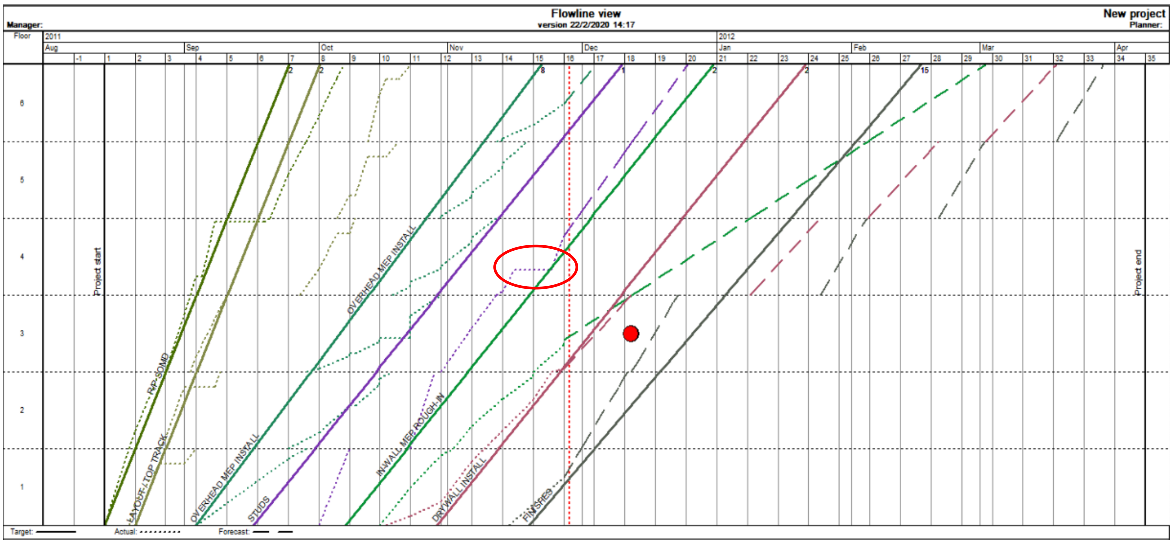


Figure 71: Week 15 update (elaboration of the author)

Figure 71 shows a design problem on fourth floor with Studs tasks (horizontal dotted line), so the crew has been forced to stop the work. In-Wall MEP was still causing delays, so we have proposed to maximize the number of resources for this task and to continue working on Saturdays. The following image shows **the week 16 update**:

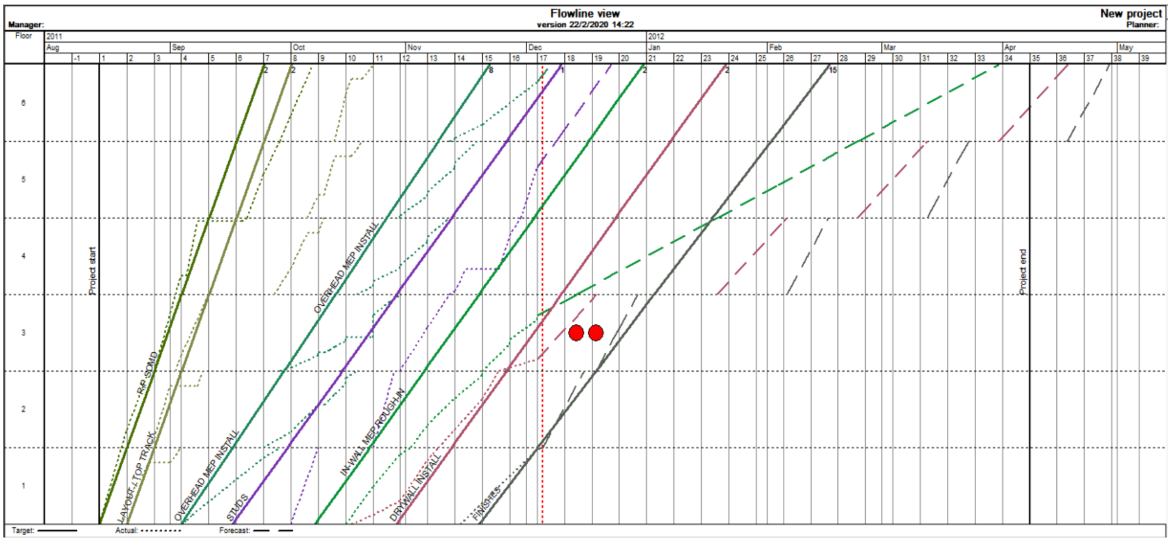


Figure 72: Week 16 update (elaboration of the author)

We have requested to add more resources to In-Wall MEP task because, as already mentioned before, this has been the most critical activity since the beginning of the project. The following image shows **the week 17 update**:

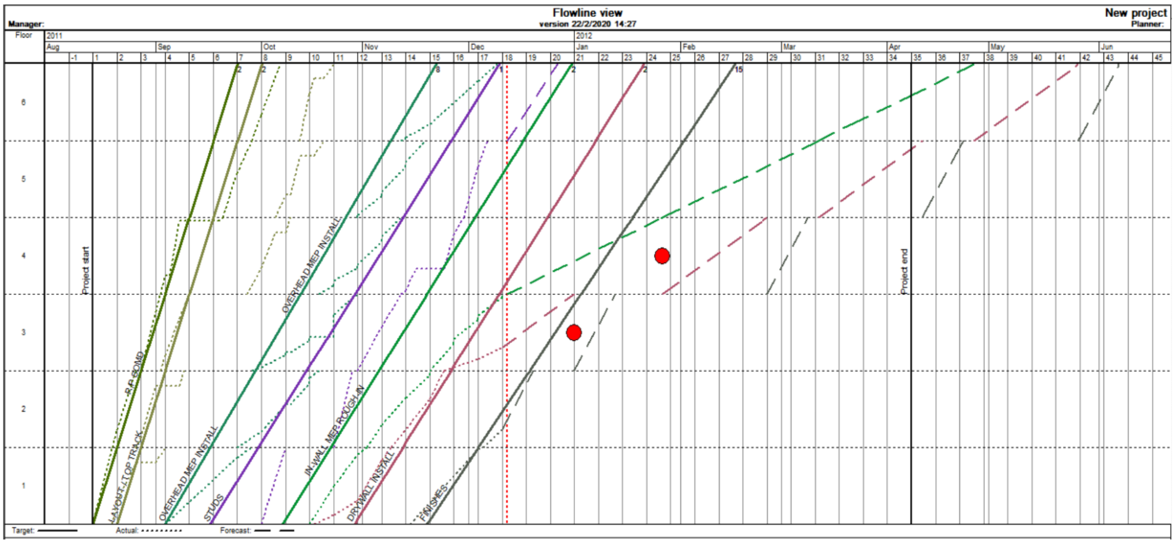


Figure 73: Week 17 update (elaboration of the author)

Due to the fact that Studs crew was about to end his work, we have requested to move 2 of those people to Drywall task. Moreover, we have requested 7 more electricians for In-Wall MEP task. The following image shows the **week 18 update**:

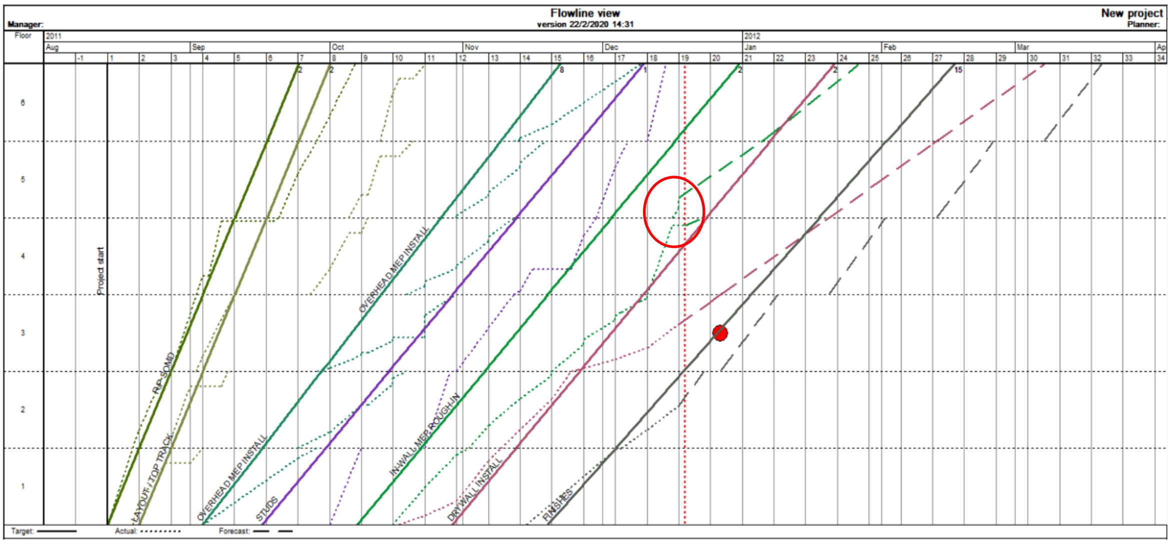


Figure 74: Week 18 update (elaboration of the author)

In this update we have faced changes coming to electrical sockets on the forth floor, so In-Wall MEP had to move to the fifth floor (red circle in figure 74 highlights the jump of location). We have asked them to come back to the fourth after design issue was fixed. Moreover we have requested more resources Drywall task. The following image shows **the week 19 update**:

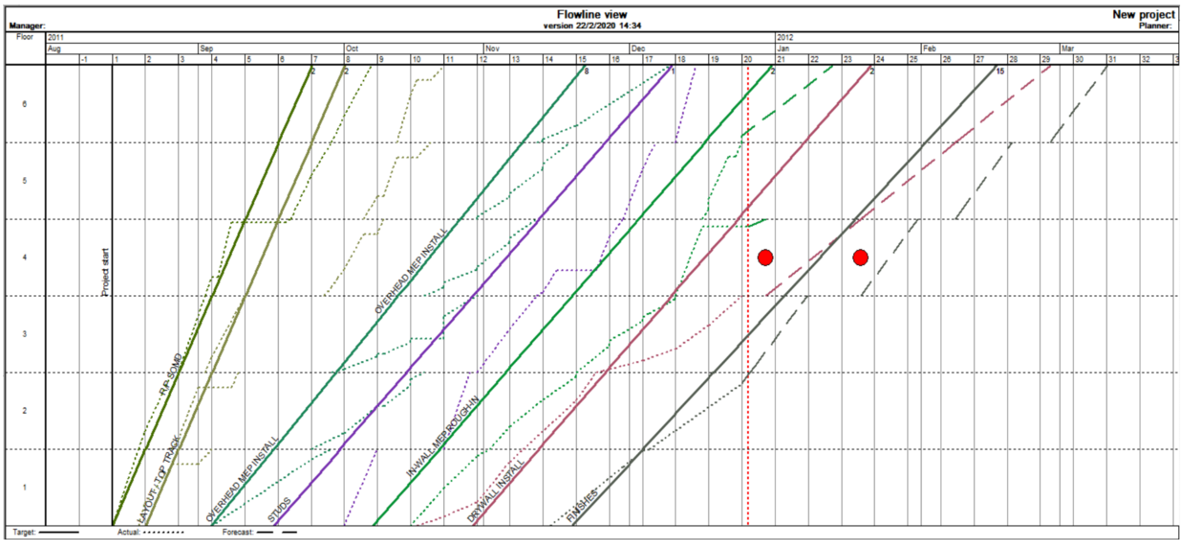


Figure 75: Week 19 update (elaboration of the author)

We have requested to add 2 more resources to Drywall task and move to the fifth floor. Moreover, we have requested 4 more resources to Finishes task. The following image shows **the week 20 update**:

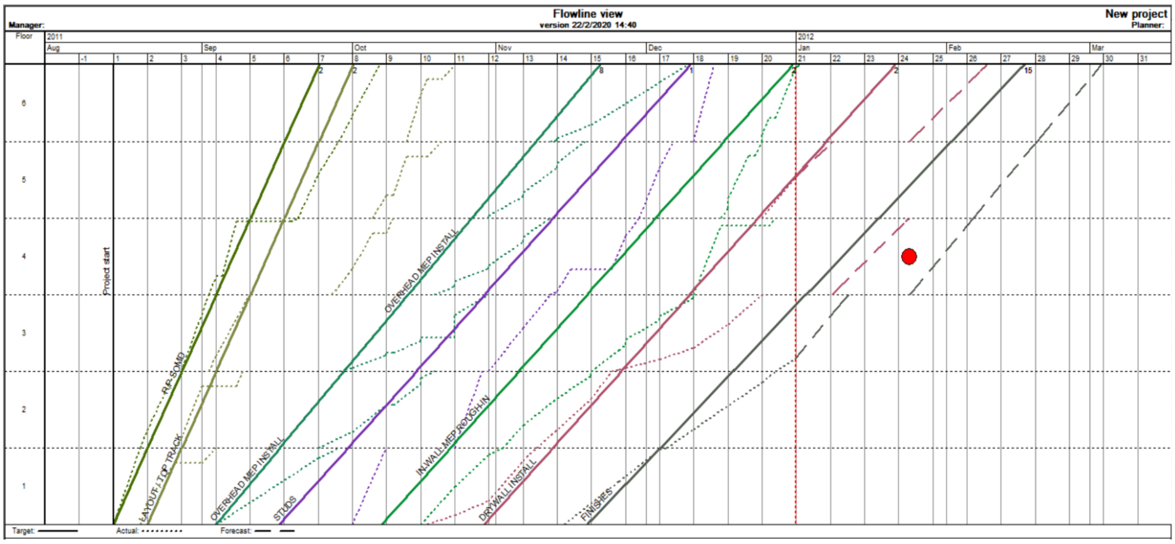


Figure 76: Week 20 update (elaboration of the author)

No control action has been taken by the team. The following image shows **the week 21 update**:

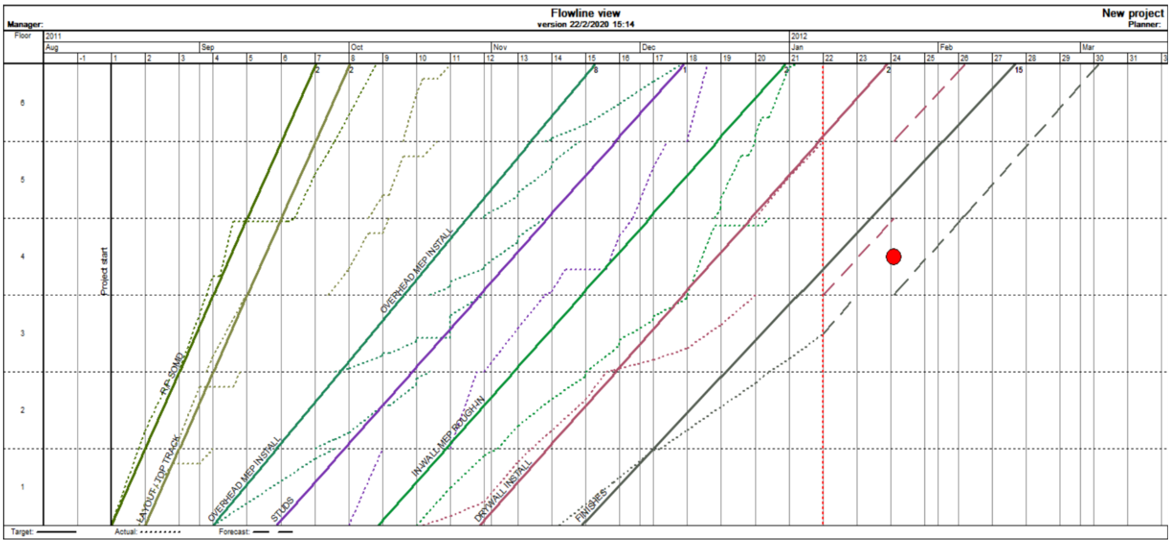


Figure 77: Week 21 update (elaboration of the author)

We have decided to split Finishes resources between floor 3 and 5 in order to guarantee the same speed of completion. The following image shows **the week 22 update**:

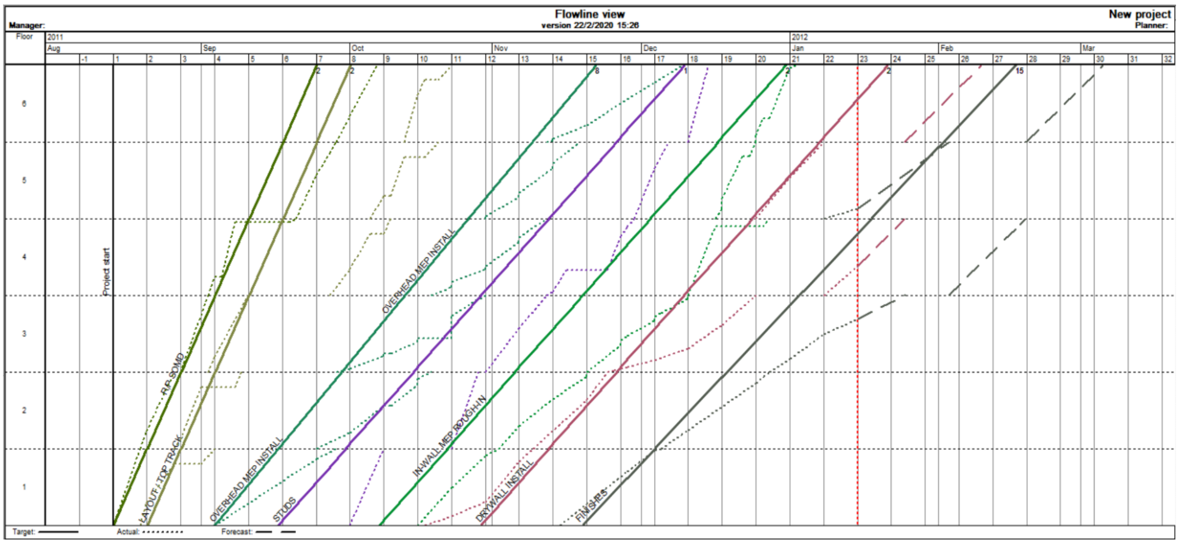


Figure 78: Week 22 update (elaboration of the author)

We have decided to continue with current resources, no control action has been taken. The following image shows **the week 23 final update** of this project:

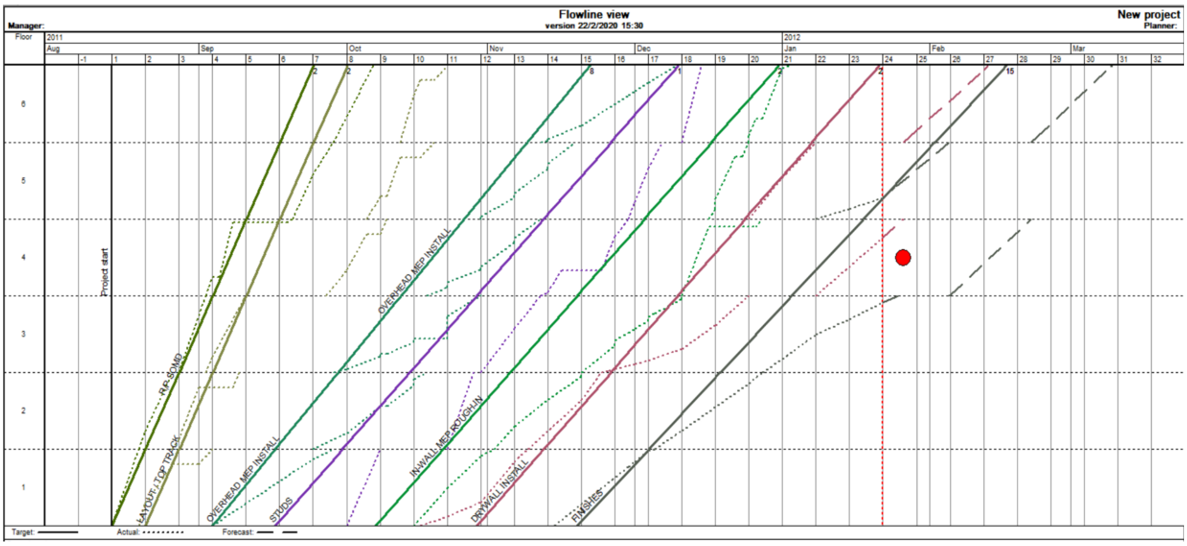


Figure 79: Week 23 final update (elaboration of the author)

7.4 Results and conclusion

The Location-Based Controlling System case study shown in this chapter is very valuable because it illustrates in a simple and intuitive way which dynamics can occur daily in any real construction project. Problems of bad weather, design errors, contractors who do not collaborate and think exclusively of their interests: these are all factors that heavily influence the correct execution of the works.

In this specific case, the most problematic subcontractor was Finishes due to its “Is other team still working? Ok, then I'll come back "or" I won't drop the team because we have enough work”. This is exactly one of the bad behaviors identified in paragraph 2.5.1 "Traditional behavior of subcontractors”.

This case study also brilliantly illustrates how the presence of a bottleneck subcontractor massively affects all subsequent activities. Here, the bottleneck subcontractor was In-Wall MEP because, even though we had reached the maximum amount of available resources, due to the complexity of the work it was too slow, causing cascading delays in subsequent activities.

In general, despite some exceptions, the subcontractors show good behavior, have been willing to frequently increase the number of resources for each assignment and have even agreed to work on Saturdays to speed up the project.

In this case study, the information and the consequences of the control actions undertaken in real time had a weekly frequency due to the desired approach of Prof. Seppänen. Obviously if the check had taken place more frequently, for example on a daily basis, there would have been the possibility of making a more reactive and immediate decision in response to individual daily critical issues.

Finally, it is important to underline that the planning of the activities was not carried out jointly by all the subcontractors; in fact, a preliminary work meeting was not organized as described in paragraph 5.1 “Combination LBMS-LPS”. The lack of pre-planning and social interactions between the various stakeholders before the execution of the project led to delays, misunderstandings, continuous requests for increased resources, non-continuous workflow, poor coordination between teams, etc., i.e. all the problems already described in previous chapters.

The case study shown in this chapter is the emblem of how there is an extreme need to integrate various planning and control models together in order to overcome the single criticalities presented by the single methods.

Chapter eight: Future development

8.1 Combination LBMS – LPS – CPM

8.1.1 Introduction

The circle opened in Chapter one with the introduction to planning and control in the construction world ideally closes with the drafting of this Chapter eight. The idea developed was to show the characteristics and potential of the three methods LBMS, LPS and CPM and then continue with paragraphs 5.1, 5.2 and 5.3 in which the models were coupled two by two and the integrative possibility and the theoretical results they would have reached were discussed.

During this thesis we have come several times to the conclusion that the methods proposed so far are singularly very valid as their use is able to give a significant performance benefit for the purposes of the realization of a project. However, they are not perfect as the criticalities listed for each model make them "vulnerable" and not always usable in every application. Therefore, the need to try to reach a broader level of integration than the ones presented up to now arises.

Here, therefore, the culmination of the theoretical dissertation is accomplished in this Chapter, in which an integrated model that simultaneously considers Location Based Management System, Last Planner System and Critical Path Method will be proposed.

Based on Olivieri, H., Seppänen, O., & Granja, A.D. (2016)., the objective of the following section is to present a combined model that is able to improve planning and process control, enhancing and refining the strengths of the starting models and trying to overcome individual weaknesses and limitations.

8.1.2 Research Method

Despite their different underlying philosophies and controlling mechanism, the authors put forward the proposition that there are possible benefits of integrating LBMS, LPS and CPM in the course of all phases of the project. An exploratory case study was developed to obtain a deep comprehension of the problem. The generated artefact is the proposed integrated model.

The case study was carried out and validated through data analysis of the main processes and tools used on planning and controlling system of a large Brazilian construction company, acting in the real estate market since 1980, with focus on construction projects for residential buildings, corporative and mixed use. The company has a matrix structure, where its projects apply the same processes, procedures and tools. Moreover, the company has a strong tradition in using LPS and CPM planning and controlling technique.

The main data were collected through electronical documents, considering procedures, schedules, spreadsheets and tools, used in a set of twenty already finished real projects. The unit of analysis used was the planning and controlling system and more than 100 documents were analyzed considering the four main aspects of LBMS and LPS, i.e., buffers, workflow, management of subcontractors and constraints. The main documents analyzed were: CPM schedule, procurement schedule and EVA (earned value analysis), constraints meetings sheets, WWP (Weekly Work Plan), PPC (Percent Plan Completed), WBS (Work Breakdown Structure), measurements criteria, sequence patterns and attack plans.

8.1.3 Integrated model

The integrated model proposed by Olivieri, H., Seppänen, O., & Granja, A. D. (2016)., has been generated based on the results achieved through data analysis on the Brazilian case study. Figure 80 shows the integrated model divided into planning and controlling phases. The processes and decisions, organized in a chart and numbered from [1] to [30], are deeply discussed below.

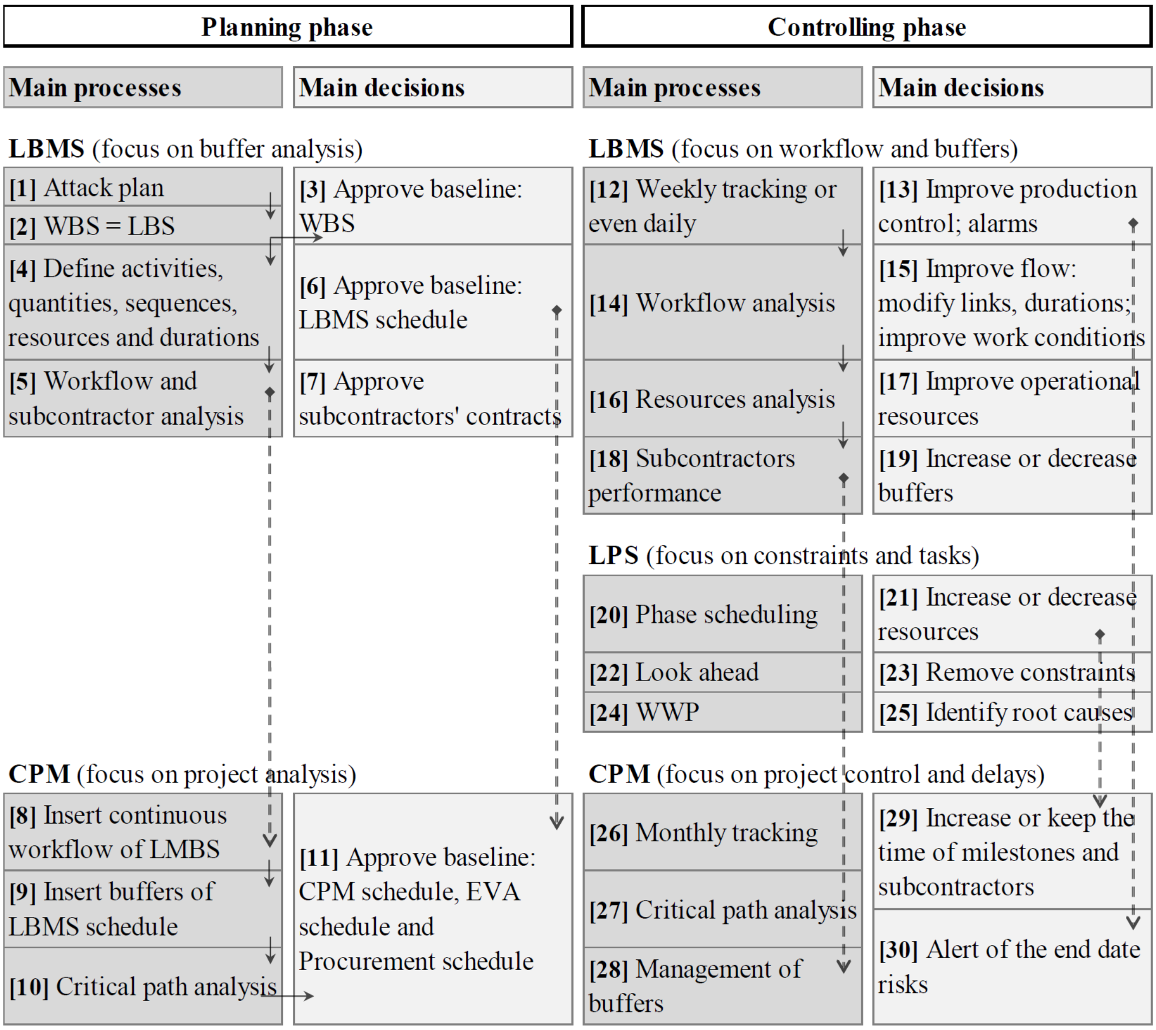


Figure 80: Proposed integrated model (Olivieri, Seppänen. Granja 2016)

8.1.3.1 Planning Phase

[1] The attack plan is developed based on an analysis of contractual phases (for example, three towers with different delivery dates), constraints of sequencing imposed by retaining walls and foundations, considerations and constraints of logistics, available resources and duration of tasks, weather conditions for each phase of the construction project (retaining walls, foundations, structure, façades and waterproofing) and safety conditions for each situation.

[2] Both CPM and LBMS schedules need to start with a common WBS and LBS. This procedure seeks to improve the quality of the schedules and the integration between them. The companies usually work with a standard WBS for the development of construction plans. From WBS´s definition, a smaller division for locations is defined,

called LBS, which is defined for each construction project, taking into consideration the number of towers, floors and apartments or commercial rooms, the area of each of the units and the technical constraints, such as for example, separation and division of façades in which the elevator is installed. LBS is a fundamental part of LBMS. [3] The baseline of WBS and LBS must be approved by the project manager.

[4] The LBMS scheduling process starts with the physical measurement criteria of the tasks, which is targeted at establishing the way the physical progress of the construction project will be measured. After that, quantities and the construction sequence are defined, considering the attack plan definitions. The analysis of resources and activities duration are determined simultaneously during schedule optimization. Finally, buffers are inserted mainly to protect the schedule against cascading delay chains. [5] A workflow and subcontractors' analysis is needed at this moment. [6] As a product of this step, adjustments in the costs and project schedule are made, followed by a baseline LBMS schedule. [7] During the planning phase, some key subcontractors' contracts are approved by the project team.

The CPM schedule is prepared based on the LBMS schedule on the same level of detail. Firstly, it is necessary to configure both CPM and LBMS calendars on the same basis. Secondly, the activities, links, sequences and durations defined in the LBMS schedule must be inserted in CPM schedule. [8] To achieve the same set of initial planned dates as in LBMS schedule, the CPM schedule is adjusted by inserting activity lags to model buffers and continuous flow. [9] Buffers must be inserted preferably as a new task or as a lag between activities and contain the same duration as LBMS buffers. [10] An analysis of the critical path is made, taking into consideration the main project milestones, the period when the main tasks are occurring, the main subcontractors' tasks and the monthly production required. [11] Finally, the EVA and the procurement schedule are developed based on the CPM and both CPM, EVA and procurement baseline are approved.

8.1.3.2 Controlling Phase

The proposed integrated model uses LBMS, LPS and CPM systems simultaneously. [12] The LBMS schedule is monitored weekly, or even daily. The activities completed are collected in field and updated in the schedules, considering the real start and finish dates and actual resources and quantities. The forecasts are compared with plans to detect future problems. Any identified future problems are discussed and control actions are planned to prevent them.

[13] The LBMS controlling process can be connected with the LPS to guide production control decisions and to generate alarms about upcoming production problems. [14] A workflow analysis is done to achieve continuous flow of crews. [15] In attempt to improve flow, the main decisions during this process involve modifying links and durations and improving work conditions of the subcontractors. [16] A resource analysis is done to evaluate the [17] operational resources and the necessity of adjustments. [18] An analysis of the subcontractors' performance may help the project team to [19] increase or decrease buffers. [20] The phase scheduling process involves subcontractors in the definition of common plans and makes it easy to commit to [21] increasing or decreasing resources.

[22] Look ahead meetings are done based on the LBMS schedules' update. The aim is to analyze the tasks that will occur on few weeks, listing the constraints that may require changes to plans. [23] Every week the constraints must be followed up by the construction project team. From the constraints meetings, the prerequisites of production are monitored and prioritized, evaluating in this way the necessary resources for executing the tasks. [24] The WWP process divides the activities by team and by day of the week, who commit to the plan. The success of this WWP is measured by PPC and any plan failures are investigated allowing [25] the identification and treatment of root causes for not completing the activities.

[26] The CPM and Procurement schedules are usually updated monthly, based on the information generated by the updating of LBMS. The actual start and finish dates of LBMS are inserted in the CPM schedule. The LBMS forecasts are not inserted in CPM, which keeps the originally planned durations and sequences. If the CPM schedule starts to deviate a lot from LBMS schedule, a schedule revision may be submitted to the Owner based on the process defined in the scheduling specification.

With the tracking of CPM and EVA it is possible to evaluate the progress of the construction project, as well as compare with the established baseline. In the CPM schedule it is possible to monitor delays on the Critical Path and in EVA the percentage progress of tasks. Procurement schedule is updated considering the predicted and accomplished dates of main resources, allowing a follow up of results.

[27] With the insertion of the LBMS actual dates is possible to calculate in CPM the total amount of delays on critical path and evaluate the impact of any change orders and delays, such as weather delays and design delays. In CPM, the same actual start and finish dates will result in different dates because the CPM algorithm does not take into account continuous work or adjust durations based on forecasts. Therefore, it can be used to achieve the traditional project management objectives. The critical path and the main milestones are checked to evaluate the risks of delays. [28] The buffers' durations inserted in the planning phase can be modified if necessary. A subcontractors' analysis is applied in attempt to compare the original buffers and milestones with the forecasts.

[29] LBMS forecasts dates will be different from CPM activity dates. CPM will be used to evaluate the critical path and to supply enough information to the project team related to delay analysis and subcontractors' performance, increasing or decreasing the original time of buffers and subcontractors. On the other hand, LBMS is more appropriate to analyze continuous workflow, buffers, durations, forecasts and to determine control actions to recover delays and it is the operational schedule which can be connected with LPS constraints analysis and daily management of activities. [30] Both LBMS and CPM schedules can supply information to develop monthly reports to the owner and to the project team. CPM will provide information to analyse delays, and the performance of subcontractors and the project. LBMS will provide information related to production control and the necessary actions to improve flow and recover delays.

8.1.4 Conclusion

The integrated model systematizes the integration of three distinct, but complementary systems, which are LBMS, LPS and CPM. Complementarity means that, despite the application difficulties and criticalities of the individual methods, the fusion between them is theoretically achievable. Standing alone, each system is strong in some areas but requires improvements in others. Thus, it is expected that through further artefact implementation, the proposed integrated model can compensate the deficiencies of using the planning and controlling systems in an isolated manner or by running various systems in parallel with no integration.

The processes and decisions proposed were developed based on using LBMS and LPS to run operations but having an aligned CPM schedule which can be used for traditional project management purposes, such as delay analysis.

However, the artefact implementation mentioned above is still missing: in fact, the proposed integration is purely theoretical up to now because no specific software has been developed yet in the construction market. Probably, in order to create a product that is useful, effective and at the same time intuitive, it would be necessary to create a project in synergy between IT developers and consultants who are experts in planning and control.

It is also worth pointing out that, once the integrative software has been created, its adoption would not be automatic because a number of other factors and complications should be addressed:

- Stakeholder reticence: although methods that can improve the effectiveness of the planning and control functions already exist, during the discussion of this thesis the "hostility" with which the actors involved in the implementation of a project present themselves has already been argued;
- Teaching of the model: a new planning and control model, after being developed, must be taught correctly to the professional figures in charge so that they can implement it in their construction projects and eventually provide feedback and numbers about its efficiency;
- Spread of the model: in order to be known by as many stakeholders as possible, the developer company or certification bodies (for example the already mentioned PMICOS) should "advertise" and show through conferences and seminars the effectiveness of the integrative system;
- Adoption time: obviously breaking down the reluctance of stakeholders, teaching and spreading a new method normally requires a time frame that will be shorter the more fertile the soil it encounters along its path.

Conclusion

The aim of this thesis was to give an answer to the question "Is it possible to improve the efficiency of a managerial process, specifically in the planning and control functions?". The discussion of this paper was carried out with an initial bibliographic and historical analysis of the most widespread planning and control methods used, from the 1960s to the present day, namely Location-Based Management System, Last Planner System and Critical Path Method. For each method, the technical and operational steps, the potential, the areas of greatest effectiveness, their versatility, but also and above all the critical issues and application difficulties were highlighted. The discussion then continued with a first attempt to integrate the proposed methods, i.e. the intent was to show if and how the combination of two different systems was able to overcome the individual problems.

The first positive results were discussed and explored during the drafting of Chapter 5 in which the following results were achieved:

- the LBMS-LPS combination has achieved the goal of creating a model that guarantees access to both short-medium production planning and long-term project plan;
- the LBMS-CPM combination showed how it is possible to overcome the main shortcomings of the CPM (lack of workflow, high number of planning elements and inability to schedule continuous resource usage);
- the LPS-CPM combination proposed a different hierarchy in the choice of individual tasks based on the calculation of pull intensity (the more advantage the task brings to the overall project, the sooner it will be performed).

Chapters 6 and 7 have shown, through real data applied to real case studies, how planning and control functions are carried out in practice using the guidelines provided by the LBMS method. In particular, the case study discussed in Chapter 7, having been planned with a traditional method (no joint pre-planning by the subcontractors), brought to light the critical issues theoretically described in the previous Chapters.

Finally, Chapter 8 presented the highest level of integration possible so far theorized by the literature, that is, proposing to the reader an integrated model that would improve the planning and control process using the methods of LBMS, LPS and CPM simultaneously.

Unfortunately, there is still no software in the construction market that has implemented the model proposed in Chapter 8, but the literature has already begun to trace a very interesting path for possible developments and future applications.

LIST OF REFERENCES

1) Arditi, D., Tokdemir, O. and Suh, K. (2002). *Challenges in line of balance scheduling*. ASCE Journal of Construction Engineering and Management, 128 (6), 545-556.
2) Ballard G. (1997). *Lookahead planning: the missing link in production control*. In Proc. 5th Annual Conf. Intl. Group for Lean Construction
3) Ballard, G. (2000*). The last planner system of production control*. PhD. Thesis. Falculty of Engineering of The University of Birmingham – UK
4) Ballard, G. (1994). *"The Last Planner"*. Spring Conference of the Northern California Construction Institute, Monterey, CA, April 22-24, 1994.
5) Bertelsen, Sven & Koskela, Lauri. (2005*). Approaches to managing complexity in project production*.
6) Dave, B., Seppänen, O., & Modrich, R-U. (2016). *Modeling Information Flows Between Last Planner and Location Based Management System*. In Proceedings of the 24th Annual Confenrence of the International Group for Lean Construction (Proceedings of the Annual Conference of the International Group for Lean Construction).
7) Dave, Bhargav & Hämäläinen, Juho-Pekka & Koskela, Lauri. (2015) *Exploring the Recurrent Problems in the Last Planner Implementation on Construction Projects*. Proceedings of the Indian Lean Construction Conference (ILCC 2015). P. 9
8) Evinger, J., Mouflard, C. & Seppänen, O. (2013) *Productivity effects of starting as early as possible in hospital construction*. Proceedings of the 21st Annual Conference of the International Group of Lean Construction, July 31 – August 2, Fortalezza, Brasil.
9) Fondahl, J. W. (1962). "*A non-computer approach to the critical path method for the construction industry*."
10) Freeman, C., & Seppänen, O. (2014). *Social Aspects Related to LBMS Implementation - A Case Study*. In Proceedings of the 22nd Annual Conference of the International Group for Lean Construction (Proceedings of the Annual Conference of the International Group for Lean Construction). Oslo, Norway.
11) Galloway, Patricia D. (2006) *Survey of the Construction Industry Relative to the Use of CPM Scheduling for Construction Projects,* Journal of Construction Engineering

and Management Vol. 132 https://doi.org/10.1061/(ASCE)0733-9364(2006)132:7(697)

12) Goldratt, E. M. (1997). *Critical Chain*, North River Press.

13) Hamzeh, F.R., Ballard, G., and Tommelein, I.D. (2008). *Improving Construction Workflow- The Connective Role of Lookahead Planning*, Proc. 16th Ann. Conf. Int'l.

14) Hamzeh, Farook. (2009). *Improving construction workflow- The role of production planning and control*. 10.13140/RG.2.1.1182.9286.

15) Harris, R.B. and Ioannou, P.G. (1998). *Scheduling projects with repeating activities*. ASCE Journal of Construction Engineering and Management, 124(4), 269-278.

16) Heigermoser Daniel, García de Soto Borja, Abbott Ernest Leslie Sidney, Huat Chua David Kim (2019) *BIM-based Last Planner System tool for improving construction project management*, Automation in Construction, Volume 104, Pages 246-254, https://doi.org/10.1016/j.autcon.2019.03.019.

17) Henrich, G. and Koskela, L. (2005) *PRODUCTION MANAGEMENT IN CONSTRUCTION REQUIREMENTS AND METHODS*

18) Huber, Bob & Reiser, Paul. (2003). *THE MARRIAGE OF CPM AND LEAN CONSTRUCTION*

19) Hyatt, C., and Weaver, P. (2006). "*A Brief History of Scheduling*." Melbourne, Australia: Mosaic Project Services Pty Ltd.

20) Jaafari, Ali. (1984) *Criticism of CPM for Project Planning Analysi*s, M.ASCE, https://doi.org/10.1061/(ASCE)0733-9364(1984)110:2(222)

21) Kala, T. & Mouflard, C. & Seppänen, Olli. (2012). *Production control using locationbased management system on a hospital construction project*. IGLC 2012 - 20th Conference of the International Group for Lean Construction.

22) Kankainen, J. and Sandvik, T. (1993). Rakennushankkeen ohjaus. (in Finnish) (*Controlling a construction project*). Helsinki, Finland: Confederation of Finnish Construction Industries, Rakennustieto Oy.

23) Kankainen, J. and Seppänen, O. (2003). *A line-of-balance based schedule planning and control system*. Proceedings of the 11th Annual Conference of the International Group for Lean Construction. Blacksburg, Virginia

24) Kastor, A., Sirakoulis, K. (2009) *The effectiveness of resource levelling tools for Resource Constraint Project Scheduling Problem, International Journal of Project Management Pages 493-500* https://doi.org/10.1016/j.ijproman.2008.08.006.

25) Kelley, James E., Walker, Morgan R. (1959) *Critical-Path Planning and Scheduling*, Proceedings of the Eastern Joint Computer Conference

26) Kenley, Russell & Seppänen, Olli. (2009). *Location-based Management of Construction Projects: Part of a New Typology for Project Scheduling Methodologies*. Proceedings - Winter Simulation Conference. 2563-2570. https://doi.org/10.1109/WSC.2009.5429669.

27) Kenley, Russell, and Olli Seppänen (2010). Location Based Management for Construction: Planning, Scheduling and Control, CRC Press LLC, 2009 https://doi.org/10.4324/9780203030417

28) Kiiras, J. (1989). OPAS ja TURVA, erityiskohteiden työnaikaista ohjausta palveleva aikataulu- ja resurssisuunnittelu. (in Finnish) *(A schedule and resource planning system for the implementation phase of unique projects*). Espoo, Finland: Helsinki University of Technolandy, Construction Economics and Management Publications 217.

29) Koskela, Lauri, Howell, Greg, Pikas, Ergo and Dave, Bhargav (2014) *If CPM is so bad, why have we been using it so long?* In: The 22th International Group for Lean Construction conference, June 23-27, 2014, Oslo, Norway.

30) Lumsden, P. (1968). *The Line of Balance Method*. Oxford: Pergamon Press.

31) Mohr, W. (1979). *Project management and control (in the building industry)*. Department of Architecture and Building, University of Melbourne. 2nd edition.

32) Olivieri Hylton, Seppänen Olli & Granja Ariovaldo Denis (2018) *Improving workflow and resource usage in construction schedules through location-based management system (LBMS)*, Construction Management and Economics, 36:2, 109-124, DOI: 10.1080/01446193.2017.1410561

33) Olivieri, H., Seppänen, O., & Granja, A. D. (2016). *Integrating LBMS, LPS and CPM: a practical process*. In Proceedings of the 24th Annual Conference of the International Group for Lean Construction (pp. 3-12). (Proceedings of the Annual Conference of the International Group for Lean Construction).

34) Olivieri, H., Seppänen, O., & Peltokorpi, A. (2017). *Real-time tracking of production control: Requirements and solutions*. In IGLC 2017 - Proceedings of the 25th Annual Conference of the International Group for Lean Construction (pp. 671-678). (Annual Conference of the International Group for Lean Construction; No. 25). https://doi.org/10.24928/2017/0177

35) Olivieri, H., Seppänen, O., Alves, T. D. C. L., Scala, N., Schiavone, V., Liu, M., & Granja, A. D. (2019). *Survey comparing Critical Path Method, Last Planner System, and Location-Based techniques*. JOURNAL OF CONSTRUCTION ENGINEERING AND MANAGEMENT: ASCE, 145(12), [04019077]. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001644

36) Peer, S. (1974). *Network analysis and construction planning*. ASCE Journal of the Construction Division, 100(CO3): 203-210.

37) PMI (2013). *A guide to the project management body of knowledge: PMBOK guide*. Project Management Institute.

38) Russell, A.D. and Wong, W.C. (1993). *New generation of planning structures*. ASCE Journal of Construction Engineering and Management, 119(2), 196-214

39) Selinger, S. (1973). *Method for construction process planning based on organization requirements*. (Doctoral thesis), Technion-Israel Institute of Technolandy, Haifa.

40) Selinger, S. (1980). *Construction planning for linear projects*. ASCE Journal of the Construction Division, 106(CO2), 195-205.

41) Seppänen, O. (2014). *A Comparison of takt time and LBMS planning methods*. In Proceedings of the 22nd Annual Conference of the International Group for Lean Construction (Proceedings of the Annual Conference of the International Group for Lean Construction). Oslo, Norway.

42) Seppänen, O., & Kenley, R. (2005). *Using location-based techniques for cost control*. In Proceedings of the 13th Annual Conference of the International Group for Lean Construction

43) Seppänen, O., and Aalto, E. "*A Case Study of Line-of-balance Based Schedule Planning and Control System.*" Proc., 13th Conference of the International Group for Lean Construction, University of New South Wales, 271-279.

44) Seppänen, O., Ballard, G., & Pesonen, S. (2010). *The combination of Last Planner System and Location-Based Management System*. LEAN CONSTRUCTION JOURNAL, 43-54.

45) Seppänen, O., Evinger, J. and Mouflard, C. (2014*). Effects of the location-based management system on production rates and productivity*. Construction Management and Economics, 32(6), 608-624.

46) Seppänen, O., Evinger, J., & Mouflard, C. (2013). *Comparison of LBMS schedule forecasts to actual progress*. In Proceedings of the 21st Ann. Conf. of the Int'l Group for Lean Construction Fortaleza, Brazil

47) Seppänen, Olli & Modrich, Ralf-Uwe & Ballard, Glenn. (2015). *INTEGRATION OF LAST PLANNER SYSTEM AND LOCATION-BASED MANAGEMENT SYSTEM*.

48) Seppänen, Olli. (2009). *Empirical Research on the Success of Production Control in Building Construction Projects*.

49) Seppänen, Olli. (2012). *A production control game for teaching of location-based management system's controlling methods*. IGLC 2012 - 20th Conference of the International Group for Lean Construction.

50) Seppänen, Olli. *Location Based Management System,* article provided by the professor Seppänen during the Operation Management in Construction course held in Aalto University, Espoo (Finland)

51) Shreve, R. (1930). *The Empire State Building Organization*. The Architectural Forum. LII(6), 771-778

52) Willis, C. and Friedman, D. (1998). *Building the Empire State Building*. New York: W.W. Norton and Co.

53) Womack, J., Jones, D. and Roos, D. (1990) *The Machine That Changed the World: The Story of Lean Production, Toyota's Secret Weapon in the Global Car Wars That Is Now Revolutionizing World Industry*. Free Press, New York.

54) Womack, James & Jones, Daniel. (1996*). Lean Thinking : Banish Waste and Create Wealth in Your Corporation*. 10.1038/sj.jors.2600967.

55) Zhao Jianyu, Seppänen Olli, Peltokorpi Antti, Badihi Behnam, Olivieri Hylton, (2019) *Real-time resource tracking for analyzing value-adding time in construction*, Automation in Construction, Volume 104 https://doi.org/10.1016/j.autcon.2019.04.003.