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Empirical research on the success of production control in building construction projects

Olli Seppänen

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Helsinki University of Technology
Faculty of Engineering and Architecture
Department of Structural Engineering and Building Technology

Publisher:
Helsinki University of Technology
TKK Department of Structural Engineering and Building Technology
PL 2100
02015 TKK
Tel +358 (9) 451 1
Fax +358 (9) 451 3758
elsa.nissinen-narbro@tkk.fi

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Abstract

The topic of this thesis was construction management and improving the production control processes in construction projects. The main goal of the research was to examine empirically how production is currently controlled and to establish the root causes for failure to implement schedules as they are planned. The second goal of the research was to improve the location-based management system and its processes.

Three case study project teams were trained in the location-based management tools and processes. Production control data was collected systematically from the project teams from the beginning to the end of all the case projects. These data were used to assess the reliability of the plans on three levels of detail. The actual production control process was followed by direct, personal observation.

The project teams were found to use the location-based controlling tools with a push methodology. It was found that cascading delay chains starting at the beginning of the interior construction phase continued until the end of the construction project. The cascading delays typically originated because of labor resource issues. The reason why the cascading delays did not affect the project finish dates was the long end-of-project buffers. These buffers were fully used up in all of the case projects. Many production problems could be forecast using the location-based controlling data. The controlling tools were developed to improve the forecasting of problems by changing the forecasting procedure, and incorporating the look-ahead planning of resources to the forecast. With these modifications, meaningful alarms could be generated earlier, and for more problems.

The main contribution of this research was to identify cascading production problems to be a critical contributor to the poor reliability of construction project schedules. By using the location-based forecasts and alarms, it is possible to forecast these problems before they happen and to prevent problems from cascading. This research contributed an improved forecast and alarm system and proposed a systematic process for their use in construction. A practical contribution of this research was the implementation of the improved forecast system in the software package, Vico Software Control 2009.

Keywords Construction management, Location-based Management, Lean Construction, Production control, Resource flow

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Tiivistelmä

Väitöskirjan aiheena oli rakentamisen tuotannonohjaus ja tuotannonohjausprosessien kehittäminen rakennushankkeissa. Tutkimuksen päätavoite oli tutkia empiirisesti, miten tuotantoa hallitaan tällä hetkellä ja selvittää pääsyyt aikataulujen huonoon pitoon. Tutkimuksen toinen tavoite oli kehittää sijaintipohjaista tuotannonohjausjärjestelmää ja siihen liittyviä prosesseja.

Kolmen case-hankkeen projektiorganisaatio koulutettiin käyttämään sijaintipohjaisia tuotannonohjauksen työkalija ja prosesseja. Tuotannonohjaukseen liittyvää tietoa kerättiin projekteista case-hankkeiden alusta loppuun saakka. Tätä tietoa käytettiin suunnitelmien luotettavuuden analysointiin kolmella tarkkuustasolla. Toteutunutta tuotannonohjauksen prosessia tutkittiin case-kohteista tehdyillä henkilökohtaisilla havainnoilla.

Projektien ohjaus oli kaikissa case-hankkeissa työntöohjausta. Kasautuvat viiveketjut alkoivat heti sisävalmistusvaiheen alusta, ja jatkuivat hankkeiden loppuun saakka. Kasautuvat viiveet alkoivat tyypillisesti työresursseihin liittyvistä syistä. Viiveet eivät vaikuttaneet projektien luovutushetkeen, koska kaikkiin hankkeisiin oli suunniteltu pitkä aikapuskuri hankkeen loppuun. Tämä puskuri käytettiin kokonaan kaikissa hankkeissa. Useita tuotanto-ongelmia voitiin ennustaa käyttämällä tuotannonohjausjärjestelmän tietoa. Tuotannonohjausjärjestelmää kehitettiin siten, että ongelmista voitiin hälyttää aikaisemmin.

Tutkimuksen päätulos oli se, että kasautuvat tuotannon ongelmat ovat kriittinen tekijä, joka heikentää rakennusprojektien suunnitelmien luotettavuutta. Käyttämällä sijaintipohjaisia ennusteita ja hälytyksiä on mahdollista ennustaa ongelmat ennen kuin ne tapahtuvat ja estää ongelmien kasautuminen. Tutkimuksen tuloksena oli parannettu ennuste- ja hälytysjärjestelmä sekä systemaattinen prosessi niiden käyttöön rakennushankkeiden ohjauksessa. Tutkimuksen ohessa käytännön tuloksena toteutettiin parannettu ennustejärjestelmä kaupalliseen ohjelmistoon, Vico Software Control 2009.

Asiasanat Rakentamisen tuotannonohjaus, Sijaintipohjainen ohjaus, Lean Construction

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Preface

This thesis is the result of my work with location-based planning and control systems since 2000. Everything started with the founding of my company, DSS, in 2000 to develop software for mass haul optimization, in cooperation with the Finnish construction company; Lemminkäinen (currently Lemcon Infra). In the Fall of 2000, I presented the results of our initial development to Professor Jouko Kankainen at the Helsinki University of Technology (HUT). He proposed that we should develop a similar software package for building construction. The first versions were built in cooperation with the Finnish contractors SRV, NCC Construction, Skanska, and Hartela, between 2002 and 2003, based on the Finnish research on location-based management. The software was first presented internationally at Berkeley and Stanford universities, and the Lean Construction Conference in Blacksburg, Virginia in 2003. Professor Russell Kenley, at the time working at UNITEC, New Zealand, saw the software in Blacksburg, and we started a cooperation to make the software align better with international research (especially relating to the Critical Path Method). Based on the international academic interest, Jouko was able to convince me to start a PhD research project using the software as a research tool.

I am extremely thankful to my supervisor, Professor Jouko Kankainen. Without him my two companies, the software products, and this PhD would not exist. During the development of the DynaProject (currently Vico Software Control) software package, we spent countless hours in the evenings and weekends together, so that I could learn everything he knows about location-based management. I had to start from scratch, because I graduated from the Helsinki School of Economics with no construction background. But, with help of Jouko, I was able to catch up with my peers who had graduated from technical universities and studied Construction Management. Jouko made me believe in the feasibility of completing a PhD degree while working long hours in a fast-growing software company. It was very enjoyable traveling the world with Jouko and others from HUT, and presenting the Finnish results at universities and Lean Construction conferences.

The University of Stanford and CIFE provided the perfect place to write and analyze data and engage in discussions with professors and other graduate students. I would like to thank Professor Martin Fischer for helping me to select the focus of my work, and for giving me the opportunity to lecture to Stanford graduate students. I would like to thank the Stanford students who participated in my lectures for asking tough questions, and therefore helping me to develop my thinking. Of the CIFE research students, I would especially like to thank Timo Hartmann and Atul Khanzode. Together with Atul, we created the first case study in the US, and developed a teaching assignment which was used for two years at Stanford. Timo helped me to become more objective with my results.

This work would not have been possible without the contribution of Professor Russell Kenley. Russell helped me to define the concept of layered logic and move above the Finnish action research tradition. Many methodologies of location-based planning developed in Finland had been based on manual techniques, but with Russell's help, we were able to unleash the real power of location-based management, and the detailed planning of crews and their locations. The software version which was used to collect data for this research contained much of Russell's input.

I would like to thank the academics in the International Group of Lean Construction for their valuable contributions to this evolving field. The work of professors Lauri Koskela, Glenn Ballard, Iris Tommelein and Rafael Sacks has been especially important to my thinking. We have not always agreed on everything, and I have often been considered a guy trying to sell software instead of being an objective researcher. This work tries to move a step back from the software and to consider the results of location-based planning and control and their link to Lean Construction in an objective way. I hope it opens up new avenues of cooperation in the future.

Many Finnish companies and organizations have contributed to the success of this research. I would like to thank the Finnish Confederation of Construction Industries for funding this research. Tekes funded my work at CIFE. I would like to give special thanks to Reijo Kangas at Tekes for supporting my research and helping me to network with the academics and companies in the Bay Area of San Francisco. The participation of construction companies was critical. I would like to thank Hartela, NCC Construction, and Skanska for letting me use their projects as case studies. I would especially like to thank the project engineers Erno Aalto (then of NCC Construction), Seppo Ruusunen (Skanska), and Tuomo Sopanen (Hartela) for their help in collecting the monitoring data on site. Dr. Jan Elfving (Skanska) has helped me throughout this research by reviewing and commenting on my results and early PhD drafts. He also helped me in the beginning by introducing me to the US academics at Berkeley & Stanford universities, the International Lean Construction Group and the companies in the Bay Area.

My colleagues at DSS, Graphisoft, and Vico Software have supported this research by incorporating the research results into their software, and allowing me to spend one year in mostly academic activities at CIFE. Thanks are due to Dominic Gallello (CEO of Graphisoft) and Clay Freeman (VP of the Construction Solutions division at Graphisoft, and co-founder of Vico Software) for letting me spend one year at CIFE. Thanks go to the developers of Control (especially Ilkka Pelkonen and Tim Wessman) for the quick implementation of the new forecasting features into Control. I would also like to thank my business partners and colleagues at DSS, Graphisoft, and Vico Software for letting me invest substantial amounts of time in this work.

Finally, thanks to my loving wife, Miia, for her emotional support and for allowing me to spend most of our evenings, weekends and holidays working on this thesis. I promise that this is the last PhD thesis I will write.

Contents

1. Introduction

1.1 Background

Project plans and schedules are critical to the success of a project. According to the PMBOK (Project Management Body of Knowledge) planning is considered one of the main tasks of project management (Project Management Institute 2004). However, in recent years, there has been increasing awareness that construction schedules are not relevant to the day-to-day management of projects. The focus of management is on planning, but keeping plans up-to-date and properly implementing those plans are challenges (AlSehaimi and Koskela 2008). Poor plan implementation leads to a requirement to make up lost time by an unplanned compression of the schedule, which happens in the majority of projects. For example, a study reported that 91% of the survey sample of 140 respondents had the need for time compression in their projects (Noyce and Hanna 1998). The unplanned compression of schedules typically leads to lost productivity and wasted time (Chang et al. 2007) and poor quality (Wegelius 1998).

Decreasing waste has been a key goal for lean construction research. The main theoretical argument in lean construction has been that the traditional scheduling and controlling theories focus on the transformation of inputs to outputs (Koskela 2000). In this view, flows and value generation are ignored. For example, traditional CPM scheduling ignores resource constraints (Lu & Li 2003) and therefore considers only the flows related to precedence. The inputs of the production process are assumed to be available when needed. Because the focus is on individual transformations, the wasted time between transformations (flow) is ignored. Koskela (2000) argues that the theory of production should combine the transformation, flow, and value points of view.

Control systems have similarly been mostly project control instead of production control systems, because they concentrate on inputs and outputs, and handle the actual production as a black box and ignore flow (Ballard 2000). This is well illustrated by early Critical Path Method (CPM) papers, which describe that the original purpose of the method was to provide a system for management by exception (Kelley and Walker 1959). The main control methodology of CPM is to update the plan with actual start and finish dates and estimated remaining duration for ongoing tasks and then run the CPM calculation (for example O'Brien and Plotnick 2006: 455-474). The project managers use the schedule to determine the start dates of activities and to push the work to start on the earliest start date (Koskela, Howell, Ballard & Tommelein 2002: 215). However, this approach does not use any information about the current status of production other than the finished and non-finished activities. This approach detects any deviations only after they have happened, allowing management by exception, but this “after-the-fact” approach to control does not allow preventive measures before problems happen (Meredith and Mantel 1995). Continuously updating the plan may result in continued confidence that problems can be fixed later instead of taking timely action, especially when future durations do not have an automatic correlation with the historical durations of the same task in other locations. Additionally, the industry standard practice is to require updates monthly (Galloway 2006). Monthly updates cannot be said to be a real-time control mechanism. Koskela & Howell (2001) called this the thermostat model of control, which is overly simplistic and ignores the need to learn the reasons for poor performance.

Two complementary systems have been developed that address production directly and are interested in work flow and production flow in addition to the transformation of inputs to outputs. The Last Planner System™ of production control focuses on the proactive control of the prerequisites of production for each transformation. Master schedules and phase schedules form goals for the look-ahead planning process which makes work ready to the workable backlog by removing constraints. Assignments are planned at a weekly level by Last Planners, who select available assignments from the workable backlog. If a task does not have the prerequisites of efficient production, it is not released into the system. Metrics have been developed for measuring the success of each of these planning levels in the Lean Construction community. The most commonly used measure of plan reliability is PPC (percentage of assignments completed) (Ballard 2000). However, the Last Planner System™ does not explicitly handle the flow of resources which may cause more problems than work flow issues (Thomas et al. 2003). Even though these issues are not directly addressed by the Last Planner System™, the Lean Construction community has recognized that resource flow issues are important in the Parade of Trades simulation (Tommelein et al. 1999). There has also been research into implementing continuous flow processes to maximize throughput while minimizing resource idle time and work-in-progress. (Ballard & Tommelein 1999).

Another production control system has a longer history and has actually been used for a longer time than the CPM methods. Early examples of these location-based planning and controlling systems include line-of-balance (Lumsden 1968) and flowline (Mohr 1979). The location-based systems use the physical work locations as the focus of their control. They are interested in a continuous resource flow throughout the building. In addition to resource availability, they explicitly consider also many other prerequisites, such as space availability, and any conflicts between subcontractors. Instead of modeling construction by discrete tasks with a duration, the location-based systems use the quantities of work and production rates, thereby going inside the black box of production. Although location-based planning and controlling started off as manual techniques, research results have recently been formalized to algorithms to incorporate CPM logic, and to calculate forecasts based on actual production rates. These algorithms have been implemented in computer software, which was used as the main research tool in this research (Kankainen & Seppänen 2003). Research has been carried out to remove most of the historical limitations of the location-based systems, such as requiring locations to be repetitive, or not including a full CPM engine (Kenley & Seppänen 2010: 123-161). The goal of a location-based controlling system is to create forecasts of the future to alert management of production problems before they happen, so that management has time to react to prevent problems. Much of the technical literature related to location-based techniques has concentrated on the theoretical aspects of planning, such as learning curves, and ignored the controlling aspects (for example, Arditi et al. 2002, Arditi, Tokdemir & Suh 2001, El-Rayes & Moselhi 1998, Yang & Iannou 2001). Finnish research tradition has, from the beginning, recognized the importance of control, however most of the results have only been published in Finnish (for example, Kiiras 1989, Kankainen & Sandvik 1993, Hannukkala 1991, Junnonen 1998, Kolhonen, Kankainen & Junnonen 2003, Koskenvesa & Pussinen 1999, Pekanpalo 2004, Soini 1988, Toikkanen 1989, Tuominen 1993, Venermo 1992, Wegelius 1998).

Various papers on Lean Construction have emphasized the complex and apparently chaotic nature of production (Bertelsen 2003, Bertelsen and Koskela 2003). Bertelsen (2003) proposed a hypothesis that construction must be perceived as a complex system. The implications of this claim include that instead of a top down approach to leadership, construction management should enter the new world of organization and co-operation. Management should be based upon the fact that project execution can be planned in detail only a few steps into the future. Kenley (2005) argues that this is a fallacy. This apparent complexity is caused by ignoring the fact that similar production is carried out continuously throughout the project by the same resources, and that there are many subcontractors working on the project handing work off to the next trade. The location-based methods try to decrease this complexity by recognizing that plans and forecasts can be created based on the production of similar work in previous locations of the same project (or similar work in previous projects). Bertelsen and Koskela (2004) argue that construction is a turbulent kind of production instead of a laminar flow with small eddies. Kenley (2005) challenges this view. The end result of this argument is critical, because it defines what kind of management systems should be used for construction. For example, the goal of a location-based management system is likely to fail if flows can not be forecast based on previous production. However, these papers do not present any empirical evidence. The hypothesis of this study is that historical production rates can be used to forecast future production rates. Forecasts of production of the same subcontractor working on similar tasks in the same project can be used to generate alarms of future interferences.

Melles and Wamelink (1997: 109-160) analyzed the complexity and uncertainties related to five different types of construction orders for different types of decision function. This research has as its case studies “unique projects”, which are defined as having both personnel used by the company (General Contractor); a large number of activities; a combination of scarce and readily available resources; and requiring operation level assignment information (p. 106). Unique projects are complex due to the uniqueness of information related to them, uncertainty related to owner requirements, material deliveries, subcontractor obligations, and an inability to use the norms related to previous projects (pp. 141-143). An information system (such as a location-based management system) can be used to decrease complexity and uncertainty at a project level by recording the progress of the project, project costs, project man-hours, relationships between activities, and the consequences of deviations. Because the throughput time of a project is typically long, adjustments can be made during the course of the project. Because of the large number of subcontractors and crews, mobilization planning is required in addition to work crew assignments and instructions for specific operations. (pp. 131-148).

1.2 Limitations of previous research

Previous empirical studies relating to scheduling and production control suffer from limitations which limit their ability to draw conclusions about the nature of production.

First, research methods have included individual case studies implemented with action research where the researcher is actively trying to improve the success of a project by implementing new methods. This research strategy has been used both in Finnish research related to location-based planning (for example, Soini 1988, Toikkanen 1989, Hannukkala 1991, Venermo 1992); and in Last Planner studies (for example Ballard 2000, Fiallo & Revelo 2002, Auada et al. 1998). All of these case studies claimed to be successful. However, there are results related to both location-based planning (Seppänen & Kankainen 2004) and Last Planner (Chitla & Abdelhamid 2003) that indicate that the beneficial results of implementing these systems are not as conclusive when the researcher does not actively affect the outcome, and when the results are analyzed quantitatively. Seppänen and Kankainen (2004) found that there were large deviations from the location-based plans in almost all empirically researched case projects. Chitla and Abdelhamid (2003) found only a modest relationship between the PPC and labor utilization factors. In all of these cases, some anecdotal benefits could be shown, but the statistical evidence of success was limited. Failure to achieve strong solutions was attributed to the bad implementation of the control system (Seppänen & Kankainen 2004), or the failure to implement all parts of the Last Planner System (Chitla & Abdelhamid 2003).

Bortolazza and Formoso (2006) actually found a statistically significant effect on PPC depending on researcher intervention.

Second, empirical research based on standardized metrics has not been implemented using multiple case studies with different characteristics. There are some exceptions. Large-scale quantitative studies of the benefits of the Last Planner System have been implemented in Latin America (Alarcón et al. 2005, Bortolazza & Formoso 2006). Alarcon et al. (2005) found that, in general, projects with a more complete implementation of the Last Planner System™ had a higher PPC. Typically, the easiest parts to implement are weekly work planning, but formal look-ahead planning was much rarer, and the use of a formal workable backlog and learning process even rarer. Although the paper reports significant performance improvement in eight companies, it does not give details of how performance was measured and states that performance measurement was a difficult task for the companies. Bortolazza and Formoso (2006) did not collect any performance improvement data except PPC and the causes of the non-completion of work packages. The empirical research about the implementation of location-based planning was implemented in Finland (Seppänen & Kankainen 2004). Empirical research has been done on the CPM schedules based on surveys (Galloway 2006). However, the survey results are based on the respondents' observations of a phenomenon without a systematic analysis of the root causes of the phenomenon.

Third, the studies have mostly concentrated on planning better schedules, and have ignored the analysis of the actual implementation. There are only a few studies of the actual success of production. Empirical studies examining the success of the Last Planner System mostly concentrate on the internal metric of the system, the percentage of the plan completed to evaluate the project success (for example, Ballard 2000, Bortolazza & Formoso 2008). Some research has tried to correlate PPC improvements with improvements in productivity (Ballard & Howell 1998, Ballard, Casten & Howell 1996, Fiallo & Revelo 2002, Ballard & Kim 2007, Liu & Ballard 2008). Most of these papers merely describe the productivity increase without giving sufficient details about how the productivity was measured. Ballard & Kim (2007) and Liu & Ballard (2008) were able to show a small positive correlation, which was statistically significant. However, these results were based on only one trade in one project. Therefore, there is no conclusive evidence that productivity is strongly correlated with PPC, although a small positive correlation has been shown in multiple case studies. Additionally the measurement of productivity in a single project is problematic because the resources lose time if they have to move to another project. The effect of starts and stops on total productivity of the subcontractor resource is not reflected in these studies because they are based on a measurement of actual hours compared to the budgeted hours in one project only.

The closest research to the topic of this thesis has been done in the field of productivity studies. Labor flow has been shown to be critical to productivity (Thomas et al. 2003). The daily productivity of labor has been shown to stay relatively constant in projects which did not experience disruptions (Thomas & Zavski 1999). Workspace congestion was found to decrease productivity, and ways were found to prevent such congestion by better planning (Thomas et al. 2006). The productivity studies highlight the importance of planning and management, and give some insights of the functioning of the production system. However, these results are based on just selected trades. Additionally, they concentrate just on the productivity of individual subcontractors on site, and stress the fact that productivity on any given project is improved by flexibly adjusting the workforce to the availability of work. The return delay risk of resources leaving the site and the difficulty of subcontractor management to find other work for the workers is ignored in this research In a similar argument Ballard, Koskela, Howell & Tommelein (2005) reject the conclusions of the paper by Thomas et al. (2003), stating that labor flow should be regulated according to the unplanned variation of work available only when all else fails. Additionally, there are safety and ethical concerns related to the flexibility strategy. Despite these shortcomings in the conclusions, data relating to productivity loss caused by labor flow issues seem to be valid.

Prior research has found correlations between good management and labor productivity. However, most of the case studies have been implemented as action research, or concentrated on just selected trades, without considering the interrelationships between trades. Therefore, the new empirical analysis of production concentrating on interrelationships between trades is needed.

1.3 Aims and objectives of this research

The topic of this research is construction management and improving the production control processes in commercial building construction projects. This research has two main goals:

- The first goal is to examine empirically how production is controlled at the moment in commercial building construction projects, especially concentrating on the root causes for failing to implement schedules as planned and the interrelationships between trades. The empirical research is carried out by using a location-based management system as the underlying model. To achieve this goal, standardized variables measuring the success of production control are developed.
- The second goal is to improve the location-based management system and processes based on actual observations in the case projects. The development

of the actual construction production control theory based on empirical results is outside of the scope of this thesis.

There are five specific research questions to be answered.

1 What is the actual production control process on site?

A model production control process based on a location-based management system was presented, and the project teams were trained using the model process. Its use was enforced only to the extent required to get reliable production control data for this research. The first research question examines whether the model process was used, and what the differences were between the actual and modeled processes.

2 How reliable are production plans for:
   a) The original baseline schedule
   b) The detailed phase schedules
   c) The weekly schedules?

The second research question evaluates the quality of the plans and production control results by comparing the actual performance to the plans made in the beginning of the project (the baseline schedule), closer to production (the detailed phase schedules) and on the previous week (the weekly schedules). The reliability of the plans was analyzed by performing a statistical analysis of a standard set of numerical variables.

3 Which factors explain the success or failure of the plans?

The third research question tries to find the reasons for succeeding or failing to realize the plans. The reasons were found by examining the correlations between the numerical variables, and examining in detail those relationships revealed by the correlation analysis and direct observations.

4 Was information provided by the location-based management system relevant for decision making?

The fourth question evaluates whether the location-based management system could have been used by the decision makers to prevent problems. This question has two components:

   a. Firstly, the information about the production problem needs to exist in the system before the problem happens
   b. Secondly, the information must exist early enough to make it possible to react before it is too late.

If the problems can be forecast before they happen, the complexity related to the interdependencies of crews and subcontractors can be greatly reduced.

5 How should the location-based management system and production control processes be changed to provide better information and decisions to prevent production problems?

The answers to question 1-4 are used to develop an improved location-based management system and processes. The resulting improved system and processes can then tested with the same data to see whether they improved the information available to the production management.

1.4 Research strategy

The research uses a case study as its research strategy. According to Yin (2003), "a case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between the phenomenon and context are not clearly evident." Because the studied phenomenon is complex, production control is an open system heavily affected by context, and multiple sources of data were used, a case study is an appropriate research strategy for this research.

Alternative research strategies; such as experiments, observation, surveys, interviews and archival analysis were considered in the planning stage of the research. Production control is difficult to research by experiments, because construction is a complex process, and it is very difficult to control all the variables outside the scope of the experiment. However, the research method to answer research question 5 is close to the experiment, because the same data are used to evaluate whether the improved production control system provides better information in exactly the same context. Surveys are limited because they reflect the respondents' observations of a phenomenon without systematic analysis of the root causes of the phenomenon. This research aims to find a deeper understanding of production control than is currently available to practitioners. Therefore, surveys were ruled out as a research strategy. Interviews were ruled out based on similar reasoning. Archival analysis was not feasible, because the variables of interest have not been systematically collected by companies based on a uniform data collection protocol. Although location-based management has been implemented in many projects and companies (for example Soini et. al. 2004), only research question 2 could be answered using pure archival analysis as a research strategy. This strategy was used previously (in Seppänen & Kankainen 2004) which motivated this research. Observation has been used in the productivity analysis, but has the drawback that it considers only observed behavior and ignores the overall context.

The research design is a multiple-case design. Three cases were used to examine the generalizability of the results to different project types, project sizes and contractual arrangements between the general contractor and the client. The research procedure follows generally the guidelines presented by Yin (2003). The cases were selected based on the replication logic, and had sufficiently distinct characteristics to examine if similar results could be found in different contexts. Location-based controlling theory was used to define the variables of interest in a uniform data collection protocol. The data were collected from each case study using the data collection protocol, then individual case results and conclusions were drawn, and finally the case study conclusions were compared to find out how well the findings aligned with each other. Triangulation was used to confirm the findings from multiple data sources in the same project in all cases, where possible. These results were used to modify the underlying location-based controlling system and create a new production control system and process to support the modified theory. The new production control system and process were tested in each case study to show that the system generalizes to many different contexts.

The study also had the characteristics of constructivist studies. A constructivist research project tries to solve the problem of an organization, which is also of scientific interest, by developing a solution construct, which is based partly on existing management knowledge and partly on the research process. The functionality of the solution is tested in practice, and its general applicability is discussed (Kasanen et al. 1991). In this study, a new, improved production control system and a supporting process were developed, tested, and discussed. The success of this part of the study can be evaluated against the success criteria of a constructivist study.

1.5 Structure of the thesis

Chapter 2 of this thesis describes the location-based management system which is used as the underlying model in this thesis. The chapter starts with a short history of the development of location-based planning and control systems, and then describes in detail the parts of the system which are relevant to this research.

Chapter 3 introduces the research methodology in detail and presents the case studies. In this chapter, the actual planning and production control processes are compared to the model processes derived from the location-based management research. Reliability is analyzed for baseline, detail and weekly schedules. In addition to reliability, the correlations between the variables are described. Production problems are analyzed and the functioning of the location-based control system is examined by looking at how early the problem could have been seen from the data produced by the system. The functioning of the production control process was evaluated by looking at how many problems were prevented by the successful control actions. Subcontractor resource use is analyzed to see if it can explain the production problems. Finally, an analysis of the functioning of the current production control system and process is done. Any issues which need to be improved are identified.

Chapter 4 describes the improved location-based control system and process using the case study results. Improvements were made based on the case study results with the goal of providing more information about the production problems earlier without adding too much data collection effort.

Chapter 5 tests some of the main findings of the research. A further analysis of the case studies is done to confirm the hypothesis which was formed after examining the case study data. The functioning of the new production control system was tested by examining any production problems found, and trying to forecast them earlier.

Chapter 6 presents the answers to the research questions, and chapter 7 discusses the reliability and validity of the results and relates them to other technical literature.

2. Location-based management systems

2.1 Location-based planning systems

2.1.1 Introduction

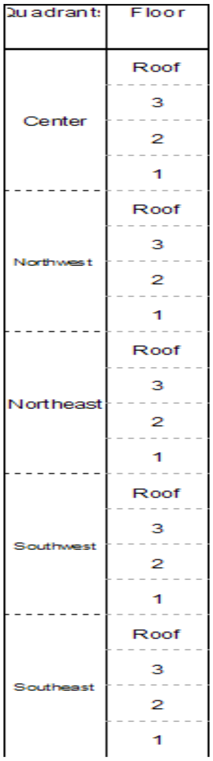
This dissertation is about improving the location-based production control system. Because location-based controlling requires the presence of a location-based plan, it is necessary to start with an introduction of the location-based planning concepts: locations, quantities, duration calculation based on quantities, resources and productivity, and layered logic. Because the focus of this dissertation is not in the details of location-based planning, these components are described only on the level of detail which is required to understand location-based controlling concepts.

The author's contribution in developing location-based planning systems has been limited to developing computerized location-based planning software, and developing the concept of layered logic and augmented critical path method (CPM) calculations to enable the automation of location-based planning theory. Most of the ideas and concepts have been developed by others. A more detailed description of location based planning theory and its development can be found in (Kenley & Seppänen 2010: 50-161).

2.1.2 Location Breakdown Structure

Locations are the core of the location-based planning and control system. They are organized hierarchically so that higher level locations logically contain all the lower level locations. Each hierarchy level has a logically different purpose. The highest levels are formed based on the structural independence of the structure. The middle levels often reflect any physical constraints (such as floors). The lowest levels are used for planning finishes. In general, the lowest level locations should be small, such that only one trade can effectively work in the area. (Kankainen & Sandvik 1993)

The Location Breakdown Structure is typically presented as the vertical axis of the flowline view, with the location hierarchy projecting horizontally. (Figure 2-1)



Quadrant:	Floor
Center	Roof
	3
	2
	1
Northwest	Roof
	3
	2
	1
Northeast	Roof
	3
	2
	1
Southwest	Roof
	3
	2
	1
Southeast	Roof
	3
	2
	1

Figure 2-1: An example Location Breakdown Structure of a medical office building project. The project has 4 quadrants and a central lobby area. Each Quadrant has 3 floors and a roof.

2.1.3 Location-based quantities and tasks

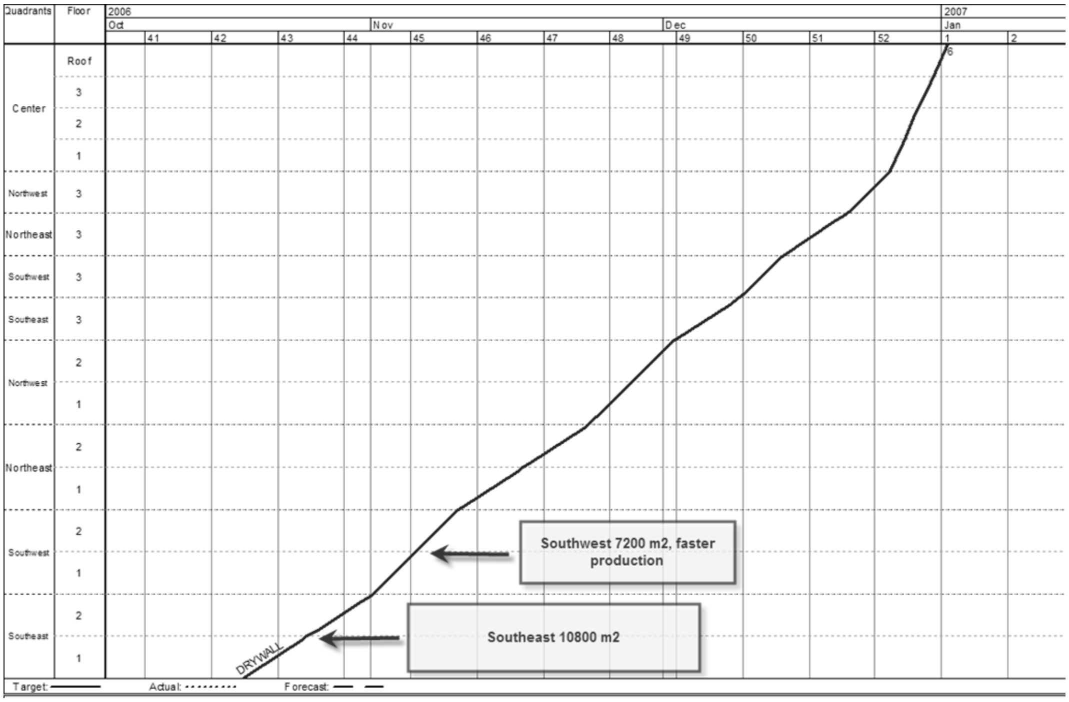
Quantities are an integral part of a location-based management system. The Bill-of-Quantities of the project defines explicitly all the work that is required to complete the building. Quantity take-off has traditionally been done using lump sum quantities. However, location-based management requires these quantities to be estimated based on the project's Location Breakdown Structure. Therefore, quantity take-off should be done after defining the locations. Typically, location-based quantities are presented in a table with locations as columns. Table 2-1 shows an example of the location-based quantities of the drywall for the project shown in Figure 1. Because of space limitations, the quantities are only shown on the Quadrant level of detail.

Table 2-1: Location-based quantities for drywall

Item	**Consumption**	**Southeast**	**Southwest**	**Northeast**	**Northwest**	**Center**	**Unit**
Drywall	0.013	10800	7200	10800	7200	3200	SF

Location-based quantities are allocated to schedule tasks to explicitly define the scope of work for each task. The work can be lumped together if it can be done with the same crew, has the same logic outside the work package, and can be completely finished in one location before moving to the next location (Kankainen & Sandvik 1993). Mendez and Heineck (1998) proposed a similar approach independently of the Finnish research. Location-based quantities are important, because when the concentration of work varies throughout the building, some trades will take longer time in certain locations to complete than others. If this is not taken explicitly into account in the plan, it will cause a starvation of work for the succeeding trades and need to work out-of-sequence (Tommelein, Riley & Howell 1999) to have unplanned crew size adjustments or to force a subcontractor to leave the site (Kiiras 1989, Kankainen & Sandvik 1993, Seppänen & Kenley 2005a).

The quantities of a task define the task's locations and duration in each location. Figure 2-2 shows a flowline figure based on the drywall quantities in table 2-1. The flowline figures show the Location Breakdown Structure on the vertical axis and the timeline on the horizontal axis. The tasks are shown as diagonal lines illustrating the flow of work. The locations with smaller quantities are produced faster assuming identical crew sizes.



Southwest 7200 m2, faster production

Southeast 10800 m2

Figure 2-2: Flowline figure showing the variation of quantities with standard crew size

2.1.4 Calculating durations based on quantities, resources and productivity

In location-based planning, durations are calculations based on quantities, resources and consumption rates. Labor consumption is a property of each individual BOQ item. Consumption indicates the amount of man or machine time (measured in man or machine hours) that it takes to produce one unit of each item. The consumption value always assumes the use of a certain optimal crew size, and it may vary for different crew sizes (Kankainen & Sandvik 1993, Arditi, Tokdemir & Suh 2002).

The consumption values can be based on the historical data of the company, or generic productivity databases. In Finland, productivity information has been collected as a joint effort by the construction industry since 1975. Productivity rates are updated every year and include both optimal productivity rates and productivity rates which include allowances for interference and work stoppages (Mäki & Koskenvesa 2002). Similar productivity databases exist in other countries; for example RS Means is a productivity database for the US industry (RS Means 2009).

|A duration in a location can be calculated by calculating the total hours of each location (quantity in location * consumption for each quantity item in the task). Because the aggregation is in hours, the task can include quantity items with different units. The total hours are divided by the number of resources to get the duration in hours, and then divided by shift length to get the duration in days. (Kankainen & Sandvik 1993) The resulting duration can be multiplied by a difficulty factor. (Kenley & Seppänen 2010: 132-133)

Duration calculations rely on the consumption rate being based on an optimal crew size. Work can be best accelerated or decelerated by increasing or decreasing the multiples of the optimal crew. If the crew composition is changed from the optimal, the consumption rate needs to be adjusted. The duration which has been calculated based on the optimal crew size, and the associated consumption rate is the optimal rhythm for the task. (Arditi et al., 2002)

Before the implementation of location-based scheduling software, these calculations were done manually in a spreadsheet first, and then the end-result was plotted in flowline diagrams (Kiiras 1989, Kankainen & Sandvik 1993, Mendez & Heineck 1998). Crew optimization was done by selecting the crew sizes so that the durations of the predecessors and successors were equal. Because of the difficulty of handling the variations in quantities, it has been claimed that location-based systems are only suitable for repetitive construction (Kavanagh 1985). However, these limitations have been overcome by the implementation of a commercial software package implementing a location-based planning system (Kankainen & Seppänen 2003, Soini et al. 2004).

2.1.5 Layered logic

Location-based planning integrates CPM to flowline scheduling. This was first attempted in a software package called RepCon (Russell & Wong 1993). RepCon classified tasks into continuous activities, ordered activities, shadow activities, cyclic activities, and non-repetitive activities. The system automated the creation of CPM logic by use of the location and recognized that logic can be typical or non-typical. Integrating network scheduling and location-based planning was also attempted by Kähkönen (1993). In his approach, locations were used to automate the generation of activity dependencies and calculating the maximum overlapping of activities in locations based on location size and work area requirements. Resource links were also automatically added to the schedule. However, activity continuity was not specifically addressed other than adding the resource links. The traditional CPM algorithm was used in schedule calculation.

The location-based planning system uses an approach related to RepCon and Kähkönen's work. Instead of considering each location as a separate entity, logic is formed between the tasks composed of multiple locations. Because logic can be automated in many ways using locations, the resulting logic is called location-based *layered logic* (a term coined by Kenley in Kenley & Seppänen 2010: 133). The basic principle is that the layered logic automatically generates a CPM network based on the locations. A detailed explanation of layered logic is outside the scope of this work and can be found in (Kenley & Seppänen 2010: 133-144). The main difference to traditional CPM algorithm is that the work can be planned to be continuous or discontinuous. Continuous work delays the start date of a task such that work can be implemented continuously. This enables planning continuous flow processes, so that crews can perform productive work with minimized work-in-process between the crews (Ballard & Tommelein 1999).

2.1.6 Logic types, buffers and lags

All the basic logic types of CPM are also available in location-based planning:

1. Finish-to-Start (F-S)
2. Finish-to-Finish (F-F)
3. Start-to-Start (S-S)
4. Start-to-Finish (S-F)

Additionally, a lag can be added to any dependency relationship. Lags are a well-known component of CPM logic. Location-based planning adds the new concept of the buffer, which is important for location-based controlling. Lags are technically mandatory delays which must be followed. In contrast, buffers are an additional absorbable allowance for disturbances. In planning, buffers and lags work in exactly the same way. However, during implementation the buffer can be absorbed before affecting the succeeding trade. Therefore, the forecast, which will be explained in more detail at the end of this chapter, ignores buffers when forecasting future problems.

In previous Finnish research, buffers have been planned by planning free locations between tasks (space buffer), and by planning start-up delays between tasks in the first location (Kankainen & Sandvik 1993). The buffers of a location-based planning system formalize this relationship to be part of the layered logic links.

Regardless of whether buffers are planned as part of logic, or by planning free locations or start-up delays, in the flowline figures, buffers can be seen as the horizontal and vertical empty spaces between two dependent tasks. (Figure 2-3)

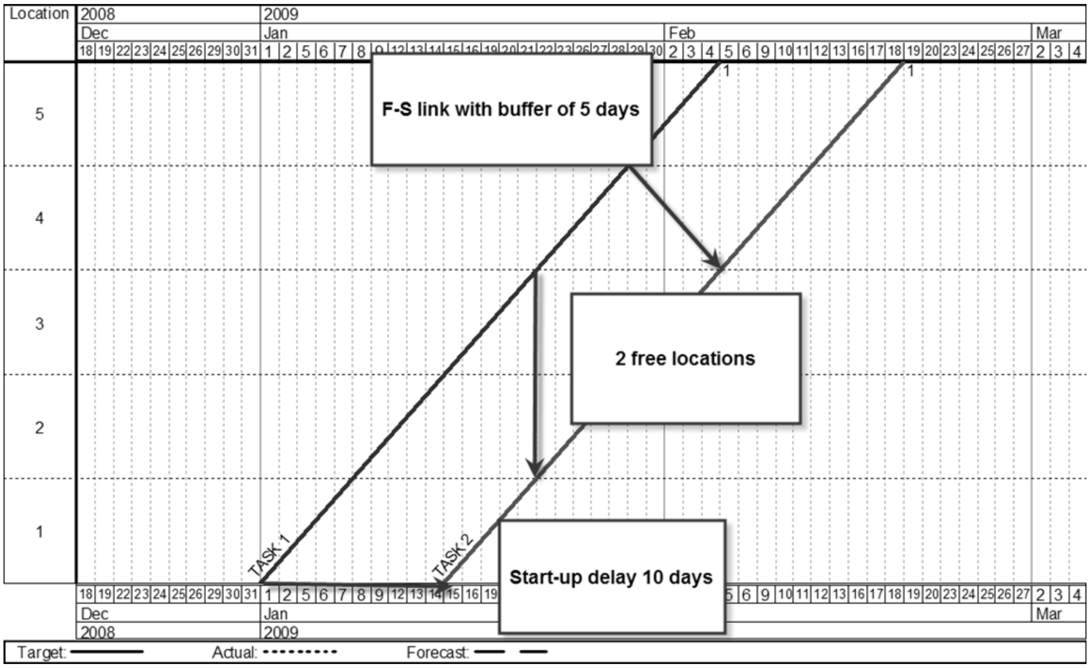


Figure 2-3: Three equivalent ways of visualizing and planning the buffer – start-up delay, free locations of F-S link with a buffer.

Buffers are not just a property of location-based planning. The critical chain method (Eliyahu 1997) applies buffers to CPM project scheduling. A CPM schedule is created by initially removing all the safety time from duration estimates and adding a project buffer to protect the critical path (pp. 154-155). The critical chain recognizes that all delays do not occur on the critical path and adds feeding buffers before the non-critical paths converge with the critical path (p.157) and resource buffer before the use of constrained resources on the critical path (p.160).

Buffers in location-based planning are different because they are not part of the task duration, but they are located between two tasks to give time to react to deviations. The goal is to protect the continuous flow of a task, instead of just protecting the critical path. Because the production rates of predecessors and successors are aligned, most tasks are on the critical path.

2.1.7 Splitting

In some cases, some locations of a task need to be split to form new subtasks. This can be necessary to allow the following planning decisions (Kenley & Seppänen 2010: 156-157):

- Different resources in a location
- Doing multiple locations concurrently with different crews
- Planning a break between some locations
- Constructing a different logical relationship in some locations
- Making part of the task continuous and another part discontinuous

When this research started, splitting was implemented by creating a new completely independent task.

2.1.8 Location-based planning methodologies

Kenley and Seppänen (2005) recognize that there are effectively two location-based planning methodologies: CPM-based and risk management based. The CPM-based methodology is a good starting point for those with CPM backgrounds, and places heavy emphasis on using layered logic to achieve continuous production with minimum durations. However, these schedules may be risky and difficult to control.

The risk management based methodology is the end result of Finnish research projects, and includes checking the feasibility of scheduling and planning buffers based on risk analysis. In earlier research before computer software was available to automate location-based planning, buffer sizes were based on heuristics. In special projects, a start-up delay of three weeks was normally used, because of the greater uncertainty (Kiiras 1989) and in routine production, the normal recommended values were two weeks of start-up delay and two floors as a location buffer (Kankainen & Sandvik 1993). These heuristics were applied mainly on the interior finishes and mechanical, electrical and plumbing work. Because the methods were manual, the early location-based schedules included only those tasks which were space-critical, and did not allow other crews in the same location at the same time. Other tasks were scheduled in Gantt charts. After the implementation of the DynaProject (later Control) scheduling software, the focus of the research shifted to the risk analysis of schedules using a Monte Carlo simulation. In the research project, four construction projects (with areas between 14,000 and 25,000 m^2) were analyzed with the tool, and the schedules were re-planned, resulting in a much higher quality final master schedule. The changes prompted by the risk analysis included changing the section building order, re-planning the overlapping interior works, and rescheduling the tasks most prone to disruptions (Kolhonen, Kankainen & Junnonen 2003).

With the computer software available, the previous restrictions of the manual systems, such as having quantities estimated only for Sections and Floors, or scheduling only space-critical tasks, are no longer relevant. All tasks can be scheduled using location-based methods, and locations can extend to the individual room level of detail. Also, tasks can be much more detailed. Therefore, the old heuristics are no longer relevant. Kenley (2004) called the Finnish approach strategic “macro-management” concentrating on minimizing the risk of interference, but claimed that macro-management does not address the real power of the location-based scheduling techniques for managing work flow on site. His proposed micromanagement approach proposed scheduling tasks on a very high level of detail to actually show the location of all work crews in the project. In the Finnish research, this level of detail was usually added during the implementation phase, in task planning, which will be explained in the following section, concentrating on controlling techniques.

2.1.9 The author’s contribution to location-based planning systems

The author’s contribution to location-based planning was the development of the DynaProject software between 2001 and to date (the current name of the software is Vico Software Control). In order to automate the planning system developed in Finland, it was necessary to define in detail the methods and algorithms related to integrating the flowline and the CPM method. After the software was implemented, the term layered logic was coined by Kenley (Kenley & Seppänen 2010: 133) to theoretically explain the software functionality. The software tool was rapidly implemented by the main players of the Finnish construction industry (an implementation case study has been described in Soini, Leskelä & Seppänen 2004). It was the main research tool in this research.

2.1.10 Summary

Location-based planning has the following basic components:

- A Location Breakdown Structure (LBS)
- Location-based quantities
- Location-based tasks
- Duration calculations based on quantities, resources and consumption rates
- Layered CPM logic
- Buffers and lags
- A CPM engine with continuity heuristics

Location-based planning attempts to achieve feasible schedules with acceptable risk levels, while maximizing continuity and minimizing project duration. Feasibility is achieved by basing durations on explicitly defined scope by using quantities and productivity rate assumptions. Buffers are added between tasks to minimize the risk of cascading return delays. A location-based, feasible schedule with known risk level can be used as the basis for effective control using the location-based control system described in the next section.

2.2 The location-based controlling system

2.2.1 Introduction

Improving the location-based controlling system is the topic of this research. To get the benefits from an optimized plan, the plan needs to be followed. Controlling means taking actions to make the plan happen, as opposed to just monitoring the plan and managing by exception. (Kiiras 1989, Ballard 2000). Controlling is divided into proactive control (preventing problems before they happen) and reactive control (evaluating the effects of deviation and mitigating its effect). (Kankainen & Sandvik 1993). Controlling also includes learning from past mistakes. (Ballard 2000) Melles and Wamelink (1997: 104) divided project-level production control into project coordination (activity sequence, durations, activity start and finish times), mobilization planning (the sequence of assignments, location and the time of the assignments, size and time of deliveries) and allocation planning (the completion and sequence of operations, the work crew member performing the operation).

Location-based tools can be used to visually show progress against planning, calculate the forecast based on actual production rates, and to ensure frictionless production by reacting to deviations with control actions. This chapter describes the components, calculations and processes related to location-based controlling, as known at the beginning of this research. The goal of this research is to test and find ways of improving these methods by using a case study approach. Before describing the location-based controlling system, other research in the production and project control of building construction projects is explored. Although the production control methods of construction projects often originate from other industries, this exploration is limited to the methods applied to building construction.

2.2.2. A history of controlling systems

2.2.2.1 Activity-based controlling systems

All planning systems have been designed for the purpose of controlling projects to ensure good implementation. For example, CPM was designed so that "the plan should form the basis of a system for management by exception… Under such a system, management need only act when deviations from the plan occur" (Kelley & Walker 1959).

In CPM, only activities on the critical path were examined, and efforts were concentrated to correct deviations only when they affected the critical path. CPM also included a crude early warning system described by Mauchly (1962) based on notifying management when the start date of an activity approached the latest start date or the finish date came close to the latest finish date.

While management by exception and updating the schedule is better than no control method at all, it is essentially an "after-the-fact" approach. Project managers should be more interested in preventing problems than curing them (Meredith and Mantel 1995). Koskela & Howell (2001) call this the thermostat model of control which is overly simplistic.

The current activity-based practice relies on fixing a baseline schedule and then updating the schedule using actual dates. Management attention is prioritized by looking at critical and near critical activities (for example, O'Brien & Plotnick 2006: 471). Based on schedule update, the contractor knows when the critical path is changing and then can resequence the work to avoid project delays (Galloway 2006). This approach may lead to schedule compression, and increased schedule pressure at the end of the project, causing productivity problems. (Thomas 2000, Nepal, Park & Son 2006). Continuously updating the plans may lead to a false sense of security and pushing problems to the future.

Critical chain contributed some new ideas to activity-based control. Instead of calculating the completion rates for all tasks, only the critical path activities are considered (Eliyahu 1997: 162). Because all buffers have been removed from durations, people do not dare to procrastinate. Critical chain also recognizes the importance of prerequisites, making sure in advance that resources are available (p.164) and giving early warnings to subcontractors and resources when work on critical path is imminent (p. 165).

2.2.2.2 Location-based controlling systems

Location-based systems are strong in controlling, because they allow a visual comparison of progress compared to the plan. The original plan does not need to be changed, because both the plan and the actual situation can be plotted onto the same diagram. However, most of the literature about location-based systems outside Finland has concentrated on planning or the theoretical issues of learning curves, instead of controlling aspects (for example Arditi et al. 2002, Arditi, Tokdemir & Suh 2001, El-Rayes & Moselhi 1998, Yang & Iannou 2001).

In contrast, in the Finnish research about location-based systems, enabling the better implementation of schedules and improving the efficiency of production have been the main goals. The research was motivated by the construction boom in Finland in the 1980s where profits were smaller than expected because of resource availability issues and end-of-project rushes. The results of 16 Master's theses level action research studies can be summarized as follows (Kolhonen et al. 2003):

- When the actual production deviates from the plans, control actions must be taken to put the project back on schedule, rather than updating the schedule
- Production control must ensure a continuous work flow by the use of free locations

Getting back to the original schedule, instead of updating the schedule is important, because all the actors in the production process rely on the latest plan when they make their resource plans. If the plan keeps changing, the resource requirements of the project change, leading to a sense of chaos. Therefore, control actions are necessary to restore production. The flexibility for control is given by the requirement to have free locations between predecessor and successor trades; i.e. buffers. Any production system with variability requires buffers. Hopp and Spearman (1996) divide buffers into time, capacity, and inventory buffers. Free locations are a type of time buffer, because if a buffer is not required, the location stays idle for a period of time.

In the early stages of the research, production control in the Finnish production control system was based on weekly planning. However, weekly planning resulted in the shifting of work, and hence problems towards the end of the project (Kiiras 1989, Kankainen & Seppänen 2003). As a result, research began on task planning as a production control method to ensure that production would be implemented according to the master schedule, and that the starting prerequisites of tasks would be fulfilled (e.g. Junnonen 1998, Koskenvesa & Pussinen 1999, Junnonen & Seppänen 2004).

Task planning is based on dividing production control into mutually-interacting parts, and securing the implementation of each task from the different aspects: scheduling, costs, quality, and safety. The master plan defines what should be done, but it is often too rigid and general to be of use to the site manager and superintendents in the planning and controlling of individual project tasks. Task planning differs from weekly or look-ahead planning in that the implementation of a whole task is planned as one entity. (Junnonen & Seppänen 2004) The definition of a task is the same as in location-based planning, i.e. the related scope of work which can be done by one subcontractor at the same time.

Task planning starts from the cost estimate, which defines the main schedule (i.e. the master or baseline schedule) which in turn defines the constraints for task plans (Figure 2-4). Task plans give the starting information for any subcontract agreements, and are revised after an agreement has been made. Task plans are reviewed together with the subcontractors in the start-up meeting, where commitments are made regarding the schedule, quality, and safety. When production is ongoing, control meetings are used to plan any control actions to get back to the targets set in the task plans. (Junnonen & Seppänen 2004)

The main contribution of task planning is the recognition that subcontractor input is crucial in ensuring that the production rate of the task is compatible with the master plan. Production rates from the baseline schedule are used in calls for tender and subcontract agreements. Task planning in conjunction with the subcontractor ensures that the baseline schedule objectives can be achieved. Task planning is a comprehensive approach including the schedule, cost, quality, safety, and recognizing the risks and potential problems of the task (Junnonen & Seppänen 2004). However, only the schedule aspects are relevant to this research.

In addition to having a feasible location-based baseline and task planning as proactive controlling methods, the Finnish research recognized the importance of reactive controlling methods when deviations happen. The main focus was on the planning of control actions to catch up with the original schedule if there were disturbances, instead of updating the schedule (Kolhonen et al. 2003). To achieve this goal, graphical control charts were developed to show the status of production compared to the baseline (Hannukkala 1991). Basic forecasting rules were defined for extrapolating the trends of the actual production to the future. Control action planning was defined as changing the forecast, instead of updating the plans (Jouko Kankainen, personal communication). The results from 16 research projects showed that the original baseline schedule is possible to be implemented as planned, but only if task planning is used and control actions are planned to correct deviations. (Kolhonen et al. 2003). Even large deviations (an 8-week delay) can be corrected (Toikkanen 1989). These results were gained with the action research methodology, where the researcher was an active participant in the production control process.

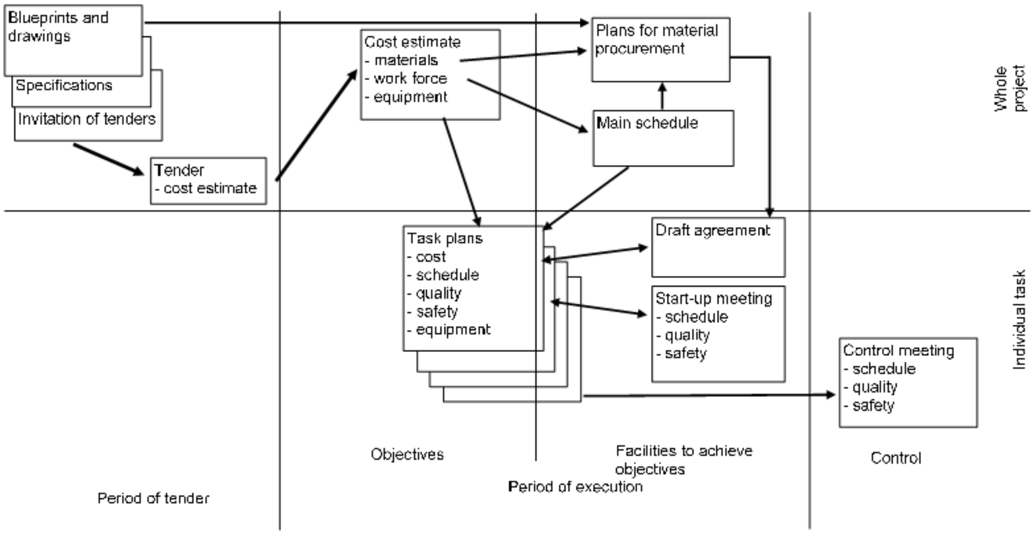


Figure 2-4: The principle of task plans and their connection with other production plans (Junnonen & Seppänen 2004)

2.2.2.3 Lean Construction

The goal of the Lean Construction philosophy comes from Lean Manufacturing systems and is to avoid waste (Shingo 1988). The Finnish research described above was done independently of Lean Construction. However, the main goals have been the same – to target the inefficiency and lack of reliability in construction; to decrease waste and improve productivity.

The tools developed to achieve this aim have been different, because Lean Construction has been mostly based on activity-based planning and control. (Kenley 2005). This is because Lean control tools were initially developed on top of the scheduling systems that were already in place. These were overwhelmingly activity-based. (Glenn Ballard, personal communication). In the world of activity-based planning and control, each activity in every location is considered a separate activity. Thus, work is organized to maximize the flow of the individual activities. Detailed planning is left late, and work is pulled as ready and as required. The detailed processes of late planning, including Last Planner™ (Ballard 2000), have been developed to ensure a continuous flow of work. In Lean Production Management, planning is called work structuring. Master schedules are limited to phase milestones, special milestones, and long lead items. Phase schedules are planned by the team who will do the work using a backward pass from a completion milestone. The goal is to develop a hierarchical planning system that adds more detail close to production (Ballard, Tommelein, Koskela & Howell 2002: 227-229). Pull techniques are defined as working backward from a target completion date, which causes the tasks to be defined and sequenced so that their completion releases work (Ballard & Howell 2003). Because preplanned, detailed master schedules are considered unreliable in this view, the focus is on improving the visibility of the look-ahead period and improving reliability on a weekly level. The observation of unreliable schedules may have arisen from the fact that activity-based schedules do not include buffers (except for critical chain, Eliyahu 1997), and are not based on the actual scope of work or resources. Additionally, activity-based schedules do not have the concept of work continuity and are not realistic models of production (Kenley 2005).

The Lean Construction community has recognized the importance of planning continuous flow. For example, Ballard and Tommelein (1999) define the steps of designing a continuous flow process and recognize that when work can be structured as a continuous flow process, it reduces the coordination burden and improves the reliability of work flow. To maintain continuous production without changing resource levels, Lean Construction advocates variability reduction, planning alternative assignments for the crews on-site (workable backlog), and to provide an alternative use of labor time such as training. (Ballard, Howell, Koskela & Tommelein 2005).

Lean Construction has developed methods which are similar to the task planning in Finnish research. First Run Studies are extensive plans of the upcoming operation by a cross functional team. They are done within the lookahead window, close in time to the scheduled start of the operation, when all the required information is available (Ballard 2000: 3-18 – 3-19). Planning is followed by a methodical study, a redesign of the operation and retrial until a standard is established. The operation is defined in the same way as in task planning as class of work (such as duct work or stainless piping). Howell & Ballard (1999) describe a First Run Study check list which includes requirements (such as quantities, completion date, duration and budget), the status of the operation (such as design review, material availability, prerequisite work, space, people, tools & equipment), Sequence (a detailed work sequence and direction of progress, and the work release criteria for the next steps) and a detailed operation plan (the flow charts of processes, prefabrication, shared resources, safety concerns, etc.). Interestingly, task planning and First Run Studies have very similar contents, and their development has happened at the same time. (e.g. Junnonen 1998, Koskenvesa & Pussinen 1999 and Howell & Ballard 1999).

The Last Planner system of production control aims to improve productivity by only allowing assignments which have been “made ready” to the look-ahead or weekly work plans and actively making tasks ready. Assignments are well defined and correctly sized directives which determine what specific work will be done in the next week or next day. The person or group that produces the assignments is called the "Last Planner" (Ballard & Howell 1994). The look-ahead process in Last Planner selects work from the phase schedule, which planners think can be made ready. Phase schedule activities are broken down into work packages and operations. The assignments for the next week will be selected from the look-ahead schedule, but only if it is sure that the task can be done. Work that is ready, but is not included in the weekly targets, is part of the work backlog, which can be used if the production unit has completed all the assignments, or fails to complete some assignments. This approach shields the production unit from variability. The success of the weekly plan is measured by calculating PPC, the percentage of assignments successfully completed. For each failed assignment, a root cause analysis is done to prevent the problem from happening again. (Ballard 2000) If the reason for non-completion is related to removing constraints, then the look-ahead process needs improvement. Sometimes an individual planner is at fault because of a failure to assess capacity or risk (i.e. forecast) and he is the focus of the improvement. Remedial actions are evaluated by continuing to monitor the reasons for plan failure. (Ballard, Tommelein, Koskela & Howell 2002: 233). In this way, forecasting and alarms are included implicitly in the social process because bad forecasts lead to plan failures which lead to remedial actions to improve forecasting and alarms.

The Last Planner System™ is supported by two commercially available software packages; The SPS Production Manager (described in Arbulu, Koercker & Espana 2005 and on the Strategic Project Solutions website, SPS|Production Manager, n.d.) has features to define, track and measure commitments; define work packages and measure their cycle times, throughput and work in process, real-time progress reporting; and resource forecasting features. The Tokmo Production System (Tokmo Production System, n.d) includes weekly work planning features and 3D-model based visual planning.

In location-based planning and control, activities in different locations are considered part of the same task. The concept of flow requires that locations are completed in sequence and resources flow continuously from location to location. A location completion releases resources to the next location. Pull is considered at the task level, instead of the activity level. Empty locations pull available resources from the previous locations. The main focus of Lean Construction in the location-based view is that resources flow without the interruptions caused by a lack of prerequisites in any location. (Kenley & Seppänen 2010: 109) The goal is to achieve a continuous flow like an assembly line on the construction site. The location-based concept of flow has been called "labor flow" as opposed to work flow, which focuses on the hand-offs between trades (Thomas, Horman, Minchin & Dong 2003). It is clear that both labor flow and work flow are critical to the success of the project. The ultimate objective of a production system should be to minimize both the work waiting for workers (work flow) and workers waiting for work (labor flow). (Glenn Ballard, personal communication).

2.2.3. The components of a location-based controlling system

2.2.3.1 Stages of information

A location-based controlling system recognizes that there are four stages of information: baseline, current, progress and forecast. The information in these stages is tracked by two sets of tasks: schedule tasks and detail tasks. The stages of information originate from the Finnish research on location-based control. However, they have been more systematically defined so that the resulting method can be implemented in software.

Baseline

The baseline stage is the initial, approved, location-based plan modeled by schedule tasks. The baseline should not be updated unless there is an Owner-approved change order, or a delay caused by the Owner. The baseline schedule is used to make commitments to subcontractors, to plan procurement, and to prepare the subcontract tender schedule and milestone information. It sets constraints to the detail schedules (task planning). To achieve these objectives, the baseline schedule should be feasible.

Current

The current stage functions in a similar way to the baseline, however it recognizes the need for changes in the project plan to take into account any new information which was not available when the baseline plan was made. The current stage can be used to implement the task planning method in Finnish literature (e.g. Junnonen 1998, Koskenvesa & Pussinen 1999, Junnonen & Seppänen 2004) or phase scheduling in Lean literature (Ballard 2000). The current stage has a mapping to the baseline stage of information by using a new set of location-based quantities (current quantities), and a new set of tasks (detail tasks) to manage the changes involved in the current stage planning.

A new set of quantities is needed, because production management needs to be aware of any quantity changes during the project. The baseline quantities contain initial assumptions about the quantities and productivity rates. When more information becomes available, the quantities may get more accurate, mistakes in quantity measurement may be revealed, or there might be variations from the original design.

All of these changes are updated to the current bill of quantities, and affect the durations of the detail tasks.

The detail tasks form the current schedule of the project. Detail tasks are formed when the schedule is approved. A detail task is initially identical to the baseline task. Therefore, each baseline task is linked to at least one detail task. Detailed planning may include adding more detail to locations, or adding more detail tasks, or changing the start dates or production rates to correspond with the subcontract agreements, or discussions with the subcontractors.

Progress

The *progress stage* monitors the actual performance of the project, and therefore tracks data in the detail tasks. The progress of production is measured by recording the task start and finish times in each location of a detail task. The actual production rates for the detail tasks can be calculated from this.

Forecast

The forecast stage uses the current plan and progress information to calculate a schedule forecast. If control actions are not taken, the production can be assumed to continue with the actual production rate currently achieved. Forecasting uses the planned logic to evaluate the impact of any deviations on the following trades. This information can be used by the production managers to make informed decisions about any suitable and immediate control actions required to restore the planned production. This is done using alarms to alert management before the interference has occurred. This model allows timely reactions, instead of just recording the deviation and rescheduling.

2.2.3.2 Mapping between stages of information

The stages of information together form a comprehensive, location-based controlling system. This section describes the mappings between the four stages of information, and how they form a comprehensive, integrated model utilizing the same information structure with different levels of uncertainty.

Revised Location Breakdown Structure

It is possible to add more detail to the LBS during implementation by dividing the existing locations into smaller sub-locations. This is useful if the most logical location breakdown structure can not be known in advance for the most accurate hierarchy levels. For example, in many projects the end-user of spaces is not known when the project is preplanned. In this case, it is possible to pre-plan the schedule using only the floors as the most accurate locations and then to develop the current plan using the actual spaces as the most accurate locations.

Locations should be added on the new, more detailed hierarchy levels, because this preserves the mapping between the baseline and current schedules. Because all the locations on the new hierarchy levels must be hierarchically below the existing locations, the more accurate data of the current plan can be summarized to the baseline accuracy level. By assuming that the higher level location has begun when any of the new lower level locations has been started, mapping the current to the baseline becomes possible. Similarly, the higher level location is finished only after all the lower level locations have been finished.

Adding locations on an existing location hierarchy level necessitates the updating of the baseline to also have quantities in the new location. Otherwise, there can be no mapping between the baseline and current schedules in the new location.

Removing locations during detail planning can be done by setting the quantities to zero in that location (no work is done there). There is no need to remove locations from the LBS, so the baseline does not need to be changed.

Current bill of quantities

The bill of current quantities is used to calculate the detail task durations. It is identical to the baseline bill of quantities, when the baseline is approved, but it is updated as the new information becomes available. Thus, comparisons between the baseline and the current bills of quantities will show any quantity changes during the project. In addition to the changes, quantity items may be defined on a more accurate hierarchy level (if the new hierarchy levels have been defined in the LBS), they may be removed or new quantity items may be added.

Detail tasks

The location-based control system uses a new set of tasks – detail tasks – to handle the updating of the schedule, while maintaining the link to the baseline. The detail tasks and current quantities form the current schedule, and are used to control the actual production and to show the effects of any deviations from the baseline.

The properties of detail tasks are identical to the schedule task properties, but they can be freely changed during the detail task planning process. Each detail task is associated with only one task on the baseline schedule. A baseline task can have multiple detail tasks associated with it. The mapping of the detail tasks to baseline tasks works in two directions: on one hand the baseline tasks set constraints on the detail tasks; and on the other hand the detail task information is used to create reports on the baseline level. In this research, the latter link is important, because the progress was monitored on the detail task level, but the same information was used to evaluate the reliability of the baseline schedules. A baseline task is considered to have started in a location as soon as the first detail task associated with it starts in the location, and it is not considered to be finished until all the detail tasks have been finished in the location.

Progress stage

The progress stage augments the baseline and current information by progress information. This information highlights the deviations from the plan, is used to calculate the forecast, and is critical in the subsequent evaluation of the quality of the original plan. Progress information is available for quantities and the actual start and finish dates of a task in each location, or the completion rate, if the task was unfinished, and interruptions of work. The actual resources are a property of a location. This information can be used to calculate the actual production rate and resource consumption with the following formulae (Seppänen and Kenley, 2005a).

(3.1) $y_E = F_A - S_A - T_I - T_h$,

where

y_E = total effective duration
F_A = actual finish date
S_A = actual start date
T_I = time lost through interruptions
T_h = time lost through holidays and days off

(3.2) $\Phi_A = Q_A / y_E$,

where

Φ_A = actual production rate (units / shift)
Q_A = actual quantity

(3.3) $L_A = R_A \, y_{shift}$,

where

L_A = actual man hours (hours / day)
R_A = sum of actual number of resources in location
y_{shift} = shift duration.

(3.4) $\chi_A = L_A / Q_A$,

where

χ_A = actual resource consumption rate (*actual hours / actual quantity*)

The actual production rates, Φ_A, can be used to forecast progress in the succeeding locations of the task. Calculating the actual production rate does not require any information about actual resources or shift lengths. The actual resource consumption rate, $\chi_{A,}$ is a much more powerful formula, because it can be used to plan control actions (for example, how much overtime should be worked, or alternatively how many resources should be added). It is also a direct measure of productivity, so it can be used to show the effects of successful or failed production control actions. However, it requires information about the actual resources and actual shift lengths.

Forecast stage

Forecast stage combines the information from the current and progress stages to calculate the forecasts to predict the total effect of any schedule deviations and variations, and therefore gives early warnings of problems.

Calculating the forecast

The forecasts assume that production will continue with the achieved production rate (rather than that planned), with the planned resources, and follows the current logic modeled with the detail tasks. A forecast is calculated exactly as the planned detail schedule, but the durations are multiplied with the duration multiplier, based on the actual progress in all of the previously completed locations. The duration multiplier is calculated for each detail task using the following procedure:

- If less than two locations have been completed, use a duration multiplier of 1
- If two locations or more have been completed, calculate the duration multiplier thus:

(3.5) $y_x = x^* (y_E^n / y_{planned}^n) + y * (y_E^{n-1} / y_{planned}^{n-1})$

where

y_x = duration multiplier
x = weight of preceding location
n = index of completed location ordered according to the completion date
y = weight of the previous location

Thus, only the two last completed locations contribute to the duration forecast, and if two locations of the same detail task have not yet been completed, the planned duration is used. The weights x and y are parameters that can be changed to adjust the relative weight of the most recently finished location. In this research, values x = 3 and y = 1 were used. The reason for not calculating the duration forecast at the start of production was to prevent the typical starting difficulties which are not expected to be repeated in all the locations to affect the forecast (Jouko Kankainen, personal communication). Only the two last locations were allowed to affect the forecast to prevent any early delays from continuing to affect the forecast.

In addition to the duration multiplier, the actual progress and current date are taken into account using the following rules:

- All started and not finished locations are forecast to finish first, then production is assumed to continue in the planned sequence
- If a location has not actually started, but could have started according to the logic, the control date (today) becomes the forecast start date
- If a location has not been finished, but should have finished according to the duration forecast, the control date (today) becomes the forecast finish date
- If a location has been suspended, it is assumed to continue on the control date (today)
- If a location has started, all the logic regarding the start of a location is ignored (F-S and S-S links). The planned logic is assumed to resume in the other locations.
- If multiple locations are going on at the same time, the duration forecast of the ongoing locations are increased to reflect the splitting of resources to the locations
- The duration forecast is calculated only for the non-finished part of the location (i.e. if the location is 50 % completed, then 50 % of the duration forecast is used for the remaining production)

By using the rules above, and the duration forecast, the complete schedule can be forecast. The detail plan logic is used to take into account any interdependencies. However, continuity constraints and buffers are ignored in the forecasting. In other words, in the forecast, continuous work can become discontinuous and buffers planned in the planning phase can be absorbed. One of the main purposes of the forecast is to identify any production problems by predicting when the buffers are insufficient to prevent discontinuities.

Calculating alarms

Alarms are early warnings of any upcoming production problems. They are generated when the schedule forecast of a preceding task pushes the schedule forecast of a succeeding task, causing either a start-up delay or a discontinuity. Alarms are also generated when a task has started out of sequence; for example a F-S relationship might have been planned, but the succeeding task starts before the preceding task finishes. Alarms are not generated when a task is delayed because of its own slow production rate. Therefore, they highlight issues which are caused by other tasks.

An alarm can happen because of the following basic reasons:

- A predecessor starts late
- A successor starts early

- Work happens in the wrong sequence
- A predecessor is too slow
- A successor is too fast
- Work is split into multiple locations

2.2.3.3 Visualization

Stages of information can be visualized using flowline figures. This dissertation uses solid flowlines for plans (baseline or detail), dotted lines for progress, and dashed lines for the forecast, and red dots for alarms or production problems (figure 2-5).

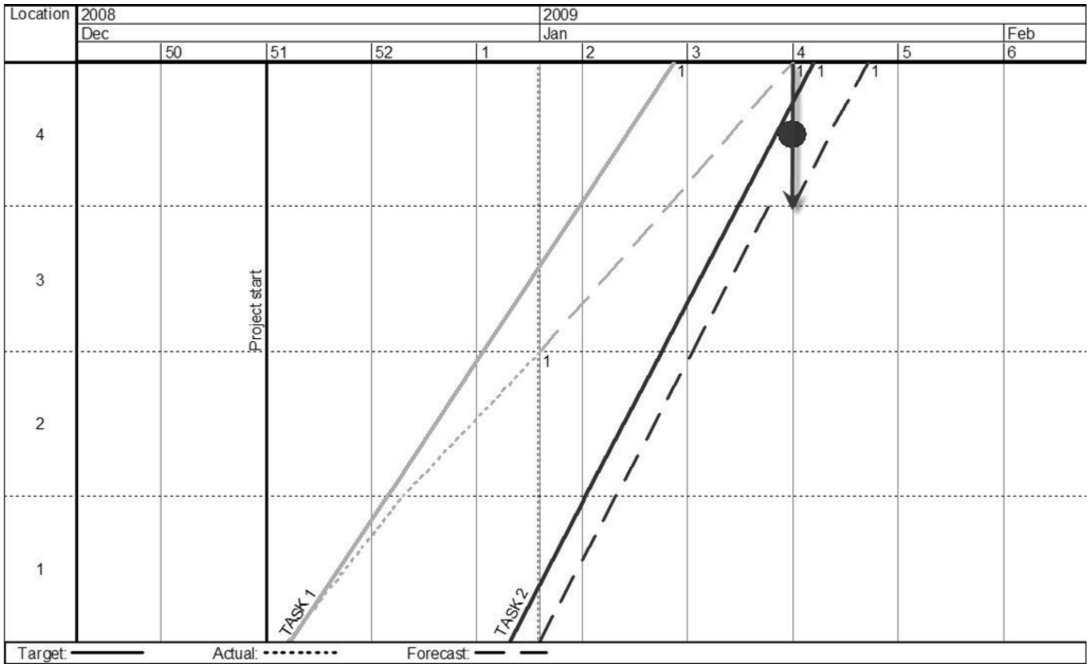


Figure 2-5: Task 1 started on time, but has had a lower production rate than planned (the dotted line has a gentler slope). If task 1 continues with the same production rate, it will cause a problem to Task 2 in location 4 (red dot, alarm).

2.2.4. Empirical research using location-based data

The four stages of information available in the location-based controlling system provide much information for the empirical analysis of projects. The results of empirical research were reported in (Seppänen & Kankainen 2004). In the research, the progress and forecast stages were compared to the baseline stage of information for selected tasks. Concentrating the analysis on the task (the work type done by one subcontractor in multiple locations) instead of the activity (the work in a location), makes this research unique, as most of other empirical research on schedules has tended to concentrate on activities or assignments (for example Last Planner™ research).

Most importantly, the paper defined a set of variables which can be calculated from location-based plans, and analyzed their correlations. The examined variables are used also in this research. They include (Seppänen & Kankainen 2004):

- Start-up delay: the actual start date – the planned start date in the first location
- Production rate deviation: the actual production rate / planned production rate
- Interruptions: the shifts of interrupted days (the days on which no work happened in any location)
- Final delay: the actual finish date – the planned finish date in last location
- Planned continuity: is the start date of the succeeding location the same as the finish date of the previous location for all of the locations? If yes, 1. If no, 0
- Actual continuity: if the number of interrupted days > 0. 1. Otherwise 0
- Minimum buffer size: the number of days between the task and the predecessor, where the tasks are closest to each other

The results showed the differences between the project types and tasks. In general, the structure stage was well controlled in all of the projects, and most problems happened in the interior work stage. Buffers were shown to decrease interruptions. This research also showed that in those projects without the active involvement of a researcher, the location-based methods did not achieve good results. Because this finding was in contrast with the earlier research done with the action research method, the research described in this dissertation was started to collect more detailed data to establish reasons why plans are not being implemented.

In this research, the variables are used as reliability indicators for the baseline schedule and detail schedules. If work starts on time, finishes on time, does not suffer from unplanned discontinuities, and has the same production rate, the plan can be considered reliable.

3 Case study research of the success of production control

3.1 Introducing the cases and research methodology

3.1.1 Description of case study I: Prisma

Prisma is a Finnish retail chain. The case project was an expansion of 6,000 m^2 to an existing Prisma store in Kirkkonummi. The structure was pre-cast concrete and had a pre-cast façade. One side of the building had a curtain wall system. Project was composed of a shop hall area of 4,200 m^2, an air raid shelter / office area, and small retail areas for entrepreneurs; including a restaurant. There was a mechanical room on the roof and a rooftop parking area.

The project was divided into five structurally independent sections of similar size. The first section had an air raid shelter. Part of the first and all of the fifth section had two floors. The other sections were the shop hall area and had only one floor. In addition to the expansion, there was some work to be done in the existing structure. This work was not included in the case study. Also, the finishes and MEP/FP systems (Mechanical, Electrical, Plumbing and Fire Protection) were planned using the structural breakdown of the five sections and two floors. All of the shop hall areas were identical. Sections one and five included offices, retail spaces, a restaurant, and a kitchen. The floor covering material of most locations was mosaic floor tiling. The kitchen and restaurant had special floor tiling. The shop hall ceiling was painted, and overhead ducts, pipes, and cable trays were visible. The fifth section had suspended ceilings in the retail spaces and offices. Sections one and five had interior walls, consisting mostly of plasterboard, but most kitchen walls were masonry.

The General Contractor of the project was Skanska Talonrakennus Oy. The project contract duration was from the beginning of August 2004 to the end of April 2005. A nine-month duration was considered tight. Otherwise, the project was considered easy to plan and control in terms of its schedule. The project had an experienced team which had built many similar projects in the past.

3.1.2 Description of case study II: Glomson

Glomson Retail Park was a two-floor retail center with four large retail spaces. The total size of the project was 10,638 gross-m^2. The structure was pre-cast concrete. One side of the façade had a curtain wall, the others were metal veneer.

The building was divided into four sections according to the sequence of the erecting structure. Section 1 had the main mechanical room on the roof. Section 3 had an air raid shelter which needed to be built before the structural work could begin on that section. The finishes and MEP were planned using the retail space breakdown. The retail spaces were allocated to sections. Section 1 included mostly administrative functions, such as offices and storage areas. Section 3 had unrented tenant space on the first floor, and a large furniture shop on the second floor. Section 4 had the main lobby and an electronics store on the lower floor, and a furniture shop on the second floor. Section 2 only had the second floor, and because functionally the shop on section 3 extended to section 2, only section 3 was used for planning the interior finishes, instead of artificially splitting the area according to its structure. Each tenant had very different specifications for their interior finishes. Consequently, almost all of the locations had different floor finishes, different types of suspended ceiling, and also changing sequences relating to the ceiling installations.

The General Contractor of the project was Hartela. The project contract duration was from September 2004 to August 2005. A one-year duration was considered standard for this project size. Structurally, the building was considered easy because of its regular box shape (refer Figure 1 in Appendix B). However, there were major uncertainties related to the earthworks and foundations, because of inadequate soil studies. Also, there was some uncertainty about tenant fit-out. One retail space had not been rented when the baseline planning started.

3.1.3 Description of case study III: Opus

Opus Business Park was an office building with six floors, and a parking hall below the main building. The total size of the project was 14,528 gross-m^2. The building was divided into two sections, each of which was built as a structurally independent entity. The sections were basically identical, except for the connecting lobby portion which was considered part of the second section (grid lines 27-20). Both sections had mechanical rooms on the roof. The first section had an air raid shelter. Additionally, there was a parking area below ground. The parking hall had to be finished before excavation of the second section could begin, because the second section was used as the parking area of the neighboring food market. The cars would be transferred onto the top of the parking deck when it was completed. The project was part of multi-phase development. Phase 2 had already been completed previously, phase 1 was delayed, and this project was initially phase 3 (Opus 3).

The structure was pre-cast concrete with some minor cast-in-place areas. The connecting lobby area had a glass curtain wall, other exterior walls were pre-cast elements with punched windows. Because the floor area decreased when going up the levels, there were small sections of roofing on various floors, starting from floor 4.

The finishes and MEP were planned for each section and each floor. The 1st floor included retail spaces and lobby functions, and was different from the other floors. The other floors had identical office functions. The floor material of floors 2 to 5 was a vinyl floor covering. The walls were movable system walls built on top of the floor covering to make it easier to accommodate user changes. Most of the MEP systems were placed in corridors inside the suspended ceiling bulkheads, and could be built before end user information was received.

In this project, both the owner-developer and General Contractor were part of the same construction group: NCC Construction Ltd. The project's original duration was from May 2004 to the end of February 2006 and was based on previous durations of similar projects. Because the client was internal, there was great pressure to cut project duration and start receiving rental income as early as possible. One of the main goals of implementing location-based planning and controlling was to compress the duration by two months, and to hand over a good quality building faster than in previous projects.

This case study has been described previously in (Seppänen & Aalto 2005). At that time, the project was still ongoing and data had not been completely analyzed. Major new findings were made during the data analysis stage.

3.1.4 Comparison of case studies

The data were collected by weekly direct observations and documentary analysis of three case study construction projects in Finland. The data were collected between August 2004 and December 2005. Data collection of the first Prisma case study (a retail mall of 6,008 m^2) happened between August 2004 and April 2005; the second Glomson case study between September 2004 and August 2005 (a retail park of 10,638 $m^{2;}$) and the third Opus case study between August 2004 and December 2005 (an office building of 14,528 m^2). All of the case studies had different General Contractors. One of the projects had the explicit goal of reducing project duration by use of location-based techniques. Although two of the projects were retail projects, one of them was for a single user and the other had multiple retail spaces. Also, the sizes and total durations were different. Therefore, it can be stated that replication logic was followed in the selection of cases. If the results of the research are similar to all these case projects, it is likely that they will also generalize to other projects.

The case studies were different in terms of total size and tightness of duration. The tightness of duration has been compared using a database of standard contract durations (Poikonen & Kiiras 1989). Table 3-1 shows summary information of the projects.

Table 3-1: Characteristics of the case projects

	Prisma	Glomson	Opus
Project type	Retail – single user	Retail – multi-user	Office – multi-user
Gross area	6,008 m^2	10,638 m^2	14,528 m^2
Total planned duration	8.5 months	12 months	18 months
Tightness of schedule (% of standard duration)	57%	71%	95%
Contractor	Skanska	Hartela	NCC
Owner	External	External	Internal
Structure	Pre-cast	Pre-cast	Pre-cast
Curtain Wall	No	Yes	Yes

It should be noted that a single user large hall can be built much faster than multi-user retail units with smaller locations, so a comparison of Prisma and Glomson just on the basis of the total square meters might not be appropriate. Nevertheless, the comparison indicates that there are differences in the tightness of schedules.

Based on interviews of the project teams, the Prisma team thought that the schedule was tight, but because they had a very good team, they could manage the short duration. The Glomson team thought that the building was simple, and the schedule was standard for a project of that size. The Opus team thought that the original total duration of 20 months was too long and compressed the schedule by two months during the planning process. According to them, the schedule for the first section was relaxed but, the second section was tight.

It can be argued that all of the case studies belong to the Unique category (Melles & Wamelink 1997: 139-148) because they had scarce personnel related to the company (project management) but most of the work was subcontracted. Prisma also had the characteristics of a Standard construction project because Skanska had built many shops for the same owner before. (Melles & Wamelink 1997: 129-139). Opus had a large requirement uncertainty because the tenants were not identified when the project started. Glomson and Prisma both had some requirement uncertainty because some tenants were known but some were unknown at the beginning of the project. The materials were standard in each project but the subcontractors were not known so delivery uncertainty can be argued to be average. The process uncertainty in all of the projects was related to building the structure in the Finnish winter. However, the productivity rates for individual building components were available, except for the MEP systems.

This chapter describes the comparison of the case study results. Appendices A, B, and C include full case study reports of each case project.

3.1.5 Data collection

In each project, the researcher introduced the production control tools, demonstrated their use to the project personnel, and participated in weekly control information updating meetings. The researcher participated in the planning of the location-based baseline schedule and the planning of the location-based detail schedules using the DynaProject (currently the Vico Software Control) software package. He did not participate in decision making, but ensured that all the relevant data were collected and the results were available to the project team. Direct observations were made in these weekly meetings about how the available information was used, and about the processes related to monitoring production status and planning detail schedules and weekly plans. Direct observations were also used to form hypotheses about possible answers to the research questions.

Documents collected included baseline schedules and detail schedules, and related production control status information from every week in the format of an electronic DynaProject file. Weekly plans were done using Microsoft Excel. The weekly plans included lists of assignments with goals for the week. Every week, a new weekly plan was created for the following week, and the status of the previous week's assignments was evaluated. Additionally, subcontractor meeting memos were collected from every project, and Owner meeting memos were collected from two projects.

3.1.6 Description of the data

3.1.6.1 Project files

The most important data were the information contained in the electronic project files. These were collected weekly from the project team after the status information had been entered and the detail plans updated. The project files of each week contained the following data (refer Chapter 2):

- Location breakdown structure
- Baseline tasks
    - Planned / actual quantities by location
    - Planned / actual / forecast start and finish dates by location
    - Planned resources
    - Planned / actual / forecast production rates

    - Planned dependencies to other baseline tasks
- Detail tasks
    - Planned / actual quantities by location
    - Planned / actual / forecast start and finished dates by location
    - Planned resources
    - Planned / actual / forecast production rates
    - Planned dependencies to other detail tasks
- Comments entered into the system by the project team
- Alarms generated by control system

Prisma had 29 files, Glomson had 40 files, and Opus had 40 files. Some weeks are missing from each project because of missed updates due to holidays, sickness, or urgent issues that arose in the projects. These were corrected in the update of the following week, and data for missing weeks were generated based on the status of the previous week and the week after. Data from project files were used as the main source of information in this research.

3.1.6.2 Meeting memos

The subcontractor and Owner meeting memos were collected from every project. Additionally, memos for schedule-related meetings with subcontractors were collected. This information was used to validate the numerical results from the project files. For example, if the project file showed that there was a problem, the subcontractor and client meeting memos from the same week were examined for validation of the problem.

The Prisma case study had 9 subcontractor meeting memos. Additionally, the material included 15 weekly, internal General Contractor meeting memos. Individual meeting memos were available for the waterproofing contractor (9 memos), 3 schedule control meetings with the plumbing subcontractor (3 memos), 2 schedule control meetings with the mechanical contractor (2 memos), and 6 meeting memos with the structural contractor. The Owner meeting memos were not available for this project. The project engineer prepared weekly documents of production status and look-ahead which were used to update the actual information in the production control system and to define the weekly assignments. The start-up meeting memos and contract negotiation memos of all the aforementioned subcontractors were made available for research.

The second case study (Glomson) had 27 subcontractor meeting memos. Individual meeting memos were available for the foundation and earthwork subcontractor (2 memos), for the structural subcontractor (1 memo), and the sitework subcontractor (1 memo). There were 12 client meeting memos.

The third case study (Opus) had 50 subcontractor meeting memos. 6 client meeting memos were available. Other data included the start-up meeting memos (24 memos).

3.1.6.3 Weekly plan data

To compare the results with the Last Planner™ results found by the Lean Construction community (e.g. Ballard 2000), weekly assignments were made and tracked for each task. The percentage of the plan completed (PPC) was measured weekly for the project and for each individual task. The weekly assignments were planned by the project team. The project teams were not specifically trained in weekly planning and the Last Planner™ system of production control was not implemented on any of the case projects. Therefore, each project defined assignments in a different way, and assignments were often not sound as defined by Ballard and Howell (1998). However, all of the assignments were linked to locations and tasks in a location-based schedule, so that it was easy to validate whether an assignment was completed or not based on the location-based status information of the following week. Table 3-2 shows an example of a weekly plan from the Opus project. In the location column, S1 and S2 denote sections, otherwise the assignments were defined by floor in this project.

Table 3-2: An example weekly plan from Opus (week 9/2005)

Task	Location	Target	Successful?
Beams	S2 / Floor 2	Finished	1
Slabs and staircases	S2 /Floor 2	Finished	1
Waterproofing	S1 / Areas 5,6	Finished	1
Mech. Vertical ducts, shaft 3	S1 / Floor 5	Finished	1
Corridor plumbing and vertical heating	S1 / Floor 5	Finished	1
Mechanical corridor ducts	S1 / Floor 4	Finished	1
Mechanical corridor ducts	S1 / Floor 5	Finished	0
Suspended ceiling bulkheads	S1 / Floor 5	Finished	0
Drywall framing and 1st board	S1 / Floor 5	Finished	0
Drywall 2nd board and insulation	S1 / Floor 3	Finished	0
Drywall 2nd board and insulation	S1 / Floor 4	Finished	0
Cable trays	S1 / Floor 2	Finished	1
Cable trays	S1 / Floor 3	Finished	1
Cable trays	S1 / Floor 4	Finished	0
In-wall electrical	S1 / Floor 4	Finished	1
In-wall electrical	S1 / Floor 5	Finished	0
Exterior wall plasterwork	S1 / Floor 3	Finished	1
Exterior wall plasterwork	S1 / Floor 4	Finished	1
Painting	S1 / Floor 2	50%	1
		PPC	**63%**

The task level PPC was calculated by calculating the total number of successful assignments related to that baseline or detail task, and dividing by the total number of assignments.

The PPC measure of each task was correlated with other production variables to establish if it had correlations with the production rates and baseline and detail plan reliability. The purpose of including this variable was not to optimize it, but to examine whether it correlated with other production variables, and, if it was found to be important, to find ways to use location-based data to create better assignments.

3.1.6.4 Direct observation

Visits to project sites were done weekly in each project, except for weeks missed because of illness or holidays. Site visits offered a good opportunity for the direct observation of the production control processes and behaviors on site. Data from direct observation included observations of the processes used by the project teams to plan their schedules and control actions. Data also revealed when the teams were either satisfied or dissatisfied with the information received from the control system. Direct observation was used to provide supporting evidence for the other results, especially any production problems inferred from the data.

3.1.7 Data analysis

3.1.7.1 Correlation analysis of the production control variables

The goal of numerical data analysis was to evaluate the performance of production control by looking at the plan performance on three levels: the baseline, detail schedule, and weekly schedule. Correlation analyses were performed on the numerical data to find correlations explaining performance. To be able to analyze theoretically meaningful variables, raw data contained in project files were refined to calculate the variables in table 3-3 (refer chapter 2, location-based control theory). Some of the same variables have been used in a research reported earlier in (Seppänen & Kankainen 2004).

The observation unit in the statistical analysis was a task. Each variable was calculated for each task. Basic descriptive statistics (minimum, Q1, median, Q3, and maximum, mean) were used to characterize the plan reliability data. In addition, standard deviation was used as a measure of dispersion. A correlation analysis was carried out to find out the correlations of variables.

Table 3-3: Calculated numerical variables

	Variable	**Calculation**
PLAN (baseline or detail task)	Planned discontinuities	Number of work breaks calculated from the schedule (work break: start date of succeeding location > finish date of preceding location)
	Continuity	If planned discontinuities = 0, continuity = 1, otherwise 0
	Minimum total float	Minimum total float (in any location)
	Maximum total float	Maximum total float (in any location)
	Minimum free float	Minimum free float (in any location)
	Maximum free float	Maximum free float (in any location)
	Minimum buffer	Planned buffer before the task
Actual	Quantity deviation	Actual quantity / planned quantity (actual quantity assumed to be equal to planned quantity when not known)
	Production rate deviation	Actual production rate (units / day) / planned production rate (units / day)
	Actual discontinuities	Number of actual work breaks calculated from the schedule (start date of succeeding location > finish date of preceding location +2)
	Actual continuity	If actual discontinuities = 0, continuity = 1, otherwise 0
	Start date deviation	Actual start date - planned start date
	Finish date deviation	Actual finish date - planned finish date
	Location sequence	1, if locations started in the planned sequence, 0 otherwise

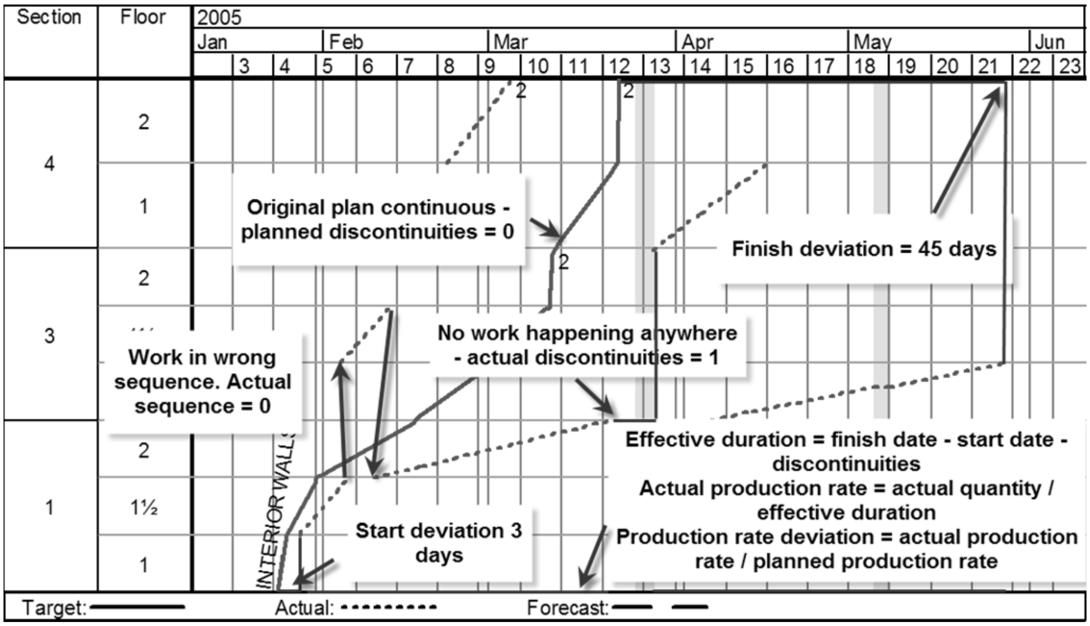
For baseline tasks, calculations were straightforward, because the baseline tasks were not changed during the implementation of the project. For detail tasks, it was necessary to decide which version of the detail task plan to compare actual progress against. Because detail tasks could change every week, it was decided that the following procedure would be used to select the detail task version for comparison:

1. Start from the version one week before the planned start of the baseline task or the actual start of the detail task, whichever is earlier
2. If the detail task's planned and actual start dates were both more than one week later than the selected week, move to one week before the planned start date
3. Repeat 2 until the current week is less than one week before the planned or actual start date

Sometimes, many iterations were needed because the detail tasks were updated many times to start later. This process was used because most of the case studies involved the subcontractor in the planning of detail tasks relatively late in the process, and any version more than one week before the actual start of production would be unlikely to consider any subcontractor input. Because the comparison was made between the plans of a certain fixed point in time and actual performance, these data reflect the reliability of the initial detail plan one week before the start of work. Because commitments were not explicitly tracked in the system, it was assumed that the plan of one week before production had been committed to by the subcontractor.

Example

Part of the data in table 3-3 was available in the DynaProject project file as numerical information. Such data included total and free float values and the buffer. Others were calculated for each task using Flowline figures. Figure 3-1, below, shows how numerical variables were calculated based on a comparison between the planned and actual data. The solid line indicates the original plan, and the dotted line the actual situation. The start / finish date deviation is the difference between the actual and planned starting / finishing date (in any location). Working in planned sequence was examined by looking at the pattern of the actual line compared to the planned line. If the locations started in the same sequence as in the plan, work was done in the correct sequence, and the location sequence variable was given the value of 1. Discontinuities were calculated by looking at work breaks, where work was not happening in any location for a period of more than two days. Each break of more than two days added one discontinuity to the count. The production rate deviation was calculated by calculating the total effective duration: finish date - start date - days of work break. The actual quantity was divided by the effective duration to get the actual production rate. The production rate deviation was the actual production rate divided by the planned production rate.



Original plan continuous - planned discontinuities = 0

Finish deviation = 45 days

No work happening anywhere - actual discontinuities = 1

Work in wrong sequence. Actual sequence = 0

Effective duration = finish date - start date - discontinuities
Actual production rate = actual quantity / effective duration
Production rate deviation = actual production rate / planned production rate

Start deviation 3 days

Figure 3-1: Example of calculating numerical data based on graphical Flowline figures

The procedure was more complicated for the detail tasks because an early version of the detail task from one week before start of production was used in comparison. Because detail tasks tended to be updated during production, it was necessary to calculate results based on two separate files: one with the original plan and one with the progress information. Otherwise, the reliability of the initial detail plan could not have been evaluated.

3.1.7.2 Production problem analysis

This research concentrates on production problems caused by interactions between multiple subcontractors. These cascading effects have been shown to be critical by simulation (Tommelein, Riley & Howell 1999). This research tries to find and quantify these cascading effects in a real-life context using actual production data instead of simulations. Issues relating to other prerequisites, such as procurement and design, are outside of the scope of this research. If a problem was identified by the project memos or other information to be caused by procurement, design, or change order, it was not considered a production problem in this research.

Production problems were identified from two sources. The main source looked at the Flowline schedules, and compared the status of the previous week to the status of the current week. The secondary source was to look at meeting memos and try to find indications of any production problems there. This was initially supposed to be the main source of information, but it turned out that projects rarely discussed production problems in official meetings, and, therefore, meeting memos were not a good data source for identifying problems.

Production problems were divided into three categories: possible production problems, probable production problems, and certain production problems. The classification was done based on the availability of triangulating evidence. If a problem was visible only in progress data, with no mention in production meeting memos and no dependency in the production schedule, the problem was classified as “possible”. If a potential production problem had been identified in the planning stage by adding a dependency between the two tasks, but there was no mention in project memos or explicit note in the production schedule, the problem was classified as “probable”. If a mention of a production problem was found in the project memos, or an explicit note in the production schedule, the problem was classified as “certain”.

In cases where no other task was happening at the same time in the location or meeting memos; direct observation or a note in the planning software explicitly indicated another reason (such as procurement or design) as the cause of problem, then the problem was ignored in the production problem analysis.

The examples below show how production problems were inferred based on progress data.

Start-up delay

A start-up delay was inferred when:

- The previous week's detail schedule for the task had a planned start date in the current week
- The task did not start in the current week
- Some other task was going on in the location where the task was supposed to start, or a technical predecessor had not been finished in the location

Because of this definition, a start-up delay did not occur if the detail tasks were updated with a later start date at least two weeks before the start of the task. In reality, this may be too strict a definition, because it is plausible that any change in the start date after a commitment is made to a subcontractor will cause a problem to that subcontractor. However, because commitments and promises to subcontractors were not recorded in the schedules or subcontractor memos, it is impossible to know whether commitments were broken. This definition was chosen because, based on direct observation, it was customary to confirm the beginning of a new task in the previous week.

Figure 3-2 shows an example where a start-up delay has occurred. The mechanical ducts should be finished before the start of the strong power cabling. Because the predecessor has not finished on time in the location where the successor was supposed to start, it has caused a start-up delay to its successor.

In this example, it can be said with reasonable certainty that the mechanical ducts delayed the start of the electrical work. This is because planner had planned a technical dependency between these two tasks, in effect recognizing that the ducts had to be finished. However, because the supporting documentation in the site memos or other documentary evidence about this specific problem was not available, it is not possible to be certain that the start-up delay was caused by the mechanical ducts being late. Therefore the problem was classified as “probable”.

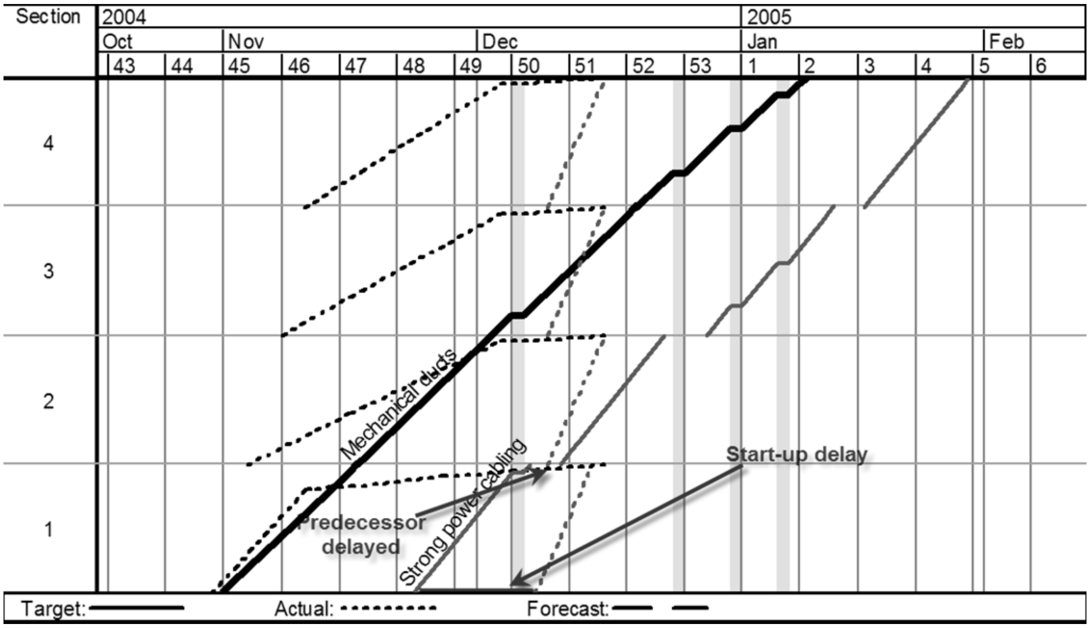


Figure 3-2: Example of a start-up delay. The predecessor was delayed in a location which caused the successor to start late in the location.

Discontinuities

Discontinuity was inferred when:

- There was an unplanned work break for a task (no work going on in any location), and the task was delayed compared to the schedule
- Other tasks were going on in the location where the task should have continued according to the plan, or a technical predecessor had not been finished in the location

In figure 3-3, below, the mechanical duct task is suspended so that the masonry walls, floor drains, floor heating, and concrete pouring tasks can go according to plan. In this case, all four tasks were considered to have caused problems to the mechanical ducts. There was a mention in site memos that the mechanical ducts would be allowed to continue after the concrete pours, so this particular problem was classified as “certain”. Other problems did not have such supporting evidence or technical dependencies in the plan, so they were classified as “possible”.

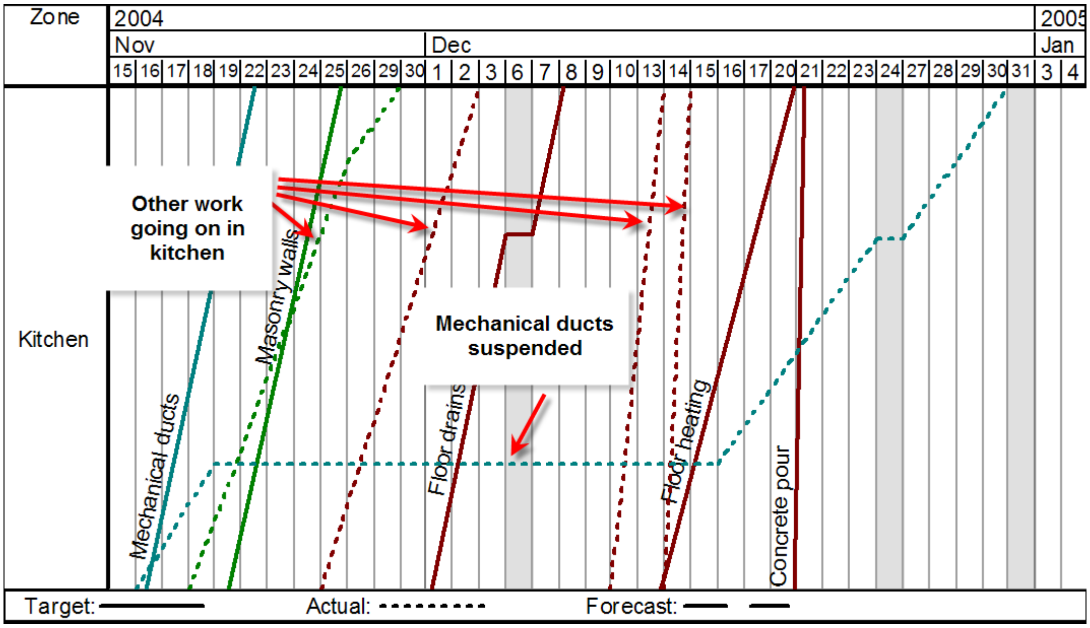


Figure 3-3: Example of discontinuity. The mechanical ducts were suspended, because other work was going on in the area.

Slowdowns

Slowdowns were inferred when:

- Two tasks were going on in the same location
- The production rate of a task slowed down by at least 20 % compared to the planned production rate and the task was delayed from the schedule

Figure 3-4 shows a clear example of a slowdown in a constrained space. There is an external deviation in the mechanical work caused by a missing design. This causes a slowdown of the plumbing and electrical tasks which have technical dependencies to the mechanical installation.

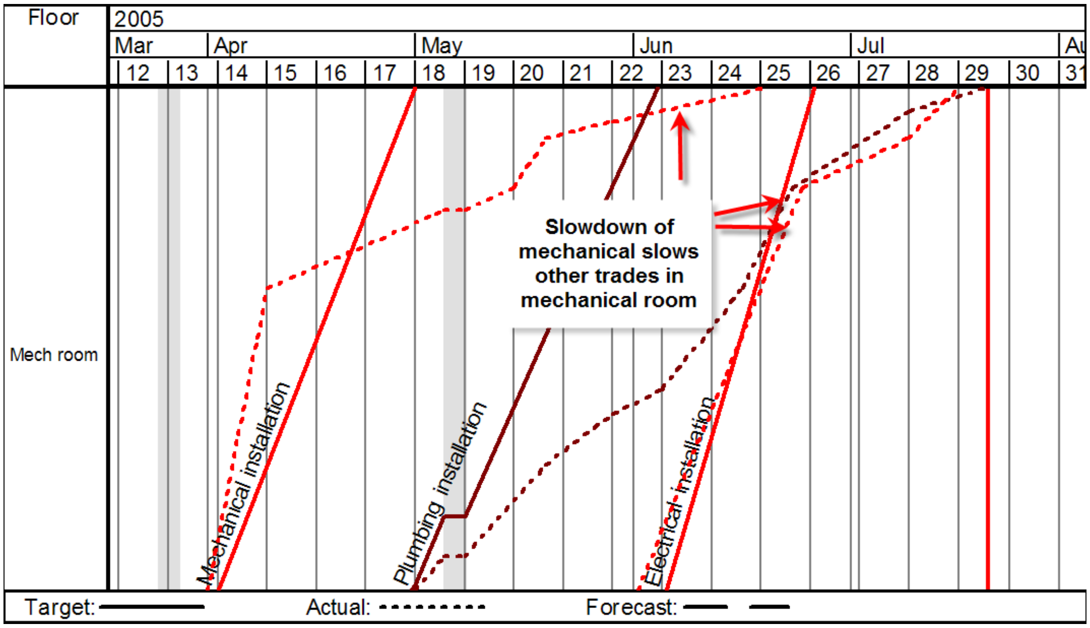


Figure 3-4: Example of a slowdown. The slowdown of mechanical work (because of design issues) in the main mechanical room causes the plumbing and electrical work to slow down.

3.1.7.3 Control action analysis

Control action is defined in this research as an action implemented by project team to prevent a schedule delay or upcoming production problems. Control actions were classified into one of three categories: changes of plan, changes of production rate, and task suspension. Control actions relating to procurement or design were left outside the scope of this research, unless they directly affected some variable of interest.

Similar to production problem analysis, control actions were divided into three categories: certain, probable and possible. A control action was classified as "certain" if there was an explicit mention of the control action in any supporting project documentation, such as meeting memos or an entry in the production control system. A control action was deemed "probable" if there was an active alarm related to the task, and the plans were changed in a way which removed the alarm, or resources were adjusted according to the project documentation (for example, two new plumbers showed up and the plumbing task was running late). A control action was classified as "possible" if a change contributing to schedule acceleration or removal of alarm happened, but there was no supporting evidence for it in the project documentation. In this case, acceleration could have occurred because of overtime or better conditions.

Change of plan

A change in the detail plan was classified as a control action if it led to the removal of an alarm in the production control system. An alarm could be removed by removing a dependency (for example, by changing design so that the dependency was not necessary), planning work for scheduled holidays, delaying a task start date, or changing the planned resources of a task.

Change of production rate

A production rate change was inferred to be a control action when the actual production rate accelerated to over 120% of the planned production rate. If the production rate increased without a corresponding increase in resources, the change was classified as “possible”. If the production rate increased and the subcontractor had more resources on site, the control action was classified as “probable”. If the project memos showed that the subcontractor agreed to bring in more resources because he was delayed, the control action was classified as “certain”.

Suspending a task

In cases where two tasks could not work productively in a location and would interfere with each other, one task might be suspended as a control action, and continued after the other task was finished in the location. This was usually classified as a production problem instead of a control action. However, in some cases, the meeting memos indicated that the task would be suspended until another task was finished. In this case, the suspension was classified as both a control action and a production problem.

3.1.7.4 Dynamic data analysis

Data were analyzed dynamically by comparing how information changed during the course of the project. This was done by comparing any changes in the project files and other documents from the same week. For each week, the following data were observed:

- The production rate of each task for that week
- Any detail or baseline plan updates
- Any alarms generated by the system
- Actual production problems

These data were analyzed to find any production problems (for example, identifying slowdowns) and to compare any alarms generated by the system to actual problems downstream. For each actual production problem the alarm related to, that problem was recorded. If there was no alarm, the reason for missing the alarm was recorded. If there was an alarm, the number of days between the alarm and the problem was recorded. For each alarm that did not have an associated production problem, the reason for the alarm was recorded. The alarm could be a false alarm or the problem could have been prevented by taking control actions, such as changing the plans or mobilizing additional resources to restore the production rate.

Dynamic data analysis was also done to see how much earlier an alarm needed to be given to initiate a control action, and if the control action was appropriate and could prevent the alarm from actualizing. This information was used to evaluate how useful alarm information was for the production team and how the alarm system could be changed to prevent more problems. Control action analysis was used to define the process for planning control actions, and to further develop the means to plan better control actions.

3.2 Comparison of the planning and controlling processes

3.2.1 Introduction

This section describes the key differences and similarities between the case studies of the processes of planning baseline schedules, detail schedules, and monitoring and controlling production. The section starts by summarizing the key differences and similarities and then describes the key findings in more detail. The case study reports in Appendices A, B, and C contain further observations of the processes.

3.2.2 Key differences and similarities in the process

The following key differences were found in the planning and controlling processes:

- Prisma started planning based on an already approved baseline schedule. Other case projects started from the beginning with the location-based method.
- Opus had a firm goal of accelerating the project by two months compared to the contractual schedule; other projects did not have such goals
- The level of detail of the planned schedules was different both in the baseline and detailed scheduling.
- Most of the tasks in Prisma and Glomson were continuous. Opus had one work break between sections for most of the tasks
- The accuracy of the progress information was greatest in Prisma, where the subcontractors contributed to the process. Other projects centralized the collection of progress information to the project engineer
- The Location Breakdown Structures of both Opus and Prisma had flaws which decreased the reliability of schedules

- Opus used their internal database of productivity rates and quantity assumptions for the MEP tasks. Glomson and Prisma did not have such information available to the project teams and planning had to rely on generic productivity databases and rough estimates of durations for the MEP tasks.

The following key similarities were found in the planning and controlling processes:

- All of the projects used detail task planning to achieve the desired end results instead of using planning tools to validate the end result. This led to the removal of dependencies in the detail task phase
- Detail tasks were updated task by task without systematically considering the effects of any changes to other tasks
- Control actions were rarely explicitly planned in any project
- Weekly planning was detached from the location-based process in all of the projects
- The progress data was accurate in terms of the start and finish dates of locations in all of the projects. Suspensions and percentages completed at the end of the week were not recorded consistently in any project.
- Discussions with subcontractors concerned start and finish dates, not production rates or resources

3.2.3 Prerequisites of location-based planning

There were differences in the quality of the starting data that was available for location-based planning and also in familiarity with the location-based planning methodology. Table 3-4 shows the key differences.

Table 3-4: Key differences relating to the starting data and familiarity with location-based planning

	Prisma	Glomson	Opus
Familiarity with location-based planning	No prior experience	The site manager had prior experience from one project, the project engineer had no prior experience	The project engineer had learnt the planning methods at school, the site manager and the rest of the team had no experience
Starting schedule	Bar chart	Draft location-based	Draft location-based
Quantities	Not location-based, distributed by assumptions. Some tasks estimated	Not location-based, distributed by assumptions. Some tasks estimated	Location-based, mostly assumptions, some real quantities
Productivity rates	Ratu*	Ratu*	NCC database
MEP schedule	Very rough guess	Very rough guess	Detailed schedule based on assumptions

*Ratu = Finnish standard library of productivities (Mäki & Koskenvesa 2002)

3.2.4 Baseline planning process

The planning processes in the three projects were similar with some minor differences. The main differences related to the composition of the planning team and who was actually using the planning software to evaluate any planning decisions. In Prisma, the project engineer was responsible for scheduling. He was helped by Skanska's planning software expert, who was using the planning software. The site manager did not participate at all, and was not present in the meetings. The site manager expected the location-based schedule to match the approved Gantt chart schedule. In contrast, in Glomson, the site manager and project engineer worked together to develop the schedule. The project engineer used the planning software. In Opus, the project engineer did most of the scheduling himself. The site manager only reviewed the results and gave high level instructions.

Figure 3-5 shows the baseline process based on the location-based planning theory (chapter 2) and actual processes of case projects. Opus and Glomson matched this process closely (figure 3-6). Prisma was different, because the original approved schedule had to be matched (figure 3-7).

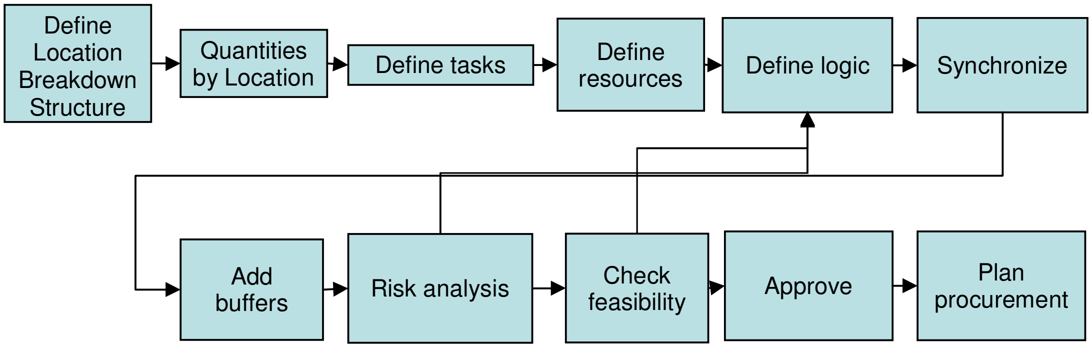


Figure 3-5: Proposed baseline planning process (Chapter 2)

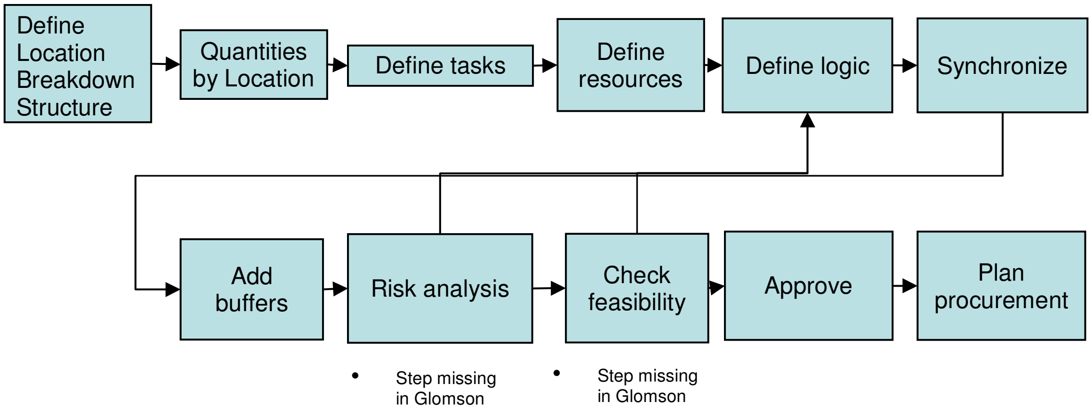


Figure 3-6: Actual baseline planning process in Glomson and Opus

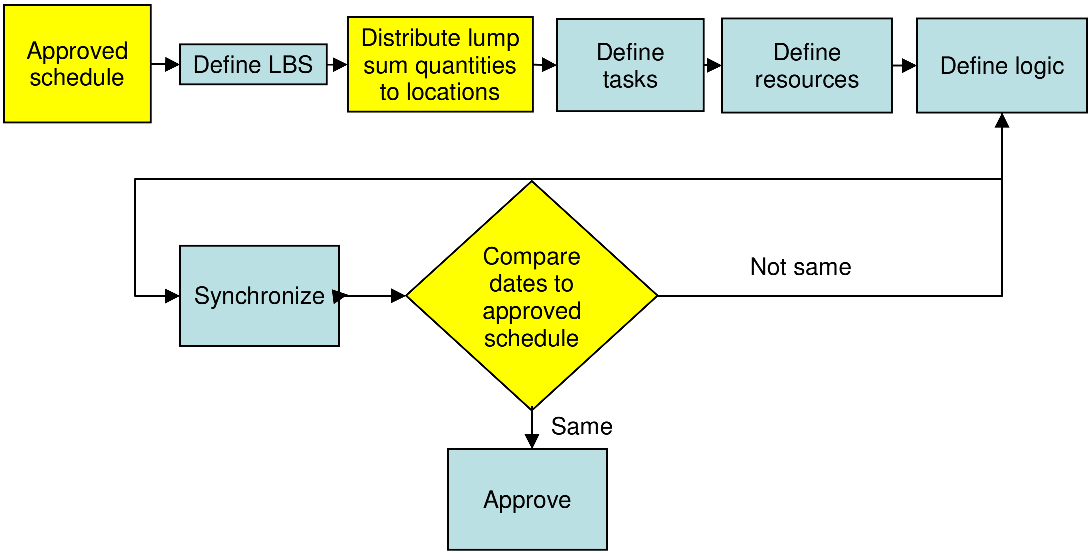


Figure 3-7: Actual baseline planning process in Prisma. Yellow elements represent additional stages in the process.

3.2.4.1 Location breakdown structures

The location breakdown structures were remarkably similar for all of the projects. Each project was first divided into structurally independent sections, then into floors and finally into spaces. In Prisma, the spaces were divided already in the baseline planning. In Glomson, the spaces and floors happened to be the same. In Opus, the spaces were added only on the first floor and for the roof location during the detail planning process. The location breakdown structures are described in detail in the case study reports, Appendices A to C.

Both Prisma and Glomson had just two floors, while Opus was a higher building of five floors and a roof. Sections 1-4 of Prisma were a large open hall inside. Although the structure was erected using these sections, the handling of the indoor work using the same location breakdown structure can be regarded as a planning mistake. The MEP work inside the building could not go in the same sequence as the structure, because the main ducts went in the opposite direction through the hall. Similarly, the location breakdown structure of Opus did not work for the MEP trades, because the mechanical room effect areas were not considered when defining the sections. Although the sections were structurally independent, both sections had to be dust-free at the same time before tests could begin. This removed much of the benefits of dividing the building into sections. Glomson was the only case study with an appropriate location breakdown structure.

3.2.4.2 Differences in baseline schedules

The baseline schedules planned for the case studies had different levels of detail and different patterns of work continuity. Table 3-5 shows some important differences in the numerical form.

Table 3-5: Differences in baseline schedules

	Prisma	Glomson	Opus
No. of scheduled tasks	40	28	66
Quantity-based tasks	50%	79%	62%
Continuous tasks	75%	85%	26%
End-of-project buffer	1.5 – 2 months	3 weeks to 2 months	1-3 months

The level of detail of the schedules was different. The MEP schedules were especially very rough in Prisma and Glomson on the baseline level. In Opus, the MEP tasks were planned in detail already in the baseline schedule. However, compared to the earlier research where the MEP schedules have been shown on very rough level of detail, the level of detail was higher. Examples of the actual task lists can be found in case study reports in Appendix A, B, and C.

Most of the tasks were planned to be continuous in Prisma and Glomson. In Opus, most of the tasks were planned to have one break in between the sections. This approach was selected after analysis and was taken into account in the contracts by having a contractual milestone for the finish date of each section.

Although all of the tasks in Opus were based on some quantities, the percentage in table 3-5 approximates how many tasks were based on real quantities instead of assumptions. For example, quantity “1 batch” is not really a physical quantity. In Opus, many quantities were suspicious; such as “Lighting” measured in square meters (13,812.38 m^2). These quantities were not regarded as real quantities in the table above. This decreases the Opus percentage, because many tasks were based on similar quantity information.

3.2.5 Detail task planning process

Detail tasks enable changing or re-planning the schedule close to production, but still preserving the link to the original baseline schedule. Each detail task belongs to one baseline task but a baseline task can be linked to multiple detail tasks – in effect, the level of detail can be increased during detail planning. All of the case projects were familiar with the task planning method (Junnonen & Seppänen 2004) and used detail tasks to implement the scheduling elements of task planning.

Prisma and Glomson did not add too much detail to the schedule, but used detail planning to update start dates and production rates. Opus added much more detail and also added new locations in this phase. The level of detail compared to the baseline can be shown by dividing the number of detail tasks the by number of baseline tasks. Table 3-6 shows the numerical differences in the case projects.

Table 3-6: Differences in the detail task planning process

	Prisma	Glomson	Opus
No. of tasks	52	38	179
No. detail tasks / no. baseline tasks	1.3	1.36	2.71
Continuous tasks	60%	58%	74%

The high number of detail tasks in Opus is explained by the fact that the detail tasks of the second section were planned at a different time than the detail tasks of the first section. Therefore, almost every baseline task had at least two detail tasks – one for each section. The level of detail was also much more detailed than in other projects. For example, the “concrete floor finishing” task was divided into five subtasks, while other projects had just the pour as a detail task. The Opus detail planning also planned for more continuity than the other projects.

In the detail task planning phase, all of the projects used fewer dependencies than in baseline planning. The dependencies tended to be especially removed from the finishes and MEP tasks so that the start dates could be freely chosen according to the information from subcontractors. For example, the Prisma shop hall had most of the dependencies removed by the end of the project. In the Glomson finishes phase, most of the tasks did not have dependencies. In Opus, most tasks had some dependencies but often tasks were just scheduled using dates. This change in scheduling process makes sense for the planner, because the dates are usually known and committed to. However, it causes severe problems for the forecasting and alarming system, which relies on accurate dependency information. The most common reason for failing to raise an alarm of an upcoming problem was that the dependency was not in the system (this result is described in more detail later in this chapter).

In all of the projects, the MEP contractors participated in the detail schedule planning of their tasks. All of the projects had many iterations and feedback rounds of the MEP detail schedule. The same was true of the structural contractor in all of the projects. The rest of the subcontractors were sometimes consulted for updated starting dates, but they were not really involved in the detail planning process. However, even though the start and finish dates in each location were discussed, there was very little discussion about what resources would be needed to finish the work in time and no discussion about overall resource use in the project.

Even though the MEP contractors participated in the scheduling in the Prisma project, they did not understand the Flowline method well enough to understand the actual flow of work. Major problems happened when the same location breakdown structure as for the structure was imposed on the MEP trades, because the main ducts and pipes flowed in the opposite direction. Similar problems happened in the Opus project, where all the contractors approved the baseline schedule. However, no-one understood at the time that the completed floors needed to be dust-free at the same time in order to test the mechanical equipment, because the equipment effect areas did not follow the section boundaries.

The detail task planning processes of the projects are compared in figures 3-8 and 3-9. For the new detail tasks, all of the projects followed closely the model process. In updating, the projects started from the desired start and finish dates and updated the production rates and logic to exactly match the desired dates.

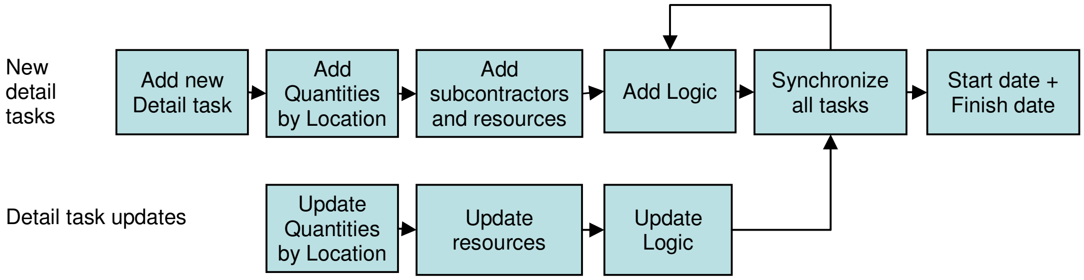


Figure 3-8: Proposed detail plan updating process

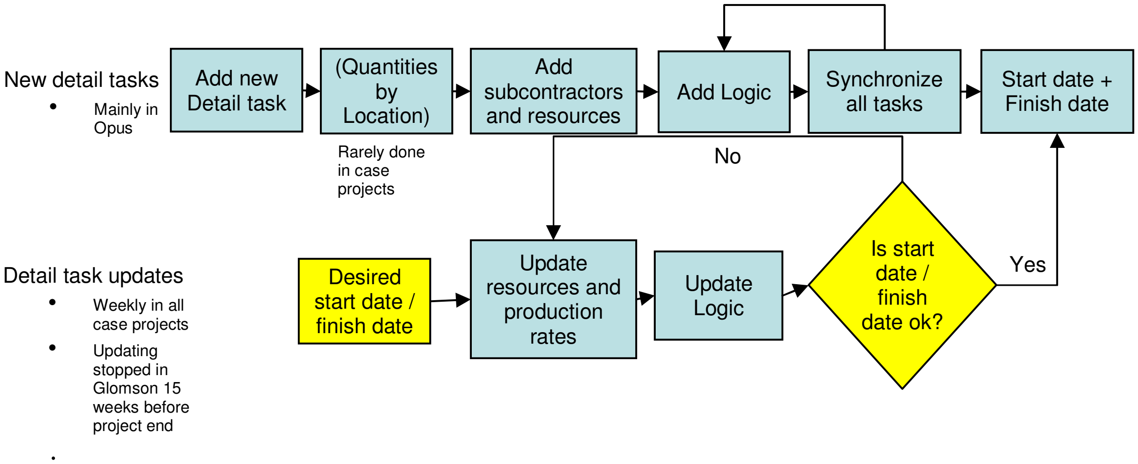


Figure 3-9: Detail task planning and updating process in case projects. The yellow boxes highlight any additional steps in the process compared to the proposed process

Example of detail task planning – Opus (from Aalto & Seppänen 2005)

The “Plasterboard walls” task is a good example of the use of detail task planning to increase the level of detail and take into account the current status of production. Figure 3-10 shows part of the Opus baseline schedule. The original intention was to build plasterboard walls only after the roof was completely waterproof, so that the risk of the walls getting damp because of rain would be removed. However, because of the delay to the structure and the roof, the walls would have started at least four weeks late with the original baseline constraint.

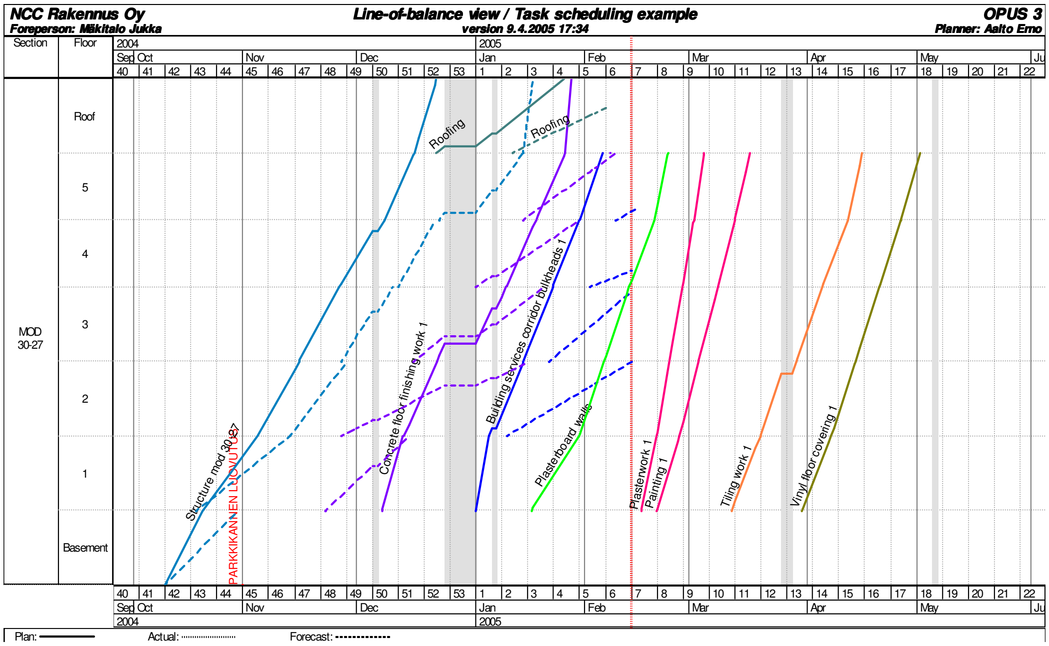


Figure 3-10: Original baseline and progress data for plasterboard walls task and its predecessors and successors. Solid lines indicate the original plan, dotted lines the actual (Aalto & Seppänen 2005)

The problem was solved in the detail planning phase by dividing the baseline task into three detail tasks: wall frames and installing board on one side, electrical piping inside the walls, and insulation and installing board on the other side (figure 3-11). The sequence was changed so that the first floor, which was more complex (auditorium, dentist and other special spaces) than the other floors, was done last. A contract was made with one subcontractor to install both the bulkheads and the plasterboard walls. One crew went through all the locations installing bulkheads. The next crew started a little later and followed the same sequence installing the wall frames and board on one side. When the bulkheads crew had gone throughout the building, they started to install the insulation wool and second board. Even though the plasterboard walls task ended two weeks later than in the master schedule, the succeeding trades incrementally caught up the delay. The tiling work and vinyl floor covering work could then start according to the original baseline schedule.

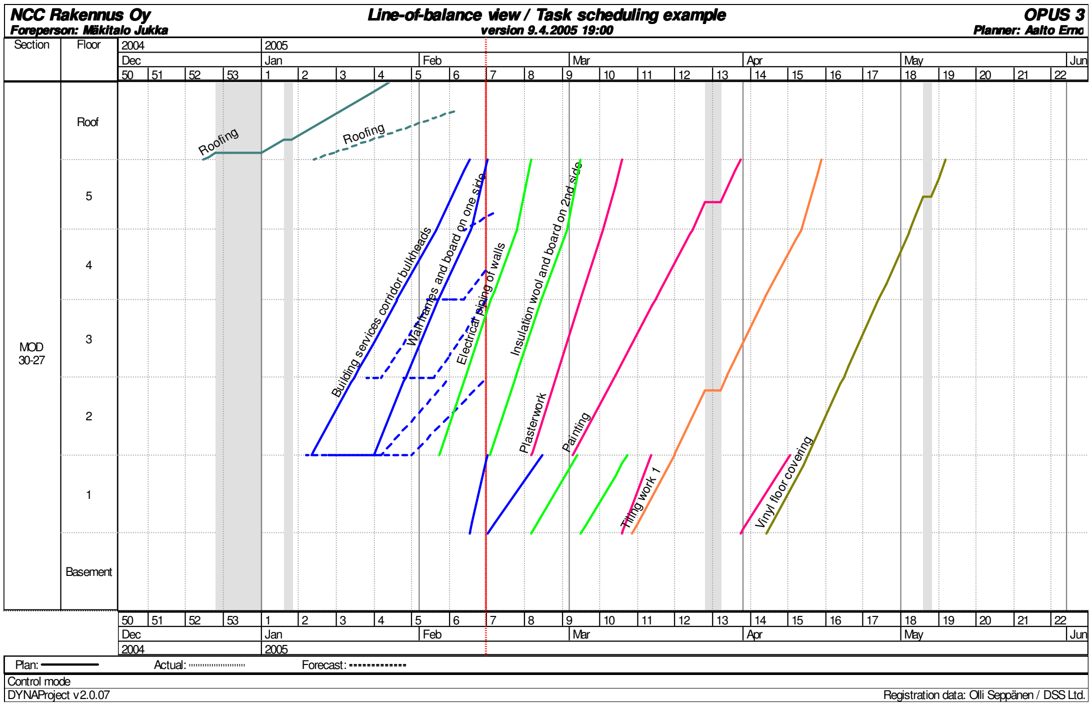


Figure 3-11: The task schedule for plasterboard walls task and its predecessors and successors (Aalto & Seppänen 2005)

3.2.6 Monitoring process

The accuracy of the monitoring information was best in Prisma. There were some errors which were corrected later on but the data were of better quality than in the other projects. The reason may be that the subcontractors participated in generating the information and evaluating the completion rates. In Glomson, there were some errors, especially with the completion rates of the MEP tasks. In Opus, there were many errors. These errors were corrected monthly when the Owner report was due. Reliance on the project engineer in monitoring the process was problematic also in cases of sickness, holidays, or other urgent work requirements. Especially in Opus, the quality of the data suffered every time the project engineer was sick or on holiday.

Deviations were reported in an inconsistent way in all of the projects. Prisma had better documentation of issues than the other projects for deviations concerning other trades than MEP (for example, structure, façade, or tiling-related). However, slowdowns or MEP deviations were rarely documented, with the exception of the main mechanical room work. In Glomson, problems were documented in the foundations and the structural phases, but mostly were left undocumented in the finishes and MEP phases. In Opus, the reporting was similarly better in the foundations and structural phases. For finishes and MEP, some reporting was done but inconsistently.

The model monitoring and controlling process and actual monitoring and controlling process in the case projects is shown in figures 3-12 and 3-13. Entering the percentage completed and task suspension information was problematic in all of the projects. In Glomson and Opus, the control actions were planned by updating the detail tasks. Weekly planning was detached from the weekly monitoring process in all of the projects.

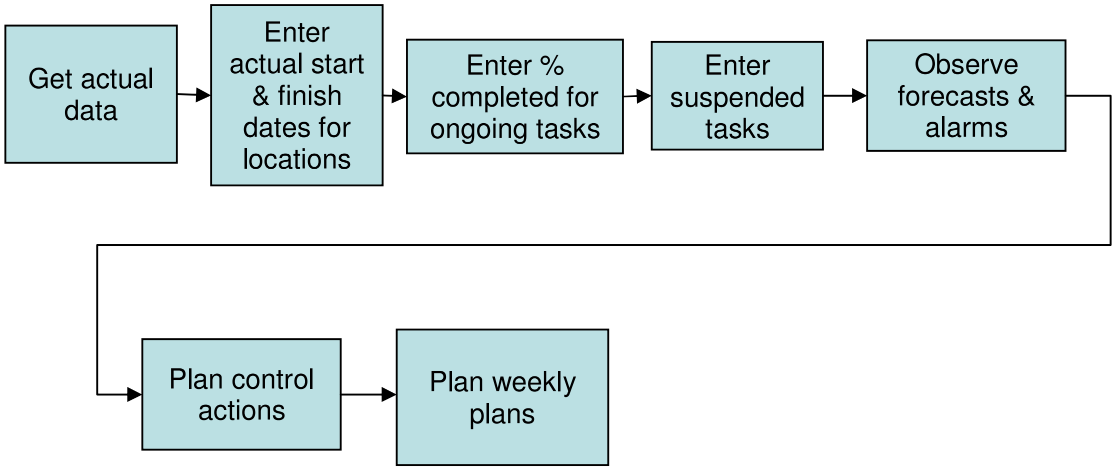


Figure 3-12: Model monitoring and controlling process

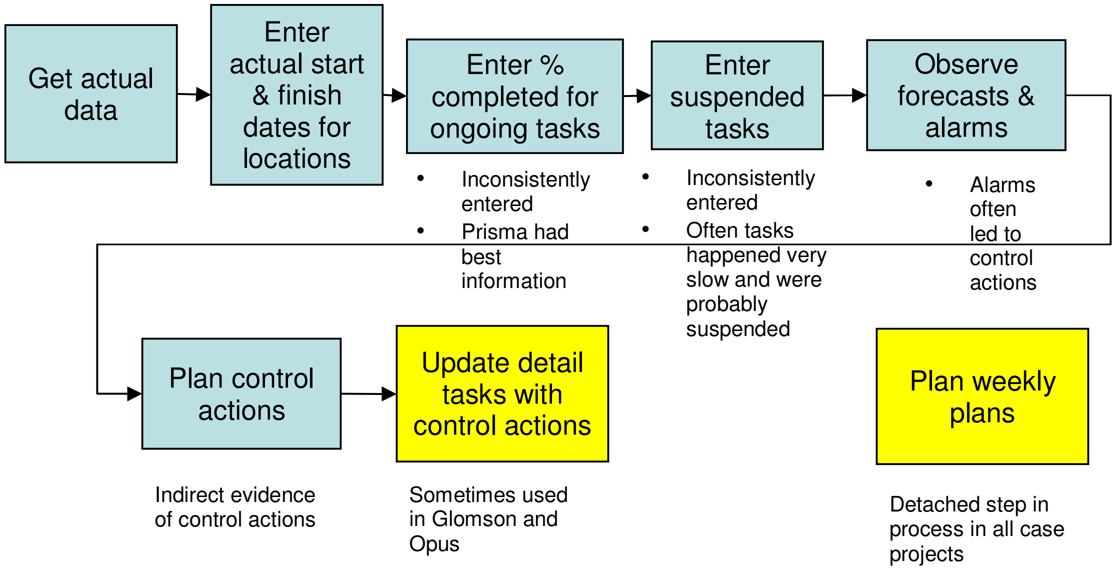


Figure 3-13: Actual monitoring and controlling process

3.2.5. Production meetings

The production meeting memos were very similar in the case projects. However, in Prisma only the MEP contractors had regular subcontractor meetings. In the other projects, all the major subcontractors participated in the meetings. All the projects described for each subcontractor the ongoing tasks, the total number of workers on site, and the need for design specifications. Occasionally, look-ahead information of the upcoming tasks was presented. In Prisma this was mainly for the construction work (reported by Skanska). In Glomson and Opus, this was inconsistent and mainly concerned the start dates of upcoming tasks or locations.

Deviations and delays were documented well in Prisma. However, the downstream effects were rarely discussed, only that the subcontractor was delayed from the schedule. In Glomson, deviations or delays were never addressed in memos. In Opus some delays were mentioned but very inconsistently. Only in Prisma would an outside observer have been able to see from the memos that there were schedule problems, but they seemingly only concerned the MEP tasks. However, the effects of delays were not discussed, only the fact that a subcontractor was delayed. In Prisma, additional schedule meetings were done with the MEP contractors with the largest delays.

In Prisma, the General Contractor also documented any requests to add resources in memos. In Glomson, control actions were never discussed. In Opus, control actions were sometimes but very rarely discussed.

3.3 Baseline schedule reliability

3.3.1 Introduction

This section summarizes key the results relating to baseline schedule reliability. Baseline schedule reliability was measured by looking at the deviations of the actual starting dates, finish dates, production rates, and discontinuities from their planned values. Correlations between the reliability variables and other production control variables were examined to find out reasons for good or bad reliability. The section starts with a summary of the key findings and then describes the key results in detail. A more thorough analysis of the results of each case study can be found in the case study reports in Appendices A, B, and C.

3.3.2 Key findings

The key findings relating to baseline schedule reliability are summarized below:

- Production rates in Glomson and Prisma tended to be slower than planned but start dates were well controlled
- Median production rates in Opus were close to those planned, but start dates tended to slip and production had discontinuities
- Because of production rate problems and discontinuities, finish dates were later than planned in all of the projects
- Tasks relating to MEP had the least start-up delays, but tended to have more slowdowns than other tasks
- A strong correlation between suffering from production problems and hence causing production problems to other tasks, indicates cascading delay chains
- Working out of sequence correlated strongly with suffering from production problems and hence causing such problems to other tasks

3.3.3 Results

Table 3-7 shows the combined reliability data from all of the projects showing the minimum, 25 % quartile, median, 75% quartile, maximum, mean, and standard deviation for the selected variables. The variables were described earlier in this chapter.

*Table 3-7: Comparison of baseline schedule reliability data. Results which are different between the case studies have been highlighted with **bold** font*

Planned discontinuities (NO)							
	Min	25% quartile	Median	75% quartile	Max	Mean	STD
Prisma	0.00	0.00	0.00	0.25	4.00	0.38	0.81
Glomson	0.00	0.00	0.00	0.00	4.00	0.36	0.95
Opus	0.00	0.25	**1.00**	1.00	**8.00**	**1.05**	**1.17**
Quantity deviation (actual / baseline)							
Prisma	0.60	1.00	1.00	1.00	1.75	1.06	0.22
Glomson	0.47	0.93	1.00	1.00	1.38	0.95	0.21
Opus	0.50	1.00	1.00	1.00	1.69	0.99	**0.14**
Production rate deviation (actual / planned)							
Prisma	0.30	0.62	0.80	1.24	5.00	1.21	1.14
Glomson	0.28	0.54	0.89	1.39	5.42	1.22	1.13
Opus	0.40	0.65	**0.95**	1.56	4.77	1.21	**0.81**
Actual discontinuities (NO)							
Prisma	0.00	0.00	1.00	1.00	4.00	0.87	0.95
Glomson	0.00	0.00	0.00	1.00	7.00	0.68	1.44
Opus	0.00	1.00	**2.00**	**4.00**	9.00	**2.29**	**2.06**
Start date deviation (days)							
Prisma	-24.00	-3.50	1.00	8.50	45.00	2.70	14.10
Glomson	-30.00	-2.50	4.50	13.25	32.00	3.54	16.00
Opus	-9.00	5.00	**14.50**	**63.75**	110.00	**32.20**	**34.34**
Finish date deviation (days)							
Prisma	-15.00	1.00	14.00	22.00	53.00	13.72	15.01
Glomson	-60.00	-1.50	10.00	24.25	59.00	12.21	25.29
Opus	-18.00	4.25	20.00	37.75	**111.00**	**25.56**	**28.26**
PPC (%)							
Prisma	0.20	0.50	**0.71**	1.00	1.00	**0.69**	0.25
Glomson	0.20	0.40	0.57	0.73	1.00	0.58	0.26
Opus	0.00	0.41	0.58	0.83	1.00	0.60	0.27

The results relating to the key findings are described below.

Production rate deviation (actual / planned)

The results relating to the production rates show a remarkable consistency. The median task in each project was slower than planned. In Opus, the production rates were controlled best with the smallest standard deviation and a median closest to the planned production rate. In Prisma and Glomson, the production rate deviations were more of a problem. Each project had tasks which were much slower or much faster than planned. This indicates poor information about the task in the baseline planning phase. In all of the projects, the maximum production rate was so high compared to the plan that the overall average is distorted to show 1.2 times the normal production rate. In this case the median production rate gives a better overall picture. The standard deviation of the production rates was smallest in Opus, which indicates that the production rates were controlled better in Opus. The direct observation results confirm this, because in Opus, the production rates were discussed using the Flowline diagrams in production meetings with subcontractors.

Actual discontinuities

The actual discontinuities variable shows how many times a task actually had a break in the workflow. The result shows that the discontinuities were not a problem in Glomson, but were a problem in Prisma and Opus. Even though Opus had planned one work break between sections, the median task suffered two work breaks. 25% of tasks suffered from more than four work breaks.

Start date deviation

Start dates were very well controlled in Prisma and Glomson, with median deviations of 1 day and 4.5 days respectively. In contrast, Opus suffered from cascading start-up delays and the median start-up delay was 14.5 days. This may be explained by the different characteristics of the baseline schedules. Prisma and Glomson both had a tight schedule. Opus had a relaxed schedule in the first section and a tight schedule in the second section.

All of the projects had high standard deviations, indicating that there was high variability depending on the task. For example, in Prisma the drywall installations started 45 workdays after the baseline, and the kitchen equipment installations 22 days after the baseline. All of the tasks with high start date deviations were concentrated in small locations. All of the shop tasks started on time or early (for example, lighting fixtures started 24 days early). In Glomson, the curtain wall installation (17 days) and the mechanical room work (23 days) were significantly delayed, in addition to the restroom tiling. This happened because of the delays in the foundations which delayed the start of the structure by 12 days. Because the structure is always on the critical path, it is an achievement that the median start date delay was low and most of the other tasks could be started on time. This is partially explained by the large location sizes which allowed more trades in locations than originally planned.

Finish date deviation

All of the projects had problems with finishing tasks on time. Interestingly, both Glomson and Prisma have worse finish date deviation results than start date deviation, and Opus has the opposite pattern. In Glomson and Prisma, where the start dates were well controlled, the schedule slipped during production. In Opus, the delay was partially caught up by the end of the task. Compared to the overall duration, the median delay was worst in Prisma (7 % of contract duration) compared to 5.5 % in Opus and 4.2 % in Glomson. However, all of the projects were handed over on time.

Direct observation shows that all of the projects caught up the delays in the schedule during the commissioning phase with hurried work on the site. The end-of-project buffer was completely used up in all of the projects.

Table 3-8: correlations which were significant in at least one of the case projects. The Prisma correlation is shown on the top, the Glomson correlation in the middle and the Opus correlation at the bottom.

	Start date deviation	Finish date deviation	Production rate	PPC	Actual discontinuities	Working in planned sequence	Discontinuity	Slowdown	DS Slowdown
Quantity based	0.101 -0.137 __-0.36__**	-0.025 -__0.493__** -0.174						-0.209 __-0.666__** -0.059	-0.266 __-0.658__** 0.093
Planned discontinuities						-0.142 -0.162 _-0.299_*	-0.034 -0.004 _0.267_*		
Planned continuity	__-0.39__** 0.084 -0.049								
Total float	-0.083 __0.532__** -0.026	-0.077 _0.375_* 0.136				0.181 0.195 __0.381__**			
Production rate	0.074 0.368 __0.413__**	_-0.332_* -0.231 _-0.258_*		_0.323_* __0.545__** 0.254					
Finish date deviation	__0.441__** __0.479__** _0.268_*			__-0.5__** -0.168 __-0.392__**			0.28 _0.429_* 0.027	0.367* _0.475_* -0.094	_0.39_* _0.461_* -0.026
Start-up delay	__0.512__** -0.004 __0.4__**		-0.095 -0.107 _0.293_*						
Discontinuity					-0.083 __0.453__** __0.534__**	-0.246 __-0.477__** -0.227			
Slowdown					-0.086 -0.028 __0.523__**	-0.127 __-0.486__** _-0.302_*			
Working in planned sequence	0.064 0.19 _-0.309_*				-0.126 _-0.338_* _-0.311_*				
Downstream start-up delay								__0.501__** 0.208 0.142	
Downstream discontinuity					-0.033 0.094 __0.479__**	-0.279 _-0.439_* -0.156	__0.446__** _0.377_* __0.361__**	__0.613__** _0.434_* __0.599__**	
Downstream slowdown					-0.142 -0.056 __0.483__**	-0.15 _-0.436_* _-0.291_*	__0.61__** 0.034 _0.307_*	__0.921__** __0.888__** __0.702__**	

Table 3-8 shows the results of correlation analysis of the variables relating to the baseline schedule reliability. It should be noted from the correlation matrix, that every time there are significant correlations from two or more projects between the same two variables, the correlation has the same sign. Even when the correlations are not significant, the correlations tend to have the same sign. In cases where the correlations have different signs, the correlations which are not significant tend to be very close to zero. All the data point in the same direction, which indicates that the correlations show generic relationships between the variables instead of being project-specific. The interesting correlations are described below.

- The quantity-based tasks had fewer start-up delays (Opus), finished earlier, had less slowdowns and caused less slowdowns to other tasks (Glomson). Closer analysis suggests that this is related to the fact that the MEP tasks had more problems and they very rarely had quantities. Because of this finding, the differences were analyzed for the construction phases (the analysis is described later in this chapter).
- Tasks which were planned to be continuous started early (Prisma).
- Tasks with a higher total float started later (Glomson)
- Tasks which started late had a higher production rate (Opus)
- Discontinuities (Glomson) and slowdowns (Prisma & Glomson) contributed to delays in the finish date
- Production rate and PPC were strongly positively correlated (Prisma & Glomson)
- Working in the planned sequence correlated with fewer discontinuities (Glomson & Opus), less slowdowns caused by other tasks (Glomson & Opus), less downstream discontinuities (Glomson) and less downstream slowdowns (Glomson & Opus).
- Discontinuities and slowdowns correlated strongly with downstream discontinuities and slowdowns. This result indicates cascading problem chains.

3.4 Detail task reliability

3.4.1 Introduction

This section summarizes the key results relating to the detail schedule reliability. The detail schedule reliability was measured by looking at the deviations of the actual starting dates, finish dates, production rates and discontinuities from their planned values. Because detail tasks could be updated weekly, the comparison was made according to the procedure described in section 3.1.7.1. Correlations between reliability variables and other production control variables were examined to find out the reasons for the deviations between the planned and actual values. The section starts with summary of the key findings and then describes the key results in detail. A more thorough analysis of the results of each case study can be found in the case study reports in Appendixes A, B, and C.

3.4.2 Key findings

- On the detail task planning level, all of the projects had similar results for the reliability variables. Glomson tended to have smaller production rates compared to the plan than Prisma and Opus. Prisma and Opus had more discontinuities.
- Cascading problem chains were found on the detail task level
- Working out of sequence was correlated with production problems
- PPC correlated significantly with the detail schedule reliability and less downstream problems

3.4.3 Results

Table 3-9 shows the combined detail task reliability data from all of the projects showing the minimum, 25% quartile, median, 75% quartile, maximum, mean, and standard deviation for the selected variables.

The detail task reliability data is very similar for all of the case projects. The difference of planning strategy, which was evident in the baseline results, is not shown in these results, because in Opus each section was planned and controlled with a separate set of detail tasks. The similarities and differences are described below for each variable.

Production rate deviation

It is interesting to note that the differences between the projects in production rate performance are reduced on the detail task planning phase. In particular, Opus has a smaller median production rate multiplier than on the baseline analysis. This, together with the direct observation results, indicates that the detail tasks were planned overly optimistically with high production rates to catch up the baseline delays. In contrast, Prisma had an increase of median production rate compared to the plan when compared with the baseline results. However, the standard deviation was largest in Prisma, indicating a larger variability. Opus had more consistent results with low standard deviation. Also, in the detail planning stage, all of the projects had outliers with very slow or very fast production rates compared to the plan.

Table 3-9: Detail task reliability data

Planned discontinuities (NO)							
	Min	25% quartile	Median	75% quartile	Max	Mean	STD
Prisma	0.00	0.00	0.00	1.00	9.00	0.66	1.45
Glomson	0.00	0.00	0.00	**1.75**	7.00	**0.97**	1.72
Opus	0.00	0.00	0.00	1.00	7.00	0.74	1.57
Quantity deviation (actual / baseline)							
Prisma	0.34	1.00	1.00	1.00	6.54	1.05	0.73
Glomson	0.77	1.00	1.00	1.00	1.87	1.03	0.17
Opus	0.56	1.00	1.00	1.00	2.17	1.01	**0.11**
Production rate deviation (actual / planned)							
Prisma	0.24	0.62	0.88	1.31	6.00	1.32	1.28
Glomson	0.30	0.59	0.83	1.13	5.20	1.10	0.92
Opus	0.27	0.67	**0.90**	1.32	5.17	1.07	**0.68**
Actual discontinuities (NO)							
Prisma	0.00	0.00	1.00	1.00	3.00	0.74	0.85
Glomson	0.00	0.00	0.00	1.00	7.00	0.84	1.39
Opus	0.00	0.00	1.00	2.00	7.00	**1.45**	**1.58**
Start date deviation (days)							
Prisma	-33.00	0.00	0.00	5.75	34.00	3.34	10.61
Glomson	-43.00	-1.00	1.00	3.75	29.00	0.58	11.24
Opus	-18.00	-1.00	1.00	7.00	82.00	4.29	11.91
Finish date deviation (days)							
Prisma	-29.00	0.00	9.00	16.00	41.00	9.44	13.79
Glomson	-45.00	-4.00	5.20	15.75	48.00	6.38	17.58
Opus	-27.00	0.00	8.00	17.00	111.00	11.12	18.13
PPC (%)							
Prisma	0%	45%	67%	96%	100%	64%	27%
Glomson	20%	40%	57%	75%	100%	59%	25%
Opus	0%	50%	67%	100%	100%	68%	28%

Actual discontinuities

Opus and Prisma had problems with performing work continuously. The median task had one discontinuity in both projects. Opus had a larger standard deviation and mean indicating that the problem was more prevalent in that project. Glomson had less evidence of discontinuities.

Finish date deviation

The finish dates were better controlled in all of the projects than on the baseline level. This is understandable because the detail task durations were often shorter, the start dates had less variability and planning was done near completion. Interestingly, Prisma performed worst on this variable, even though it had the lowest total duration. On the baseline level, Opus had a smaller finish date delay than start date delay. On the detailed level, Opus had the same pattern as other case studies. This is another indication of optimistic planning in Opus during the detail scheduling phase to catch up the baseline delays.

Table 3-10: Significant detail task correlations (cell values correlations Prisma / Glomson /Opus)

	Finish date deviation	Production rate	PPC	Actual dis-continuities	Working in planned sequence	Start-up delay	Dis-continuity	Slowdown	Quantity -based
Planned discontinuities	-0.173 0.039 __-0.206**__		0.046 -0.068 _0.173*_	_0.305*_ 0.263 __0.761**__					
Quantity-based				_0.258*_ 0.214 _0.215*_					
Production rate			-0.065 __0.565**__ __0.252**__						
Start date deviation	__0.408**__ __0.56**__ __0.366**__	0.121 0.14 _0.184*_	0.242 0.073 __-0.239__	_-0.318*_ 0.036 -0.119		__0.349**__ 0.189 __0.337**__			-0.036 _-0.351*_ _-0.18_
Finish date deviation		__-0.426**__ _-0.379*_ __-0.37**__	__-0.429**__ -0.285 __-0.447**__				0.132 _0.394*_ ___0.21**___	0.098 0.234 __0.287**__	
Start-up delay		-0.115 -0.152 _0.163*_			-0.048 0.177 _-0.187*_				
Discontinuity			-0.085 0.300 _-0.2*_		-0.042 -0.237 __-0.229**__				
Slowdown		-0.21 -0.314 __-0.251**__	-0.025 _-0.396*_ ___-0.234**___		0.134 _-0.371*_ ___-0.202**___				-0.259 __-0.497**__ -0.045
Downstream start-up delay					-0.186 _-0.377*_ -0.145	0.058 -0.192 __0.198**__			
Downstream discontinuity	0.198 _0.353*_ _0.185*_		-0.244 -0.109 __-0.26**__		-0.208 __-0.495**__ -0.127		0.089 0.177 _0.182*_	0.043 0.191 __0.422**__	
Downstream slowdown	__0.386**__ 0.256 __0.268**__	-0.213 -0.25 _-0.157*_	-0.157 -0.321 __-0.253**__		-0.032 _-0.355*_ -0.109		0.232 -0.018 _0.169*_	__0.726**__ __0.78**__ __0.547**__	__-0.36**__ __-0.582**__ 0.019

Table 3-10 shows the correlations of detail task variables in the case projects. Only the correlations which were significant in at least one case project are shown. Most of the interesting correlation analysis results are described below:

- Delays in the finish date correlated positively with delays in start date, low production rate (all of the projects), low PPC (Prisma & Opus), discontinuities (Glomson and Opus) and slowdowns (Opus)
- The correlations between working out of sequence and production problems. By directly examining the data in more detail, many examples were found where two tasks had been planned to not happen at the same time in the same location, but because of a change of sequence in one task, they were forced to happen together.
- Suffering from production problems caused by upstream tasks correlated strongly positively with causing downstream production problems, which again indicates cascading production problems

The results relating to working in a planned sequence and cascading production problems are important for answering the research questions of this research. The data relating to these issues were investigated in more detail by direct observation of Control files.

Working in planned sequence

In Glomson, the locations were large and work could start in any location. Therefore, instead of starting work in a location defined by the plan, the subcontractor could select from many possible locations. Based on an examination of the project files, this was not controlled by the General Contractor, but instead the detail plans were updated after the real sequence had been observed on site. In Opus, it was difficult to change to a sequence different from that planned because of the smaller size of the locations and the tighter dependencies between the tasks. Sequence changes normally happened because the preceding task was proceeding too slowly and entered the same location.

Production problems

Evidence of cascading production problems were seen in all of the projects. Figure 3-14 illustrates one example of cascading slowdown problems in the Opus project. Even though the tasks are not technically dependent on each other, they slow each other down when they enter the same location at the same time.

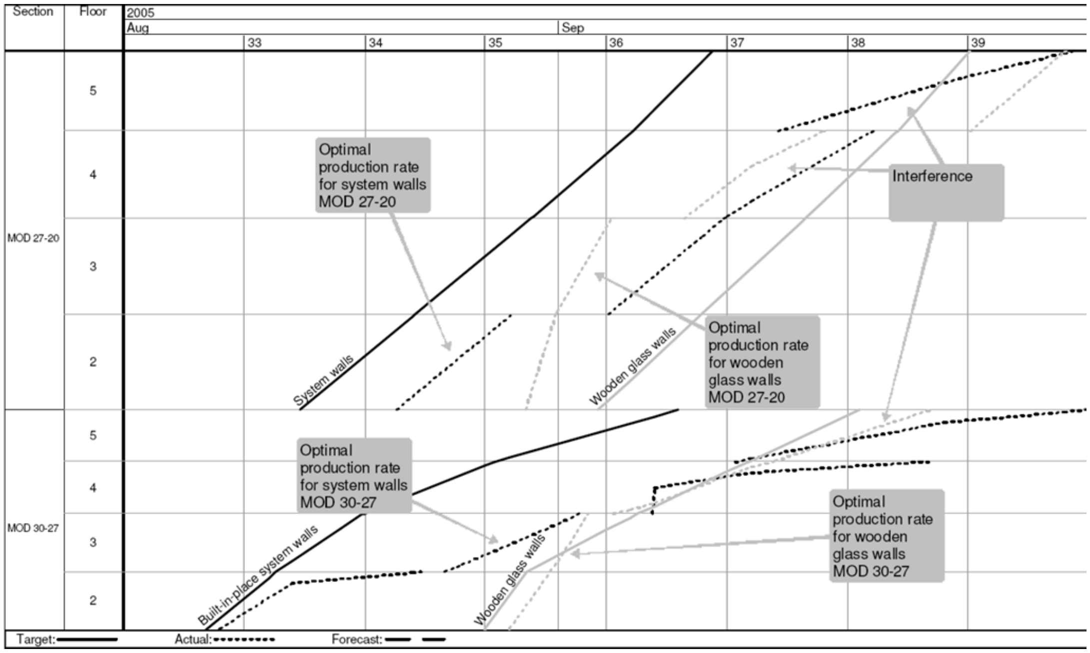


Figure 3-14: Example of cascading production problems

3.5 Weekly plan reliability

Weekly plans were planned and controlled weekly in all of the case projects to calculate PPC. All of the projects were instructed to use the same task names as in the detail tasks to make possible calculating the PPC for each detail task. However, the process how the weekly plans were created was different in each project.

In Prisma, the weekly plans were created in the weekly meetings with the project engineer based on his document of the status of each task and look-ahead information he had collected before the meeting. The detail tasks were updated accordingly so that the next week corresponded with the weekly plans. The weekly plans were heavily influenced by what the project engineer thought was possible based on his discussions with the team and the subcontractors.

In Glomson, the weekly plans were created by the project engineer. The site manager approved the weekly plans. However, subcontractor input was rarely requested. In Opus, the weekly plans were created by the project engineer based on the location-based schedule. They were very often based on what should happen instead of what could actually be done.

Each week, the PPC was calculated and shown to the project engineer. However, the PPC was not exposed to the other team members. In Prisma, the project engineer tried actively to increase the PPC score by involving the subcontractors in the weekly planning. In Glomson there was no evidence of any interest in improving the PPC. In Opus, the weekly plans were consistently too optimistic, reflecting the need to improve the production rate to catch up the baseline schedule.

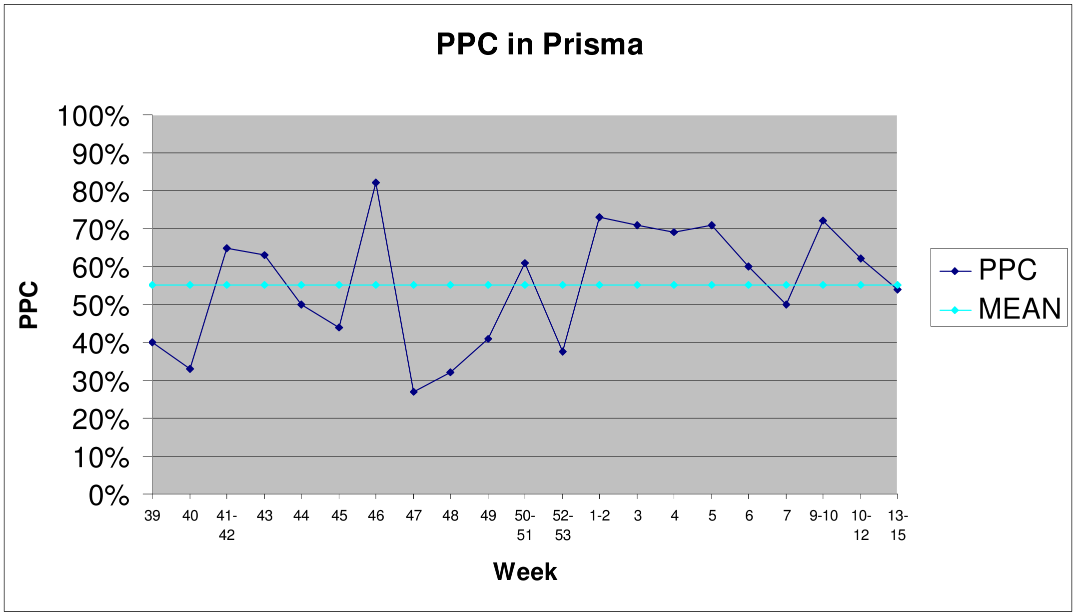


Figure 3-15: PPC as a function of time in Prisma

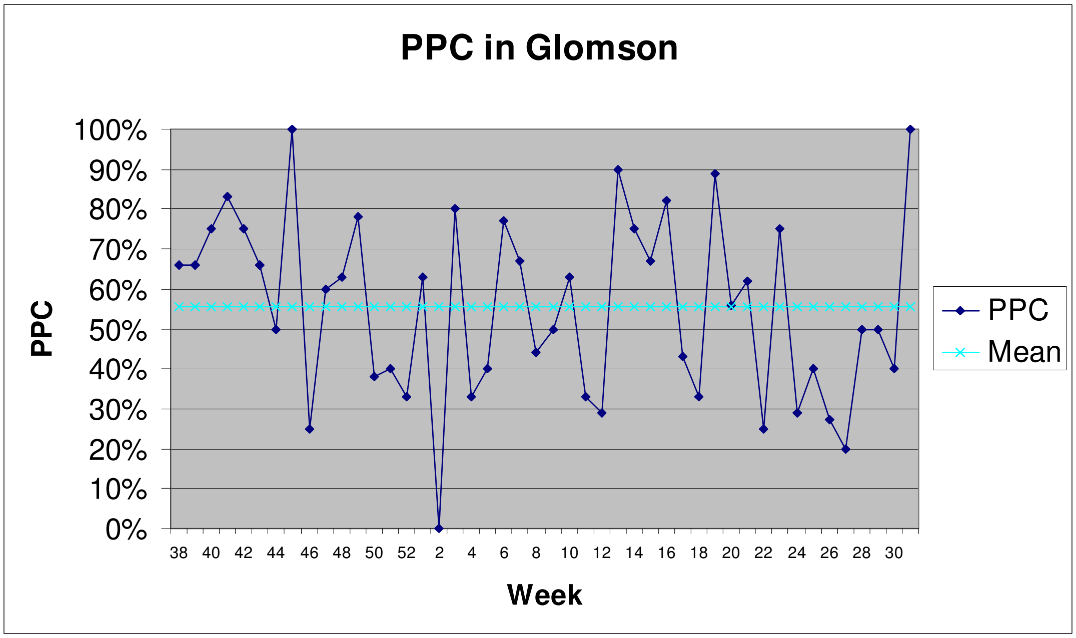


Figure 3-16: PPC as a function of time in Glomson

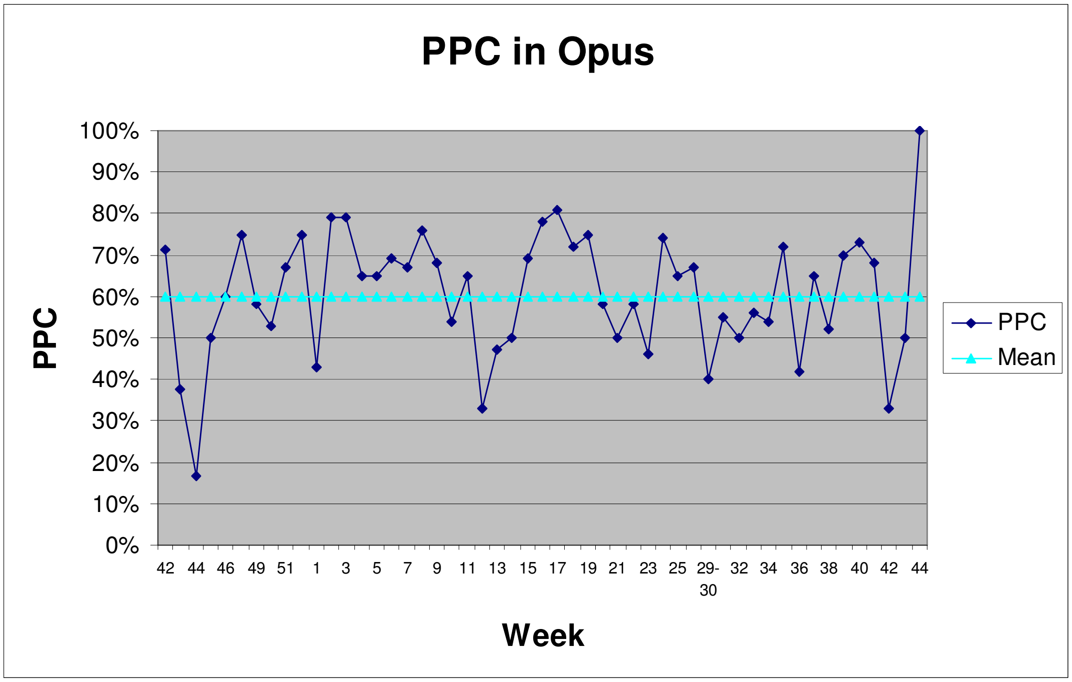


Figure 3-17: PPC as a function of time in Opus

Figures 3-15, 3-16 and 3-17 show PPC as a function of time in each one of the case studies. The PPC profiles of the case projects reveal different patterns. In Prisma, PPC is low between weeks 47 and 53, then it increases to 70 %, and keeps steady for four weeks. At the end of the project, there is another dip back to the average levels. In Glomson, the pattern is more chaotic, with the PPC jumping up and down around the average. In Opus, there are periods of high PPC, and some periods with low PPC.

3.6 Analysis of the production problems

3.6.1 Introduction

The results relating to production problems are important for answering the research questions of this research. This section describes the types and certainty levels of the production problems found. The production problems are described by type (start-up delay, discontinuity, and slowdown) and by certainty (possible, probable, certain). To evaluate the functioning of the alarm system and the control actions, the problems were divided into categories: cases where no alarm was generated; cases where an alarm was generated too late; cases where an alarm was generated and control action was taken, but the problem happened; and cases where an alarm was generated, control action was taken and the problem was successfully prevented. Finally, the reasons for false alarms are explored. For each group of cases, the reasons for the failure or success of the alarm system or the control actions are explored. The section starts with a summary of the key findings, and then describes the results in more detail. Because the same reason may contribute to multiple groups, there is some repetition in this section. The results are summarized at the end of the chapter, and their implications to the production control system and processes are discussed.

3.6.2 Key findings

Key results relating to production problems:

- Glomson had fewer production problems than the other projects compared to size and duration. Slowdowns were at the same levels as in the other projects, but there were much fewer start-up delays and discontinuities
- In Prisma, a larger percentage of the production problems could be classified as "certain" than in the other projects, because of the good documentation of the production problems
- Slowdowns were not documented well in any of the projects

Key findings relating to the functionality of the alarm system:

- In Prisma and Opus, the alarm system was able to generate alarms for 36% and 40% of production problems respectively. In Glomson, the alarm system functioned poorly and generated alarms for 11 % of production problems. The difference may be related to the fact that Glomson used fewer dependencies in the planning phase.
- In Glomson and Opus, the proportion of false alarms to total alarms was high (79% and 62%). In Prisma, only 26 % of the alarms were false alarms.
- The main reasons for not generating alarms were missing dependencies, two trades working in the same location without technical dependency, and two trades working in the same location where there is no technical dependency, but the tasks could not happen at the same time
- The main reasons for the delayed alarms were start-up delays in the first location, too optimistic forecasting assumptions for suspended tasks, last minute detail task updates, and a sudden slowdown of the predecessor
- False alarms were most often generated because of a wrong dependency or wrong progress information

Key findings relating to effectiveness of the control actions:

- Glomson had the least evidence of control actions in proportion to the project total duration and size. Opus had the most control actions.

- In Glomson, most of the control actions (80%) were not related to an alarm in the alarm system. In Prisma, 17 % of the control actions were not related to alarms. Opus had 42% of control actions unrelated to alarms.
- Opus had the most effective control actions; 45 % of the control actions, which were related to an alarm, prevented an alarm from turning into a production problem. The same number for Glomson was 15 %, and Prisma 39 %.
- Detail plan changes were the most effective control actions, especially in Opus where 69% of the plan changes were successful. Prisma and Glomson had maladaptive plan change practices where dependencies were removed, but a problem later happened. Only 37% of the plan changes in Prisma and 29% in Glomson successfully prevented problems.
- Production rate increases prevented problems in Prisma and Opus 33% and 30% of the time respectively. In Glomson, they prevented problems 12% of the time. Typically, production rate increases were made to catch up with a subcontractor schedule delay, instead of preventing production problems. The production rate increases often failed because they were taken too late, or were too small to be effective.

3.6.3 Number of production problems

Table 3-11 shows the number of production problems in each of the case projects. The problems have been divided into categories (start-up delay, discontinuity, and slowdown) and certainty classes (certain, probable, possible).

There are many differences in the distribution of the issues and their certainty. In Prisma many more issues could be labeled “certain” because of the good documentation of the deviations and production problems. Only the slowdowns were not adequately documented. Prisma also suffered disproportionately from start-up delays, and did not have many discontinuities. In Glomson there were about the same number of production problems as in Prisma, although the project was larger and had a longer total duration. Very few issues could be labeled “certain” because of the lack of documentation of the deviations and problems. Opus had three times more deviations than Prisma, and Glomson and had a very large proportion of discontinuities. Opus tended to have more probable issues than the other projects. The large number of problems in Opus is partially a factor of the longer project duration (50 % longer than Glomson); and partially a factor of the higher level of detail. The number of tasks was much higher in Opus than in the other case studies, which may inflate the number of identified problems.

Table 3-11: Production problems in the case projects

	Prisma	**Glomson**	**Opus**
	Total problems		
Total	124	122	357
Certain	36	5	33
%	29%	4%	9%
Probable	30	46	166
%	24%	38%	46%
Possible	58	71	158
%	47%	58%	44%
	Start-up delays		
Total	34	8	96
Certain	10	1	4
%	29%	13%	4%
Probable	18	5	60
%	53%	63%	63%
Possible	6	2	32
%	18%	25%	33%
	Discontinuities		
Total	36	20	129
Certain	19	0	16
%	53%	0%	12%
Probable	6	8	61
%	17%	40%	47%
Possible	11	12	52
%	31%	60%	40%
	Slowdowns		
Total	54	94	132
Certain	7	4	13
%	13%	4%	10%
Probable	6	33	45
%	11%	35%	34%
Possible	41	57	74
%	76%	61%	56%

3.6.4 Failure to generate an alarm

To improve the forecasting and alarming system, the cases where problems happened and no alarm was generated were examined in the case studies. Table 3-12 shows the reasons for failing to generate an alarm by case study sorted to have the most common problem on top.

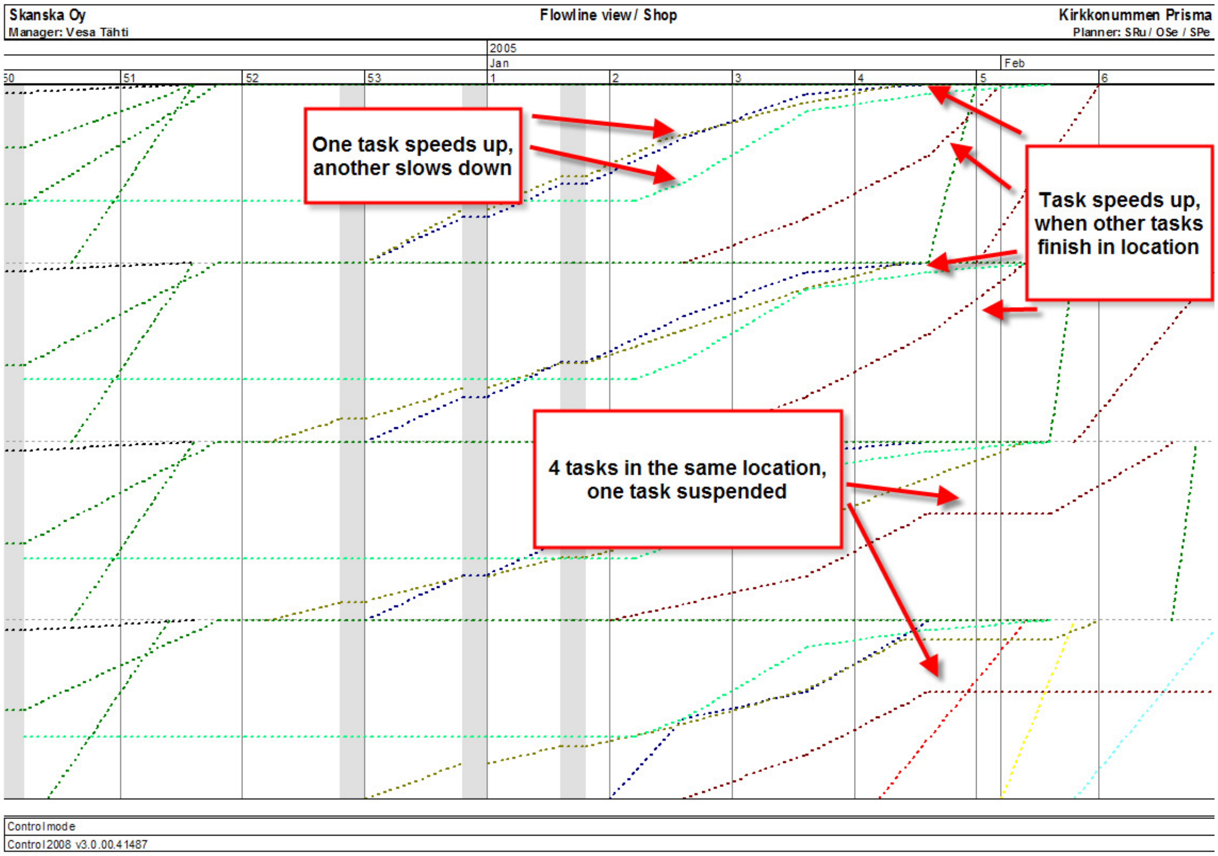
Table 3-12: Reasons for failing to generate an alarm

	Prisma	Glomson	Opus	Total
Total cases	**89**	**106**	**233**	**428**
Many tasks in the same location	37	54	65	156
Missing dependency	25	36	52	113
Not at the same time in the same location	17	12	76	105
Inside the same baseline task	4	0	13	17
Change of plan	3		7	10
Wrong actual data			10	10
Wrong dependency	1	3	2	7
Too optimistic forecast			5	5
Other	2		3	5
Only finish-to-finish dependency		1		1

There was a total of 428 problems where an alarm was not generated. The most common and third most common reasons for no alarm are related. Many tasks in the same location means that there were many tasks in the location and one or more of them could not work productively but slowed down. Not at the same time in the same location means that the tasks could not work in the same location at the same time and one of the tasks had to be suspended. This was very common in Opus – possibly because of the smaller location size. In Prisma and Glomson, slowdowns tended to happen instead. In both of these cases, there is no mandatory technical dependency, but the tasks could not happen in the same location at the same time efficiently. Ordinary CPM logic fails here, because it forces the planner to choose which task should go in first, and fails to acknowledge that sometimes tasks can happen in any sequence, but not at the same time. Figure 3-18 below shows an example in the Prisma shop hall where four tasks are happening in the same location and they are slowing each other down.

The second most common reason for failing to create an alarm was that a dependency was missing in the system, although it clearly should have been there. This problem can be fixed through a process change and with training.

The next most common problem was that the detail tasks of multiple subcontractors were included in the same baseline task and no alarm was generated. This problem can be fixed by changing the alarm logic in such a way that an alarm will be generated if the detail tasks have different subcontractors.



One task speeds up, another slows down

Task speeds up, when other tasks finish in location

4 tasks in the same location, one task suspended

Figure 3-18: Four tasks in the same location in Prisma causing slowdowns and suspensions to each other.

In ten cases, a sudden change of plan created a problem. These can be fixed by not concentrating the detail task updating process just on the next week, but by looking ahead for a longer period of time. Sudden plan changes can be prevented also by frequent reviews, and by asking the subcontractors to comment on the plan. Sudden changes of plan happened in Prisma and Opus, where the detail tasks of the next week were always edited to match the weekly plan of the week.

In ten cases, there was wrong actual data in the system. This can be improved by distributing the responsibility for monitoring to the subcontractors and committing more time to making sure that the progress information is correct. The production control system should be seen as a daily management tool, not just a tool for creating Owner reports.

In seven cases there were wrong dependencies. These can be fixed by changing the process so that the dependency networks are constantly reviewed in the subcontractor meetings.

In five cases, an alarm was not generated because the schedule forecast was too optimistic. There were two reasons for this over-optimistic forecasting. One of them was that a suspended predecessor did not continue. The forecasting system kept assuming that the task would continue on the control date. This can be fixed on process level by reviewing all of the suspended tasks in the subcontractor meetings and on the system level by introducing a new concept of likely continuation date entered based on the subcontractor meeting discussions.

Another reason for over optimistic forecasting was when an alarm was not generated because the production rate forecast was not updated before two full locations were completed. This can be fixed by changing the forecast to take into account all of the production progress data regardless of completing locations.

In one case, an alarm was not created because there was only a finish-to-finish dependency in the system. This can be fixed by new rules of how to create alarms for finish-to-finish dependencies.

3.6.5 Delayed alarms

In all of the case studies it was shown that alarms which were raised more than ten days before the problem were more likely to result in a control action which could prevent the problem. Table 3-13 shows the reasons for not raising an alarm more than ten days before for all of the alarms which were generated ten or less days before a problem. These reasons can be used to modify the alarm system to generate alarms earlier.

Table 3-13: Reasons for raising alarm too late

	Prisma	**Glomson**	**Opus**	**Total**
Total cases	**20**	**6**	**78**	**104**
Start-up delay in the first location	1	1	23	25
Sudden slowdown of predecessor	2		19	21
Preceding task discontinuous, forecast assumes that continues right away	2		14	16
Detail plan update	4		10	14
Forecast too optimistic (needs 2 locations to forecast production rate)	4	2	3	9
Other	5	1	1	7
Wrong progress data	1		3	4
Out-of-sequence work	2	1	1	4
Sudden change of sequence of predecessor			3	3
Successor started too fast			1	1

The start-up delay of a predecessor in the first location was the most common reason for failing to raise alarms early enough. The forecast always assumed that the delayed tasks would start on the control date. The forecast can be improved by reviewing the prerequisites of the upcoming tasks of the look-ahead period and determining a likely start date based on any discussions (similarly to the likely continuing date for suspended tasks).

The second most common reason was that the preceding task suddenly slowed down to have a much lower production rate than previously. This may result from shifting resources to other projects, or to other tasks or unanticipated production problems. Resource issues can be solved by openly discussing manpower availability for the next few weeks in the subcontractor meetings and taking this into account in the forecasts.

The third most common reason was that the preceding task was discontinuous and the forecast assumed that it would continue right away. This is the same reason as for failing to raise an alarm (section 1.14) and can be fixed by introducing a concept of likely continuing date based on the subcontractor meeting discussions.

The detail plan update was the fourth most common reason. The schedule of the next few weeks was updated, and this resulted in an immediate alarm - often too late for control actions. This can be fixed by introducing a better look-ahead process.

Fifth most common reason was that forecast was too optimistic and adjusted production rate forecast only after two complete locations were finished. This can be fixed by starting production rate forecasting immediately when data becomes available.

The remaining reasons involve sudden changes in the sequence of locations or starting work disregarding any planned dependencies. These can be solved by changing the detail plan updating and look-ahead processes.

3.6.6 Ineffective control actions

Sometimes a control action was taken to remove an alarm, but the problem still happened. Most of the problems are not caused by the alarm system but by problems in the control action planning process.

Table 3-14: Control actions which did not prevent problems

	Prisma	**Glomson**	**Opus**	**Total**
Total cases	**16**	**2**	**12**	**30**
Changing / removing dependency as "control action"	8	1	3	12
Production rate increase not consistent			4	4
Successor start date delayed - however, the start date was supposed to be next week	3	1		4
Plan changed to remove alarm, but the control action was not implemented as planned	2			2
Control action too late			2	2
Predecessor increased production rate but successor too fast	1			1
Error in progress information	1			1
Predecessor increased resources, but was slowed by another task			1	1
Other	1			1

The most common reason for removing an alarm, but not removing the problem was simply changing the detail plan so that the dependency was removed. Although this removed the alarm, it often did not remove the problem, because it did not involve a decision to change something on site. This control action may work if the dependency was clearly wrong and all the parties agreed that work could commence in another sequence. Alternatively, something could be changed on site to remove the dependency (for example, cables can be installed after the painting of the ceiling if the cables are prepainted the same color). All of the projects resorted to removing or changing dependencies, and problems still happened. This was especially prevalent in Prisma, where alarms were removed eight times by changing or removing dependencies.

In four cases, all in Opus, the production rate was increased but the increase was not consistent. It seems that the production rate decreased back after the production management stopped paying attention to the problem thinking that it had been solved. This problem can be prevented by moving to the daily monitoring of tasks which are likely to cause downstream problems in the near future.

In four cases, an alarm was removed by moving the successor start date. However, if the successor was supposed to start next week, this clearly is a problem to the subcontractor. This can be again solved by using the forecast information to make sure that start date commitments can be met.

In two cases, a control action was implemented but too late, and the problem already happened before the control action was effective. This can be solved by starting control action planning immediately when an alarm is raised.

In two cases, both in Prisma, a control action plan was created and this removed the alarm. However, the control plan was not actually carried out. This can be solved by committing to control plans and by switching to the daily monitoring of situations where downstream effects are likely.

In one case, the predecessor increased production rate enough but the successor started to work faster, which resulted in problems. This can be solved by the better communication of production rate targets.

In the final case, the predecessor task increased resources, but was slowed down by another task. These issues can be solved by involving more parties in the control action planning process and a better commitment to plans.´

In 37 cases (1 in Prisma, 10 in Glomson and 26 in Opus), a control action was taken but it was either too late (12 cases) or too small (25 cases) to remove the alarm and the problem still happened.

3.6.7 Effective control actions

There were some successful control actions which removed the alarm and also removed the problem. These were most common in Opus, but also happened in Prisma. In Glomson, there were very few control actions which removed problems. However, the total number of control actions is the same as in Prisma. This result may be explained by the fact that fewer alarms were generated in Glomson.

Table 3-15 shows all of the control actions and the control actions which prevented a problem. Other control actions were either ineffective in preventing a production problem, or were taken even though there was no alarm in the system. For example, in Opus, the production rate was often increased just because the contractor was delayed from the baseline schedule although his delay was not affecting anyone else.

Table 3-15: Total control actions and effective control actions

	Prisma	**Glomson**	**Opus**	**Total**
Total control actions	**36**	**40**	**89**	**165**
Change of production rate, certain	1	0	0	1
Change of production rate, probable	5	6	9	20
Change of production rate, possible	9	27	44	80
Change of plan, certain	6	1	5	12
Change of plan, probable	12	2	27	41
Change of plan, possible	1	4	3	8
Suspending task, certain	1	0	0	1
Suspending task, probable	0	0	0	0
Suspending task, possible	1	0	1	2
	Prisma	**Glomson**	**Opus**	**Total**
Control actions which prevented problem	**14**	**6**	**40**	**60**
Change of production rate, certain	0	0	0	0
Change of production rate, probable	1	0	3	4
Change of production rate, possible	4	4	13	21
Change of plan, certain	3	0	1	4
Change of plan, probable	4	2	23	29
Change of plan, possible	0	0	0	0
Suspending task, certain	1	0	0	1
Suspending task, probable	0	0	0	0
Suspending task, possible	1	0	0	1

The production rate changes did not often have good documentation. Only once in Prisma, the production rate increased and there was supporting evidence (memo note) that the increase was actually as a result of a control action. The production rate increase was classified as "probable", if there was an alarm, the production rate increased and the number of resources increased at the same time. Other production rate increases were classified as "possible", and were much more common. Opus had the largest number of production rate changes. This result was also shown in the baseline and detail task reliability results earlier in this chapter, and was confirmed by direct observation. Opus was the only project where the production rates were discussed in the production meetings using Flowline diagrams. Prisma had few production rate changes. Glomson had many production rate changes, but only few of those prevented a production problem.

Plan changes were a common form of control action in Opus and Prisma. In Glomson, plans were changed as a control action only 7 times. Typically, start dates were shifted or the schedule was accelerated by planning to add more resources. Sometimes decisions were made about changing the sequence of work to prevent two tasks from happening in the same location simultaneously. In Opus the plan changes were often successful in removing alarms and preventing problems. In Prisma, plan changes were less successful, and often involved removing dependencies which were valid (see the earlier section about control actions which resulted in problems).

In Prisma, tasks were suspended two times to allow another task to continue in a location. This was done in the small locations of section five to allow concrete pouring to happen in the area. In one case, this suspension was also noted in the subcontractor meeting memos.

3.6.8 False alarms

False alarms are problematic for an alarm system because they may undermine the confidence of project teams in the system and make them ignore valid alarms. In total, the case studies had 104 false alarms. Table 3-16 shows the false alarms categorized into reasons. Interestingly, Prisma and Glomson had very few false alarms compared to Opus.

Table 3-16: Reasons for false alarms in case studies

	Prisma	**Glomson**	**Opus**	**Total**
Total cases	**13**	**11**	**80**	**104**
Wrong dependency	7	2	15	24
Wrong progress data	2	1	17	20
Alarms between tasks of the same subcontractor	2	1	12	15
No problem even though in same location at the same time	1	2	9	12
Tasks can be done in any sequence	1	2	6	9
Meeting memos show that delay was caused by some other reason			8	8
Minor part of scope not finished		2	3	5
Commitment to subcontractor not threatened			3	3
Too optimistic forecast of successor			3	3
Forecast start-up delay did not happen for predecessor			3	3
Other			1	1

The most common case type in all of the projects was a wrong dependency or wrong dependency type. This is more a process issue than system issue, and can be solved by a systematic review of the dependencies in production meetings.

Wrong progress data generated many false alarms, especially in Opus where the quality of progress data was poor. This issue can be solved by implementing distributed progress data gathering strategies, and by discussing the control charts in the subcontractor meetings.

In 15 cases, an alarm was generated between two tasks of the same subcontractor. In reality there was no problem, because the same resources would continue to the other task after finishing the previous task. These internal issues can be removed by only creating alarms when subcontractors are forecast to cause problems to other subcontractors.

In 12 cases, the tasks happened in the same location at the same, time but there was no production problem. However, the dependency was not incorrect because the same tasks had previously (or later) had problems when they happened together in another location. These cases may signify that weekly planning was successfully used to enable trades to work in the same location without causing interference with each other.

In 9 cases, the tasks could be done freely in any sequence. An alarm was generated because the successor started before the predecessor. This can be solved by adding another dependency type for tasks which can happen in any sequence, but can not go on at the same time.

In 8 cases, the production meeting memos show that a production problem was caused by some other cause, for example, a procurement or design-related reason.

In 5 cases, a very small part of the scope was not finished, and alarms were still generated. This can be fixed by the process change of marking the predecessor finished and planning new detail tasks for not finished parts, and planning their dependencies and dates based on the information about why they can not be finished now.

In three cases, the alarm was wrong because the subcontractor had not been selected, or the schedule did not reflect a commitment to the subcontractor. These issues can in fact be much more common, because nothing is known about commitments. These three cases were special cases, because this lack of commitment was noted in the memos. This can be addressed by including an additional property in the detail task plan – whether the dates and production rates have been committed to. All of the non-committed tasks are work-in-progress. Alarms should be created only when a commitment is threatened.

In three cases, the successor schedule forecast was too optimistic, and an alarm was created. In reality, the successor was proceeding slowly enough to prevent a clash between the predecessor and successor.

In three cases, an alarm was caused by the forecast start-up delay of the predecessor (for example, because its predecessor was delayed). However, the predecessor could start on time and therefore the alarm was false.

3.7 Analysis of construction phases

Based on the correlation analysis, it seems that MEP tasks behave differently from other tasks. This result received further support in the Prisma case study based on direct observation in the weekly progress meetings, and in the Opus case study by discussions with the project engineer.

To evaluate the hypothesis that there is a fundamental difference between the interior / MEP work and other work stages, the main numerical variables were calculated for each construction phase: Foundations, Structure, Roofing, Façade, Interior construction work, Interior MEP work, and Commissioning. The results were calculated for production rate deviation, start date deviation, finish date deviation, PPC, each production problem type, and each downstream effect type. The analysis was done only for the detail tasks. The results for all of the variables are presented in the Appendix detailing the case study results.

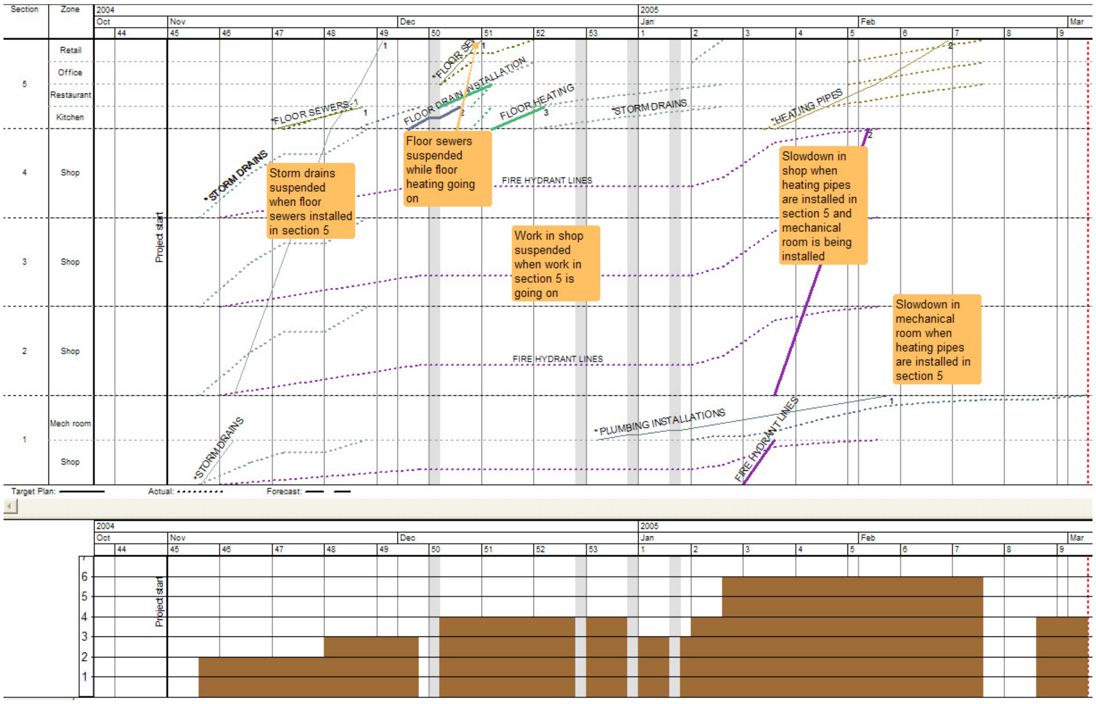
The most important result from this analysis was that large differences between construction phases were found for discontinuities, slowdowns, downstream discontinuities, and downstream slowdowns. In all of the projects, the MEP and interior work both suffered and caused the most problems. It seems that cascading problem chains happen mostly in the MEP and interior finishes phases.

3.8 Analysis of resource use

Because of the findings that the MEP and interior finishes caused most of the problems, they were analyzed in more detail. The results described previously in this chapter resulted in the hypothesis that production problems may be caused by a lack of information about the quantities, resources, and productivity rates of the MEP subcontractors. Additionally, the direct observation of the Flowline diagrams in Prisma indicated that the MEP contractors tended to work fast in one location and suffer from slowdowns in other locations. This hypothesis was tested by comparing the planned resource graphs to the actual resource graphs, and actual resource graphs to actual progress on site.

The results in all of the projects show that planned resource use was not level, while the actual resource use was more or less level. In Glomson and Opus, the resources were planned explicitly using either quantities from subcontractor or assumed quantities. In the Prisma, MEP tasks were not resource-loaded but for analysis purposes, man hours were calculated based on the actual resources used and allocated to the original plan. Whether the resources were planned implicitly or explicitly, the resource loading was not level in any of the projects. Analysis of the actual production shows that when production speeds up in one task or location, it simultaneously tends to slow down in other locations. These issues are not controlled by the General Contractor and may be root causes for cascading delay chains.

Figure 3-19 shows the actual resource use and progress of the Prisma plumbing contractor. Figure 3-20 shows the planned resource use during the same time period. By comparing the figures, it can be seen that the resource assumptions of the plan were very different from the actual resource use. In this case, the General Contractor was unaware of the resource requirements of the plan, because the MEP tasks were not resource-loaded. Resource-loading was performed after the fact by allocating actual man-hours to tasks. Similar examples were found in all of the case studies. In Glomson, the electrical contractor was analyzed and in Opus, the plumbing contractor showed a similar pattern. Also other contractors with multiple tasks, such as the drywall contractor and mechanical contractor demonstrated similar issues. These results are described in more detail in Appendices A, B, and C.


Storm drains suspended when floor sewers installed in section 5

Floor sewers suspended while floor heating going on

Work in shop suspended when work in section 5 is going on

Slowdown in shop when heating pipes are installed in section 5 and mechanical room is being installed

Slowdown in mechanical room when heating pipes are installed in section 5

Figure 3-19: Plumbing contractor actual resource use and progress in Prisma

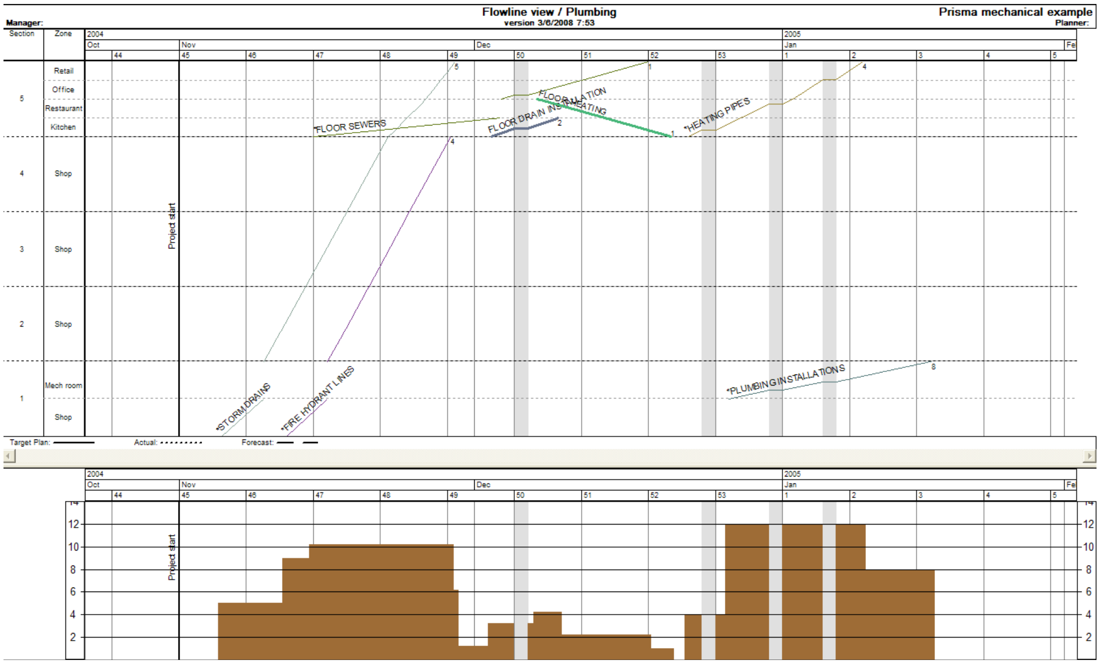


Figure 3-20: Initial detail plan and planned resource use of the plumbing contractor

3.9 Analysis of the function of the production control system and process

3.9.1 Summary of results

All of the case projects finished on time. Opus was able to compress the original contract duration by two months, and other projects finished according to the original contract duration. However, all of the projects had many production problems and waste in production. The reliability of the baseline schedules, detailed schedules and weekly schedules were poor, based on the deviations of the start dates, finish dates and production rates, compared to the planned, and percentage of plan completed results. This poor reliability manifested itself as an inability to finish tasks on time. Start dates were more reliable. All of the projects used up their end-of-project buffers and used the commissioning period to catch up with the schedule. Instead of finishing all of the tasks before the start of the tests, all of the projects had work continuing in parallel during testing and final cleaning.

Problems were found in selecting an appropriate Location Breakdown Structure for the projects. All of the case studies used structural independence as the main guideline for dividing the project into sections, and then divided these sections into floors. However, this only worked if the functional spaces inside the building corresponded with the structural sections. Disregarding the main mechanical room effect areas was shown to remove the benefits of splitting up the building, because complete floors had to be dust-free at the same time, instead of being able to complete one section completely before moving to the next one. The direction of the optimal workflow needs to be considered when deciding the sections, or schedule reliability will suffer. Case research shows that in most cases, the Location Breakdown Structure for the interior work needs to be different from the Location Breakdown Structure of the Earthworks, Foundations and Structure. The MEP contractors especially need to participate in defining the Location Breakdown Structure because of their different workflow requirements.

Frequent detail schedule updates contributed to the production problems. The detail schedules were updated task by task, and the total effects of the updates were not examined. The projects tended to have large sections of the schedule as work-in-progress, and, therefore, the total status of the project was rarely up-to-date. Dependencies were often removed to allow for more planning freedom (i.e. the free ability to select dates). Frequent changes of the sequence without considering the dependencies and checking for location availability contributed to production problems. Commitment information was not available in the schedules, so it was unclear which schedules were work-in-progress and which had commitments.

The reliability of the weekly plans measured by use of the Percentage of Plan completed (PPC) correlated with the reliability indicators of the higher level schedules. Tasks with higher PPC also had higher production rates and caused less downstream problems. On the other hand, PPC was affected by production problems caused by upstream trades. It can be concluded that removing the production problems caused by other tasks will increase both production rate and PPC, and this will in turn decrease the production problems caused by the task to downstream tasks. This can be achieved by decreasing the variability of the production system or by increasing buffer sizes. Because the production problems had a large correlation with PPC, these interdependencies are a significant contributor to the success of production control.

All of the projects showed strong evidence of cascading production problems. In particular, tasks which suffered slowdowns were extremely likely to cause either slowdowns or discontinuities to other tasks. These cascading effects concentrated on the MEP and interior finishes tasks.

Because production problems concentrated on the MEP tasks, they were analyzed more closely. It was found that all of the MEP subcontractors tended to have very different resource profiles on site than was assumed by the plans. The resource peaks planned in the General Contractor’s schedule were not matched by the actual resource use. These results led to the hypothesis that cascading delay chains may start when the schedule assumes more resource than is available. On the other hand, in those periods when a subcontractor has more resources than assumed by the plan, working out-of-sequence and starting early could happen, which also led to production problems. Because of the theoretical significance of these results, they will be further validated in the tests described in Chapter 5.

Discussion and identification of production problems was found to be poor in the case studies. Start-up delay and discontinuities had more mentions in the production meeting memos than the production rate problems. There was little evidence of discussions about production rates. Instead, the method of control was to compare the status of each task and location to the baseline schedule. Lack of communication about production problems contributed to few successful control actions in the projects. Most of the production problems seemed to happen without the knowledge of project management. As a notable exception, in the Opus case study, production rates were discussed using the Flowline diagrams and the results show that the control actions relating to production rates were much more common in this project. However, most of those control actions were not related to the actual, identified upcoming production problem, but may have been taken because of the subcontractor being delayed from their original schedule without considering the production status.

Based on direct observation and a comparison of the planned and actual resource use, it can be said that there is not enough communication between the General Contractor and the subcontractors about the resources they are going to mobilize. As a conclusion, for multi-skilled MEP contractors it is not enough to show a continuous Flowline to ensure efficient production. Instead the overall resource use needs to be considered.

Many problems were identified in the production control system itself. Alarms were often not generated at all, or were generated too late for them to be useful. The main problems were found to relate to missing or wrong dependencies, over-optimistic forecasts, having many tasks in the same location, and starting work in the wrong sequence. To correct these problems, both the production control process and the production control system need to be changed.

3.9.2 Needs for improvement in the production control process

The results in all of the case projects highlight the importance of involving the main subcontractors in the planning and controlling processes. In particular, the Location Breakdown Structure, resource-loading, and dependencies should be agreed on by all parties working together. Open discussions about production problems and their solutions need to be added to the production meetings.

Detail task planning during implementation should happen construction phase by construction phase instead of updating individual tasks in isolation. It seems that the detail tasks should be used to record the commitments to phase schedules instead of using them as look-ahead schedules. This conclusion follows on from the fact that updating the detail tasks led to many problems, and continuous updates made it unclear which commitments had been made. Dependencies must be considered when updating, or a significant value is lost from the location-based management system. However, changes of dependencies can be used as control actions if the total effect of the change is evaluated.

The planning methodology for the multi-skilled trades must be changed from just trying to plan the continuous work for a single type of tasks. Because the multi-skilled trades have many tasks going on at the same time, and the same workers are employed in the production of multiple tasks, the overall resource profile becomes an issue. Although work continuity is often desirable from a learning and productivity point of view, multi-skilled contractors can easily switch location or task when they encounter production problems. This leads to frequent out-of-sequence work and unanticipated production problems, which can start cascading delay chains. The conclusion from this finding is that the production control system does not work without the leveling of resources, and planning and committing to schedules as a team. Subcontractors also need to take a more pro-active role in monitoring and controlling production. Although working out-of-sequence can help to improve resource utilization in the short run, the resulting cascading problem chains are likely to eventually affect the subcontractor himself.

Input from all of the main subcontractors is required to develop a Location Breakdown Structure which works for all of the trades. Quantities, or at least man hour information, should be used to resource-load all of the tasks of the important subcontractors. Schedules should be planned by using dependencies which are defined together in logic workshops. Subcontractors should be interviewed to establish their own assumptions about resource requirements, so that the General Contractor's and the subcontractors' expectations are not totally different. Because the contractors have often not been selected when the baseline scheduling starts, the baseline schedules could be approved in two stages: 1) the earthworks, foundations and structure and 2) the MEP and finishes. All of the parties should also commit to the baseline schedule as an overall framework, and especially to the overall resource profile. The analysis of the resource profiles helps to find unrealistic assumptions already in the baseline planning process.

The schedules should be mutually committed to by both the General Contractor and the subcontractors. By recording the commitment, work-in-progress plans can be separated from the final, committed versions. These tasks with commitment can be used to evaluate if a production problem is really breaking a commitment. Alarms should be generated only if a commitment is threatened. Committed tasks should not be updated unless there are changes in the data on which the commitments are based (for example change orders).

Problems with the quality of data and the lack of documentation contributed to the failures of the control actions and the failure to predict upcoming production problems. To improve the quality of progress information, subcontractor self-reporting should be implemented. For the benefit of the accuracy of production control system, it is important to get data for all of the tasks and all of the locations on the status date. If a location has not been finished, a completion rate should always be estimated. Otherwise the forecasts of problems and alarms will not be made on time. For locations where it is impossible to complete all of the work, a punch list of missing work could be created, and the remaining work could be allocated to a new detail task with the correct dependencies. In this case, the original location could be marked as finished, and the schedule will show the additional work later in the project.

Production meetings should be changed so that they focus more on planning ahead and solving problems, instead of describing what has happened in the past. In all of the projects, the production problems were inadequately documented in the meeting minutes. In addition to discussing the status compared to the schedule, the production rates and upcoming production problems should be discussed. Discussing the production rates by using Flowline figures resulted in better control of the production rates and catching up delays during production. This result indicates that using Flowline diagrams to illustrate production rates has a beneficial impact on production control. A common problem revealed during the analysis of the problems was that the start dates of the new tasks and continuation dates of the existing tasks were not known by the General Contractor. Verifying the start dates and screening for prerequisites should become a systematic process in the production meetings.

Figure 3-21 shows an adjusted detail planning process, including commitment. Figure 3-22 shows an adjusted production control process, including resource commitments and weekly plan commitments.

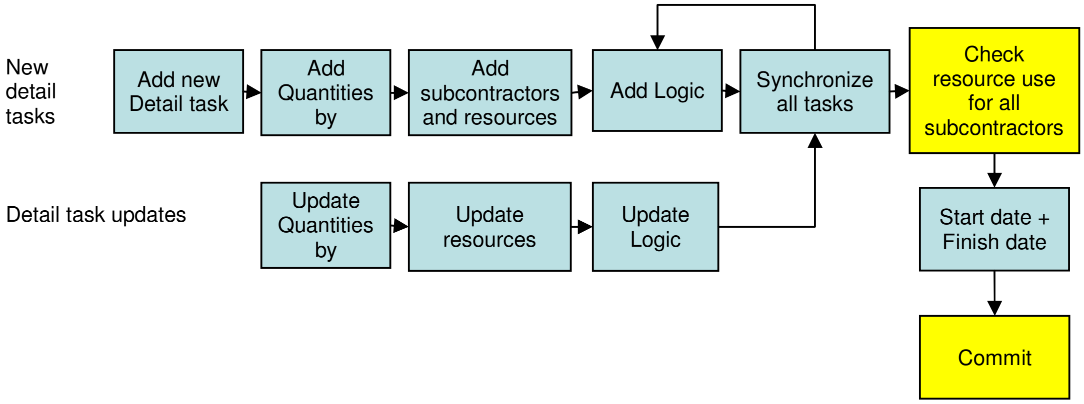


Figure 3-21: New detail task planning process including resource leveling and commitment

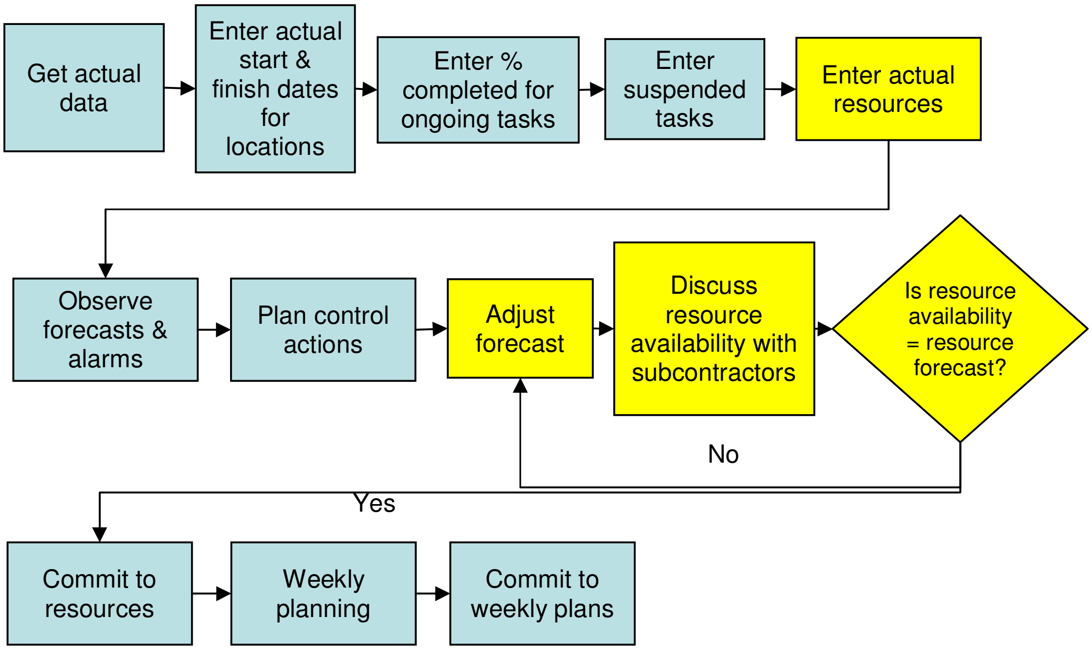


Figure 3-22: New production control process

3.9.3 Needs for improvement in production control system

The results show that cascading production problems were a big problem in all of the case studies. The problems were often prevented by successful control actions. Control actions were more likely if an alarm was generated earlier than 10 days before the problem. However, alarms were often not generated, or they were generated too late to be useful. Therefore the production control system needs to be adjusted so that alarms can be generated earlier. To achieve this aim, the forecasting system, resource system and alarming system need to be changed. All of the case studies revealed the need to explicitly record commitment in the system and use commitments as the basis for the alarm system. Because of the importance of the PPC metric and the necessity to transform the production rate goals to concrete, well-defined assignments, weekly planning should be incorporated as part of the system.

Many alarms were not generated because of missing dependencies. Missing dependencies often happened during the detail task planning phase because the detail plans were updated based on dates agreed with the subcontractors, instead of using schedule logic to calculate the dates based on dependencies. This approach led to many errors during scheduling. In addition to dependencies which were missing based on planner omission, many dependencies were found to be voluntary, such that a sequence could easily be changed. However, these tasks could not happen productively in the same location. Many missing dependencies also related to the fact that there were long delays in the schedule and the planner did not think that the two tasks could every happen together. To solve these issues, the alarm system should generate an alarm whenever two tasks are going to be in the same location, whether there is a dependency or not. The planner should then be able to ignore an alarm in this location, ignore alarms in all of the locations, or accept alarms a potential problem which need to be solved. These alarms should be visualized in a different way than alarms deemed as certain.

The forecasting method caused some missing alarms. For example, in all of the case projects, the structure was broken into multiple subtasks which were done by the same set of resources. Because the forecast was updated to take into account the actual forecast only after the two locations were completed; for these split tasks which only had one location, it was never updated. In Prisma, there was a problem with large locations with long durations in each location. Tasks were produced simultaneously in all of the locations. Also in this case, the requirement to finish the two locations before updating the forecast production rate did not work in practice. A better solution would be to start forecasting immediately when the progress information is available.

The forecast was also overly optimistic concerning the start dates and continuing dates for the suspended tasks. The not-started tasks or suspended tasks were assumed to start either on the planned date or at the present date, whichever was later. The solution could be to add starting and continuing prerequisites to the system for all not-started or suspended tasks. For each prerequisite, the system should have a description, a responsible person and a date associated to it. The task forecast start or continuation date should be delayed until the last date in prerequisite action list.

The results show that alarms were often generated because part of the schedule was work-in-progress, or alarms were generated between two tasks of the same subcontractor. Alarms should be generated only when a commitment on the detail task level is about to be broken. Each detail task should have a status: work-in-progress or committed. Alarms should be generated only if a delay of the task is going to delay a committed detail task in a location, and only if the delay is caused by a different subcontractor. This will prevent having too many false alarms when schedule planning is in progress. Commitments should also prevent changing the time of the detail task. An alarm should be generated also when the detail task dates are changed directly or indirectly (for example, by changing a predecessor task). Some missing alarms were caused because different subcontractors were working on the detail tasks of the same baseline task. This was caused by the fact that the subcontractors were not selected when planning the baseline schedule. To solve this problem, baseline tasks should be disregarded in the alarm system and only detail tasks should generate alarms.

Documenting control actions by updating the detail tasks often caused more problems than benefits because it confused the original commitment and often forced the planner to remove dependencies to other detail tasks to achieve the desired result. Instead of updating the detail tasks, a control action should be a separate action to get back to the original commitment. This would work best by adjusting the forecast instead of the detail task because the original commitments should not change when there are problems (unless the problems are caused by something outside the control of the parties). When the forecast is adjusted to model control actions, there should be a visual change in the forecast line to help everyone understand that something will be done differently from the previous production. Effectively, the detail tasks would be used to document and commit to a phase schedule, and the forecast which has been updated with control actions would form a look-ahead schedule.

Because the success of the weekly plans correlated closely with the success of the detail and baseline schedules, the weekly plans should be directly incorporated into the system. The system already has information about the baseline (what SHOULD be done), the commitments (what WILL be done), and the forecast (which tells that what CAN be done if everything continues in the same way as the last week). The forecast can be used to automatically initialize the production targets for the next weeks. However, this is just an initialization, because the weekly plans need more detail than this to be well defined and sound (Ballard 2000). However, to preserve the link between the detail schedule and the weekly plans, all of the weekly plans should be linked to the locations and quantities of the location-based schedule.

All of the case studies revealed the great importance of the resource leveling of multi-skilled trades. This can be taken into account in the planning process, but must also result in changes to the production control system. Previously, location-based control systems assumed that resources were working on only one task at the same time. “Actual resources used” was a property of a task and a location. The General

Contractor did not know how many resources had been used in each location, so planned resources were assumed. However, many of the slowdowns identified in the case projects could have been caused by the fact that the same resources were being used on multiple tasks, which caused them all to be slower. The forecast system must be changed to accommodate subcontractors who have multi-skilled resources who can work on multiple tasks at the same time. This is the only way how the resource requirements of the future can be forecast for each trade. The actual resources need to be the property of a subcontractor, instead of task or a location. A resource forecast should be calculated for future production, and forecasts should be adjusted if the forecast assumes more resources than those which will actually be available.

4 Improved location-based controlling system

This chapter presents the changes and adjustments made to the location-based controlling system and process based on the case study findings. Only those improvements targeted to fix the root causes of failing to alarm on time, or generating over-optimistic forecasts are described in this chapter (refer to section 3.9.3. which describes the key improvement needs).

4.1 Changes to the location-based planning system

The location-based planning system required a change in the splitting procedure. The original splitting methodology (refer to Chapter 2) created two independent tasks when a task was split. These tasks were not connected in any way, even though in reality the work was similar. This led to forecasting problems. The system was modified to allow splitting, but to retain a logical connection between the tasks. This was implemented by not splitting the quantity item, but by retaining the connection by sharing the same quantities.

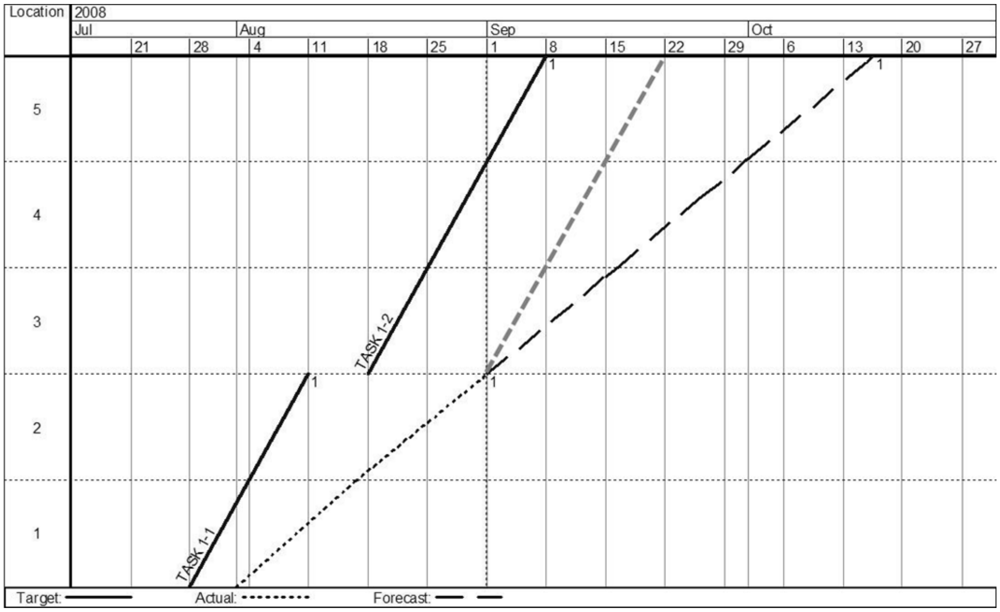


Figure 4-1: The original splitting procedure results in an over-optimistic forecast for the second subtask of task 1 (the gray dashed forecast). The new splitting procedure continues with the same slope for the second subtask (the black dashed forecast).

As an example, Task 1 has been split into two parts with a planned break in between (Figure 4-1) the two parts. The first part has completely finished and the production rate was slower than planned. With the original system, the forecast assumes that the second part will continue at the planned production rate, even though it is similar work, and done with the same resources (the gray dashed line). With the new system, the forecast correctly recognizes that the task will continue with the same production rate unless control actions are taken (the black dashed line).

4.2 Changes to the location based controlling system

4.2.1 Actual resources

During the research, it was found that it was very difficult to collect the actual subcontractor resource information by task and location. The amount of resources could change daily, and multi-skilled subcontractors, such as the MEP contractors, could be working on multiple tasks at the same time and changing the task based on the achieved productivity and space congestion. However, in all cases, the subcontractor resources were reported on a weekly level.

To solve this problem of starting data, a system was designed to calculate task and location resource use based on the work completed and the total resources on site. On days with multiple tasks happening at the same time, the procedure uses the planned productivity levels to distribute resources to the subtasks. The calculation happens as follows:

1. For each day, the value of the actual production in man-hours is calculated by multiplying the actual quantity produced by the planned consumption for each quantity item in a task.
2. The total actual resources are distributed to the tasks and locations based on the value of man-hours. This gives the total actual man-hours in each task and location, where production was ongoing on a day.
3. This assumption can then be modified by the project team

This procedure can be best illustrated with an example showing the original and new systems. Table 4-1 shows the planned quantity data for two tasks and two locations. The planned production has one resource for both tasks.

Table 4-1: Planned quantities for two tasks and two locations

		Location		
	Consumption	1	2	Unit
TASK 1	0.5	80	120	M2
TASK 2	1	90	100	M2

Let us assume that the two locations of task 1 and the one location of task 2 are ongoing at the same time, with task 1/location 1, and task 2/location 1 starting on Monday and task 1/location 2 starting on Wednesday. In the original system, it was assumed that each location would have the planned resources working on them. The actual resources could be entered when the location was completed. In the new system, the actual resources are defined for each day. Let us assume that there was just one person on Monday and Tuesday and two people on the other days of the week. Table 4-2 illustrates the calculations for each workday. First, the value of production in manhours is calculated for each task and location (actual production / number of days * planned consumption rate). Then the actual resources are distributed to the locations based on the value of manhours.

Table 4-2: Actual resource calculations for each workday

VALUE OF WORK PERFORMED (manhours)	MO	TU	WE	TH	FR
TASK 1 location 1	4.8	4.8	4.8	4.8	4.8
TASK 1 location 2	0	0	5	5	5
TASK 2 location 1	7.2	7.2	7.2	7.2	7.2

ACTUAL RESOURCES	**MO**	**TU**	**WE**	**TH**	**FR**
TOTAL	**1**	**1**	**2**	**2**	**2**
TASK 1 location 1	0.4	0.4	0.6	0.6	0.6
TASK 1 location 2	0.0	0.0	0.6	0.6	0.6
TASK 2 location 1	0.6	0.6	0.8	0.8	0.8

There is a large difference in the actual productivity information calculated based on the new and old systems. The old system would assume that one resource is working in each ongoing location. This would result in the assumed resource use of 40 manhours in Task 1 location 1 (5 days * 8 hours / day), 24 manhours in Task 1 location 2 and 40 manhours in Task 2 location 1. The actual productivity rate for task 1 would be 64 manhours / 78 m^2 produced = 0.89 manhours / unit. With the new system the resource use would be 20 manhours for location 1, 14 manhours for location two, and the actual productivity rate would be 34 manhours / 78 m^2 = 0.44 manhours / unit.

In the case studies, the actual resource consumptions were sometimes too large and sometimes too low, depending on the actual resource numbers. Because the forecast used the actual production rate instead of the productivity rate in the calculations, this did not cause problems with the forecast. However, control actions could not be planned based on the productivity data because of the resource calculations. The new actual resource system does not require more data than is available in the subcontractor weekly reports and gives more accurate results.

4.2.2 Improved forecasting system

Many problems were identified with the original forecasting system based on the case study findings. Because of the over-optimistic forecasts, many alarms were received too late for them to be useful in preventing problems before they occurred. The main problems can be summarized as follows:

- The production rate forecast activated only after two completed locations; sometimes this meant that the production rates were not forecast at all
- Splitting created task parts which were disconnected in the forecast, although they represented similar work for the same subcontractor
- Suspended tasks were assumed to continue immediately on the control date
- Not started and delayed tasks were assumed to start immediately on the control date
- The forecast did not consider the actual resources

The improved forecasting system starts forecasting immediately when the progress data is available for a task. Instead of working on the basis of comparing the actual duration to the planned duration, the new forecast takes into account the actual resources and uses the actual resource consumption as the basis of the forecasts. The work is assumed to continue with the same actual productivity, but with the planned resources, unless adjustments have been made in the look-ahead plan (section 4.2.3). This requires significant changes in the duration forecast calculations. In the improved forecasting system, the duration forecast is calculated as follows:

1 Calculate the actual resource consumption of a schedule task (χ_A^{task}) with locations i = 1,…,n

$$\chi_A^{task} = \left(\sum_{t=\hat{t}-x}^{\hat{t}} \sum_{i=1}^{n} L_A{}^i\right) \Big/ \left(\sum_{t=\hat{t}-x}^{\hat{t}} \sum_{i=1}^{n} Q_A{}^i\right), i \in task \tag{4.1}$$

where

L_A = actual manhours
Q_A = actually produced quantity
$\hat{t}$ = current time
x = parameter defining the considered time period

If x is selected to be large, historical problems will continue to affect the forecast also after problems have been corrected. If x is selected to be small, the forecast may become unstable and change every week. After some experiments, x was selected to be 100 work hours in the test part of this study.

2 Calculate the actual resource consumption of each subtask with progress information

$$\chi_A^{subtask} = \left(\sum_{t=\hat{t}-x}^{\hat{t}} \sum_{i=1}^{n} L_A{}^i\right) \Big/ \left(\sum_{t=\hat{t}-x}^{\hat{t}} \sum_{i=1}^{n} Q_A{}^i\right), i \in subtask \tag{4.2}$$

3 Forecast the remaining durations of all ongoing locations

If one location of a subtask is ongoing:

$$d^i_{remaining} = \chi_A^{subtask} \frac{(Q^i - Q_A^i)}{R \times S} \tag{4.3}$$

where

R = the planned number of resources in the subtask
S = shift length in hours

If more than one location is ongoing:

An iterative procedure is needed, because it is assumed that the planned resources are shared between locations. Therefore, when one location is finished, the resources must be made available to other locations. For each ongoing location, the remaining duration is calculated with the formula (4.4). In effect, the remaining duration is multiplied by the number of ongoing locations.

$$d^i_{remaining} = \chi_A^{subtask} \frac{(Q - Q_A^i)}{R \times S} \times \sum_{i=1}^{n}, i \in ongoing \tag{4.4}$$

Then the minimum remaining duration is found for the ongoing locations. The procedure jumps to time

t = $\hat{t}$ + min ($d^i_{remaining}$), $i \in ongoing$

The forecast of the produced quantity at that time point for each remaining location is calculated:

$$Q_A^{i\,t} = Q_A^{i\,\hat{t}} + \frac{R \times S \times (t - \hat{t})}{\chi_A^{subtask} \times \sum_{i=1}^{n}}, i \in ongoing \tag{4.5}$$

The procedure continues by starting from time t and removing from consideration all locations which are forecast to be completed at time t. If more than one location is still ongoing, the procedure continues in an iterative fashion, otherwise the procedure finishes using equation (4.3) for the last ongoing location.

4 Calculate the duration forecast for the task parts which have not started

The duration of the not started task parts will use the actual resource consumption of all the ongoing task parts (χ_A^{task}). If no task part has started, the planned durations are used.

$$d^i = \chi_A^{task} \frac{Q}{R \times S} \quad (4.6)$$

4.2.3 Planning the look-ahead schedule by adjusting the forecast

The problems relating to the multi-skilled MEP resources which shared the same resources over multiple tasks prompted the development of the location-based method of look-ahead schedules. Based on the findings of this study, updating the detail plans was not enough to achieve the goals of look-ahead.

In the location-based control system, there is information about the actual productivity, actual resources on site, quantity of work remaining in locations, and preceding and succeeding tasks. The location-based look-ahead begins with an unadjusted forecast which can then be adjusted based on the commitments on resources and production management decisions about prioritization, overtime work, and the start and continuation dates of the tasks.

The look-ahead calculations affect the calculation of the duration forecast. A basic approach is to initialize the look-ahead using the planned resources and formulae (6.1) to (6.6). Look-ahead planning happens by adjusting the forecast resource number or shift length, therefore affecting variables R and S in formulae (6.3) to (6.6). The resource numbers and shift lengths can be changed daily based on subcontractor input. Therefore, the forecast calculations need to be done in an iterative fashion, calculating the remaining duration based on formula (6.3). If the number of resources or shift length change before the end of the remaining duration, the procedure will jump to that date, calculate the work accomplished using formula (6.5), and then calculate the remaining duration using the new number of resources and shift lengths.

Example

In section 4.2.1, an example where two resources were working on two tasks and three locations at the same time was presented. The calculations of the original forecast, the new forecast and the adjusted forecast based on look-ahead are presented below.

The original forecast

Because the two locations have not been finished, the original forecast would use the planned slope for task 2, and half the planned slope for task 1 / locations 1 and 2 (assuming an even split of production). These forecasts are shown with green lines in figure 4-3.

The new, unadjusted forecast

The actual resource consumption of task 1 (χ_A^{task1}) was calculated in the example and was 0.44 manhours / m^2. For task 2, the actual resource consumption was:

$$\chi_A^{task2} = 28.8 \text{ manhours} / 36 \text{ m}^2 = 0.8 \text{ manhours} / \text{m}^2$$

The unadjusted forecast calculates the durations for the ongoing locations first based on the planned resource use (1 resource in each task). When more than one location is ongoing at the same time, the resources are assumed to be evenly split between the locations. The remaining durations for the ongoing locations are (using formula 4.3 for task 2 and formula 4.4 for task 1)

$$d_{remaining}^{task1-location1} = 0.44\frac{(80-48)}{1\times 8}\times 2 = 3.52 \text{ days}$$

$$d_{remaining}^{task1-location2} = 0.44\frac{(120-30)}{1\times 8}\times 2 = 9.9 \text{ days}$$

The minimum of location remaining durations is 3.52 days, so the procedure iterates to time t+3.52 and calculates the remaining duration of location 2 at that point, assuming that the resource released from location 1 goes to work in location 2. This requires the calculation of the forecast at that time point for location 2.

$$Q_A^{task1-location2^{\,t+3.52}} = 30 + \frac{0.5\times 8\times 3.52}{0.44\times 1} = 62 \text{ m}^2$$

In 3.52 days, the location 2 cumulative production should be 62 m^2. Starting from that time point, the resources become available from location 1, and the remaining duration can be calculated based on formula 4.3:

$$d_{remaining}^{task1-location2} = 0.44\frac{(120-62)}{1\times 8} = 3.19 \text{ days}$$

The task 1/location 2 remaining total duration is thus 3.52 days + 3.19 days = 6.71 days.

For task 2/location 1, formula 6.3 can be used:

$$d_{remaining}^{task2-location1} = 0.8\frac{(90-36)}{1\times 8} = 5.4 \text{ days}$$

Finally, the forecast of the not started task 2/location 1 is calculated using the task 2 consumption rate:

$$d^{task\,2-location\,2}_{remaining} = 0.8\frac{(100-0)}{1\times 8} = 12.5 \text{ days}$$

The results are plotted in figure 4-3 using the red color for forecasts. The slope of task 1/location 2 changes at the time point 3.52 days from the current time because of the additional resources. Task 2/location 2 cannot start immediately when location 1 finishes because of the F-S logic between tasks 1 and 2 (refer to Chapter 2 for the start date forecasting principles).

The adjusted forecast

The adjusted forecast is based on the production management decisions which can be modeled as the number of resources working. For example, it might be decided that all of the resources are used to finish location 1 of task 1 first, and then work will continue with an even split between tasks 1 and 2. The resulting forecast would have a faster finish for location 1, task 1, and then a faster than actual progress for location 2 (figure 4-3, black forecasts).

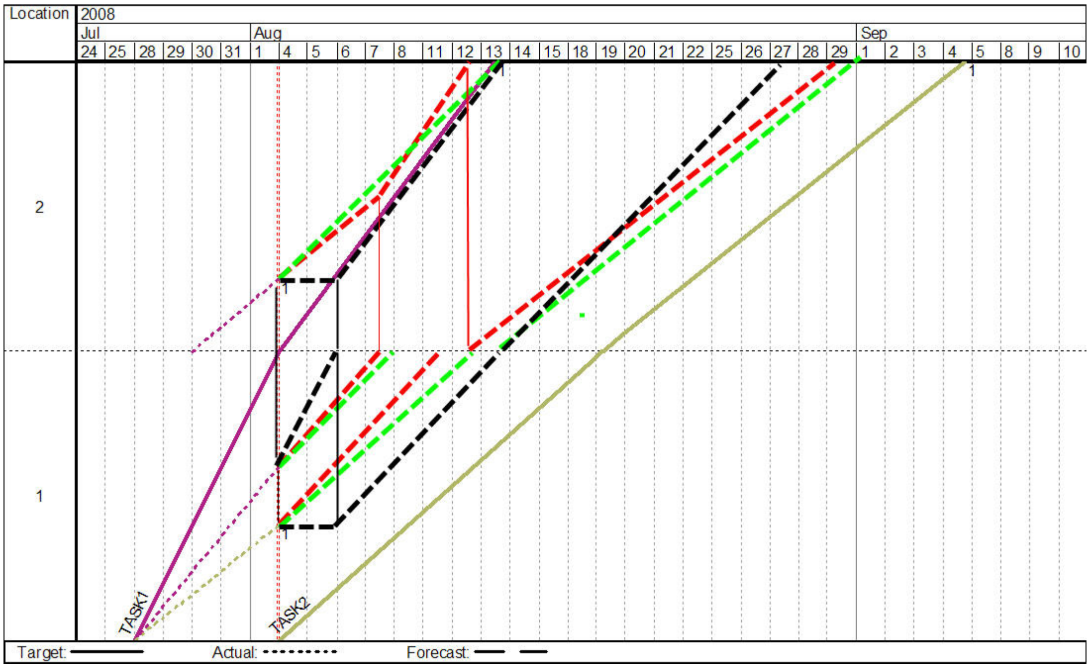


Figure 4-3: Three forecasts with the same progress data. The green forecast is the original, assuming an even split between the locations. The red forecast is the new forecast, assuming that the planned resources are shared between the two locations of the same task. The black forecast takes into account the production management decisions to suspend the two tasks and prioritize task 1 location 1.

4.2.4 Improvements to the alarm system

A central finding in the case studies was that tasks were interfering with each other when they were in the same location, even though they might not have a technical relationship. These tasks could happen in any sequence, but not productively at the same time. These relationships were sometimes added by the planners by deciding which task should be going in first. However, more often than not, these relationships were not added to the schedule. Missing logic was also common in those circumstances where the predecessor is delayed from the original schedule or the successor is started early, or some preceding work has been done out-of-sequence. In these cases, the planner did not think that a dependency would be needed and when circumstances changed, the logic was not added.

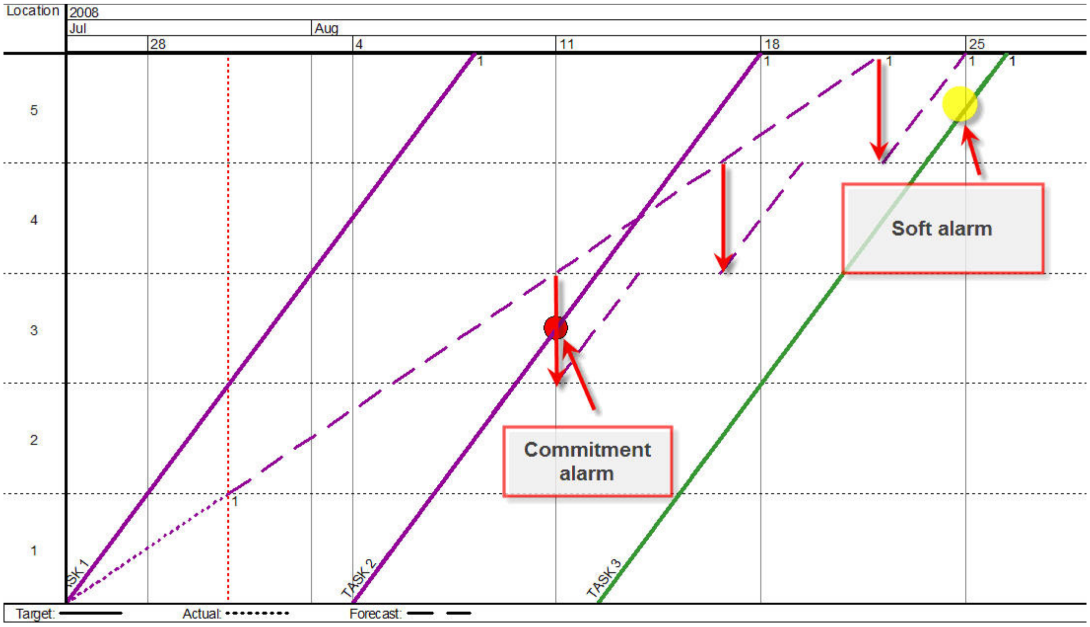


Figure 4-4: A commitment alarm causes a shift of the forecast based on the dependencies. A soft alarm is generated when two tasks happen in the same location without a dependency. In this case, the forecast line of the successor does not shift

To solve these problems, the concept of soft alarms was added to the system. Soft alarms are generated whenever two (or more) detail tasks of different subcontractors are forecast to enter the same location at the same time. Soft alarms do not affect the forecasts in any way; they only indicate potential problems that could happen in the location. It is then possible for the planner to adjust the look-ahead schedule to prevent any interference. Soft alarms can be visualized by using a yellow color (commitment alarms are shown using red). Figure 4-4 illustrates both the commitment and soft alarms. Task 1 is delayed and causes Task 2 to be delayed from its committed start date. This delay causes task 2 to be delayed, so that it will enter location 5 at the same time as task 3, causing a soft alarm.

4.3 Improved production planning and control processes

4.3.1 Progress data

Progress data is critical for calculating an accurate forecast, and to be able to perform look-ahead planning based on historical trends. All of the case studies had at least some problems with the progress data. In many cases, the production status was not updated for many weeks, so it was not possible to know if the work was ongoing, or if it had been suspended. The project engineers were responsible for collecting the actual data, and they often assumed the completion rates of work in a location to be higher than they actually were. This led to 95 % complete locations, and then very slow progress for the last 5 %. A notable exception to this was the Prisma case study, where the project engineer got the status and look-ahead information directly from the subcontractors. Using this process contributed to having less problems with the progress data. The actual resource use was not collected or allocated to the tasks which caused problems with calculating the actual productivity and forecasting.

Based on the good results of the Prisma project, it seems that the best way to organize progress data collection is to distribute the responsibility to the subcontractors and superintendents. They should report each week the status of each task in each location, giving the actual start date, the actual finish date, and the percentage completed if the location is not completely finished. If there is no change in the completion rate from week to week, it may be assumed that the work in the location is suspended. This information can then be checked weekly by the project engineer or the site manager by walking through the site and checking the progress against the subcontractor reports. Additionally, the subcontractors should report the average actual resources on site each week.

4.3.2 The use of forecasts and alarms

Although the forecasting and early warning of production problems are critical parts of the location-based controlling system, there was little evidence of their actual use in the case studies. The alarms prompted corrective action in some cases, especially when an alarm was given much earlier than the anticipated problem. The reasons for not using the forecast information may partly result from the problems in the forecast itself, and partly because the project management did not have guidelines for how the forecast should be used in management.

The unadjusted schedule forecasts assume that production will continue with the actual productivity using the planned resources. Forecasts and alarms should be used as an early warning system to show any potential problems if production continues without changes. If the forecasts deviate from the commitments, the control action process should be triggered to get production back on track. A possible process for doing this is to print out simple flowline diagrams with the problem task and immediately succeeding tasks visible, and to arrange a meeting with the responsible subcontractors to find out what can be done to prevent the problem before it happens.

There are some less important deviations which can be followed for a time before starting the control action process. For example, tasks can often have starting difficulties which can not be expected to continue for the duration of task. For this reason, the forecast can look very pessimistic at the beginning of production. If there is no immediate consequence of a delay, it is possible to follow the situation closely for some time before triggering the control action process.

Some tasks may be delayed without causing problems to any other tasks. Schedule deviation is critical only if it directly threatens the end date or a milestone date, or if it causes a production problem to another subcontractor signified by an alarm. The time to the next production problem may be used for prioritizing the control actions.

The forecast is always based on the assumption of resources. The resources should be explicitly discussed with the subcontractors on a weekly basis to compare the amount of resources subcontractors are actually going to have on site to the assumptions in the forecast. If there is a difference, either the subcontractor behavior needs to change, or the forecast needs to be adjusted. If this validation is not done, the forecasts may be over-optimistic and fail to correctly predict the production problems.

4.3.3 Look-ahead planning and control action planning using the forecast

Look-ahead planning in the location-based controlling system adjusts the forecasts based on the accurate information about the available resources, assuming that productivity continues at the same level. Look-ahead planning should be done together with the subcontractors to make sure that the plans can be actually carried out. Look-ahead planning aims to change the forecasts so that any forecast production problems are completely eliminated, or at least minimized. This can be achieved by increasing or decreasing the resources, allocating resources differently between tasks, suspending tasks, expediting or delaying start dates, working on holidays or weekends, working longer hours, or focusing management attention to increase the productivity of the task.

For any suspended tasks, look-ahead planning includes planning and committing to the continuation date. Because look-ahead planning operates on the forecast, commitments made in the detail task planning phase are not affected. Therefore, the role of look-ahead planning is to find feasible control actions to get back to the original commitments and to prevent production problems on site. Because look-ahead planning uses the actual productivities and the quantity remaining is known, it will automatically result in correctly sized assignments for the weekly plans. The goal is to further enhance the weekly plan reliability by sizing the assignments correctly, and by minimizing production problems by adjusting the forecast so that the production system alarms are minimized.

These new additions to look-ahead planning should be considered additional tools in addition to those previously defined in the Last Planner literature. Look-ahead planning must also include checking the starting prerequisites of any locations which have not started and delaying the start dates of locations which cannot be made ready on time (Ballard & Howell 1998, Ballard 2000).

4.3.4 Weekly planning

After the look-ahead plan has been updated and approved, the weekly plan assignments can be initialized from the look-ahead plan of the next week. The look-ahead plan operates on the location level of detail. The weekly plan assignments are initialized by evaluating the forecast percentage of completion or quantity at the end of the weekly planning period for each location. This gives a target quantity or completion rate for all ongoing tasks and locations. To achieve the criteria of sound assignments (Ballard 2000), the weekly plan assignments often need more detail. For example, the location-based forecast may show that using the planned resources, the production of drywall will be 70 % complete after the next week. In the weekly planning process, the actual walls to be built may be specified in the drawings to make it easier to confirm that the assignment has been completed.

If workers do not commit to weekly plan assignments, this information needs to feed back to the look-ahead planning process to see how much more needs to be produced in the following weeks. The reasons for not committing should be recorded to find out which assumptions of the look-ahead were incorrect. For example, the work could be more difficult than previously, resulting in a lower production rate with the same resources. This information is valuable, because it affects the actions that need to be taken in the future to prevent further such problems. The look-ahead of the next week should be adjusted to correspond with the weekly plan commitments.

4.4 Summary

This chapter has presented the improvements both to the production control system and to the production control process. The main changes to the production control system include the changes in the forecasting and alarm systems. The new forecast is able to take into account the production management decisions about task prioritization, resource use, and the start dates and continuation dates. The new alarm system is able to generate alarms also when there is no explicit dependency in the system. To facilitate these systems, the actual resources were changed to be the properties of the subcontractor instead of being properties of the task and location.

Process improvements were proposed for gathering the progress data and using the alarms and forecasts as management tools. Look-ahead planning in a location-based context was defined as updating the forecast based on the available information. This look-ahead can then be used to generate the weekly plans. The weekly planning is integrated into the system to function as a check of the look-ahead – if the workers do not commit to the production of the adjusted forecast, there may be need for further changes to the forecast.

In the next chapter, the new production control system and process are tested and validated.

5 Tests of the new production control system

5.1 Introduction

This chapter tests the new production control system and process from three points of view:

1 The functionality of the alarm system
2 Explaining cascading delays and their reasons
3 Integration of weekly planning to the location-based process

The functionality of the alarm system was tested by choosing random examples from the original case studies where the original alarm system failed to generate an alarm, or gave a delayed alarm. The tests were carried out using the same data. However, an assumption was made that the new process was followed, and therefore, better data about suspensions and completion rates were available. The new alarm system performs better if it creates alarms in cases where the previous system did not, and if alarms can be generated at least three weeks before the problem occurs.

Chapter 3 presented hypotheses about the reasons for cascading delays (refer to section 3.9.1). Specifically, the analysis indicated that slowdowns and discontinuities tended to cascade, especially in the finishes and MEP stage. An analysis of the resource use also showed that the resources may have been a contributing factor in initiating these cascading delay chains. In this chapter, additional validation is sought for these cascading event chains by following the delay chains of randomly chosen problems in each case study and establishing their reasons.

Finally, the performance of weekly planning based on the forecasts adjusted with the forecast information was evaluated by comparing the same time period with the same progress data in both systems. The original PPC was compared to the PPC based on the assignments calculated based on the adjusted forecast.

The description of each test starts with an introduction of the test and the method used. The results are then summarized, and more detailed examples are presented. Finally, a conclusion of the results of the test is presented.

5.2 Performance of the alarm system

5.2.1 Introduction

Cascading production problems were shown to be key issues affecting the reliability of the plans on all levels: the weekly, detail and baseline plans. The case studies showed evidence of control actions, which successfully prevented cascading problems, when alarms were given. The probability of a control action increased if the alarm system generated an alarm ten days or more before the problem. Based on the information about the reasons for delayed or missing alarms, the new systems for generating forecasts and alarms and the new processes for using them were developed in Chapter 4. These systems and processes are tested here by taking a sample of production problems where the original production control system and process failed to generate an alarm or generated one too late. The new production control system and process work better if they generate more valid alarms, and earlier, than by using the original system.

5.2.2 Method

The performance of the alarm system was examined by looking at randomly selected cases of each identified problem type. Delayed alarms caused by last-minute changes of plan were not analyzed, because they are more a process issue than an alarm system issue. At least one problem of each type was selected from each case study to ensure generalizability. The random selection was done by sorting the production problems of each case study by problem type and then using the Rand() function in Excel to generate random numbers between 1 and the total number of cases in that problem type. A total of 30 problems were analyzed.

A complete set of progress data for both tasks relating to the problem, and all tasks which caused problems to either one of the tasks was entered to the beta version of Control 2009 software, which implements the new forecasting system described in Chapter 4. If the original progress data contained mistakes, which were corrected later in the analysis, those corrections were assumed to be available on time. For example, the suspended tasks and completion rates were assumed to be available. Because of the cascading nature of the problems, this method resulted in replicating almost all the data in the original files to the new format. Because the forecast also uses the information of the detail plans, those plans were copied exactly to the new format for each week. The end result was one file for each week in each case project, concentrating on the finishes and MEP phases. The original files did not have the actual resource information. This information was entered for each subcontractor based on subcontractor meeting memos assuming that the reported number of resources was working on each day of the week. The forecasting assumption for the future weeks was that the same amount of resources would continue working on each ongoing task. New resources would be mobilized according to the plans for the new tasks only if the subcontractor actually mobilized new resources in the next week, or if some other task was finished.

For each randomly selected problem to be analyzed, the situation was first evaluated using the progress data from three weeks before. If an alarm did not happen at that point, the analysis moved one week closer to the problem until an alarm was generated, or until the problem happened. For each case, a short description of whether an alarm was generated, and how much earlier the alarm was generated, was recorded. Interesting cases were documented in more detail for further analysis.

5.2.3 Results

The new alarm system was able to generate an alarm for all except one of the evaluated cases with the missing alarms in the original alarm system (categories 1-3 in Figure 5-1). The alarm system was able to generate alarms earlier in many cases.

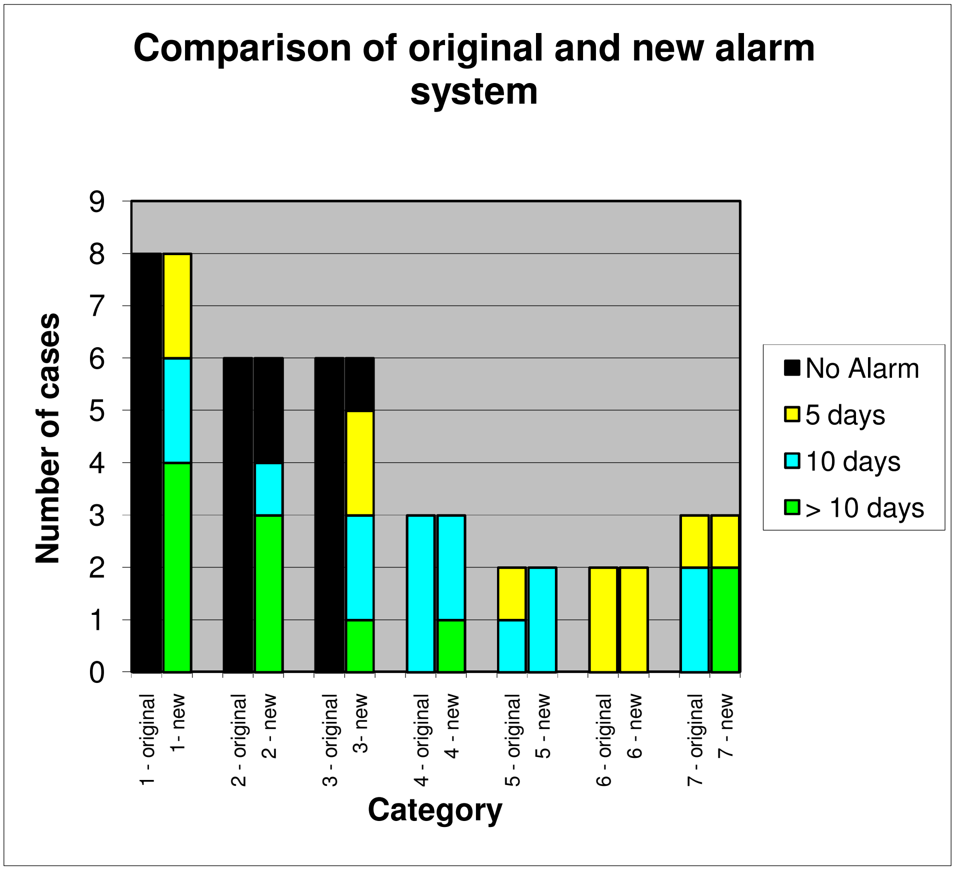


Figure 5-1: Comparison of the original and the new alarm system. The categories are 1- Many tasks in the same location 2 – Missing dependency 3 – Not at the same time in the same location 4 – Start-up delay in the first location 5 – Sudden slowdown of a predecessor 6 – Preceding task discontinuous and 7 – Forecast over-optimistic

Of the 30 examined cases, the original alarm system was able to give an alarm in 33% of cases. The new alarm system was able to give an alarm in 90 % of cases. In the cases where alarm was generated, it was given 10 days before the problem in 60% of cases, and 5 days before the problem in 40 % of cases with the original alarm system. With the new alarm system, alarms were generated over 10 days before the problem in 41 % of cases, 10 days before the alarm in 33% of cases, and 5 days before the alarm in 26 % of cases. These results show that the new alarm system is able to give more alarms earlier than the original alarm system.

Having look-ahead information available about the resource availability of future weeks and the start and continuation prerequisites of tasks would have improved the situation in many cases. The results in Figure 5-1 assume only a small amount of additional information compared to what was available in the original production control system (refer to Methods). If the additional process steps of the systematic screening of prerequisites and discussions about resource availability had been implemented, many alarms could have been given earlier. Figure 5-2 shows the results assuming that the resource availability of the next two weeks, the new starting tasks in the next two weeks and any currently suspended, continuing tasks in the next two weeks were accurately known. The figure compares the results of the additional information to the results of the new alarm system without any additional information.

With the additional information, one new alarm could be generated; raising the alarm percentage to 93% (previously 90%). In many cases, alarms could be given earlier. The proportion of alarms given over 10 days before a problem increased to 57 % (previously 41 %). 25 % of alarms were given 10 days before (previously 33%) and 18 % of alarms were given 5 days before (previously 26%). These results show that additional information from better communication with subcontractors would have revealed more problems over 2 weeks before they happened, allowing enough time for them to react.

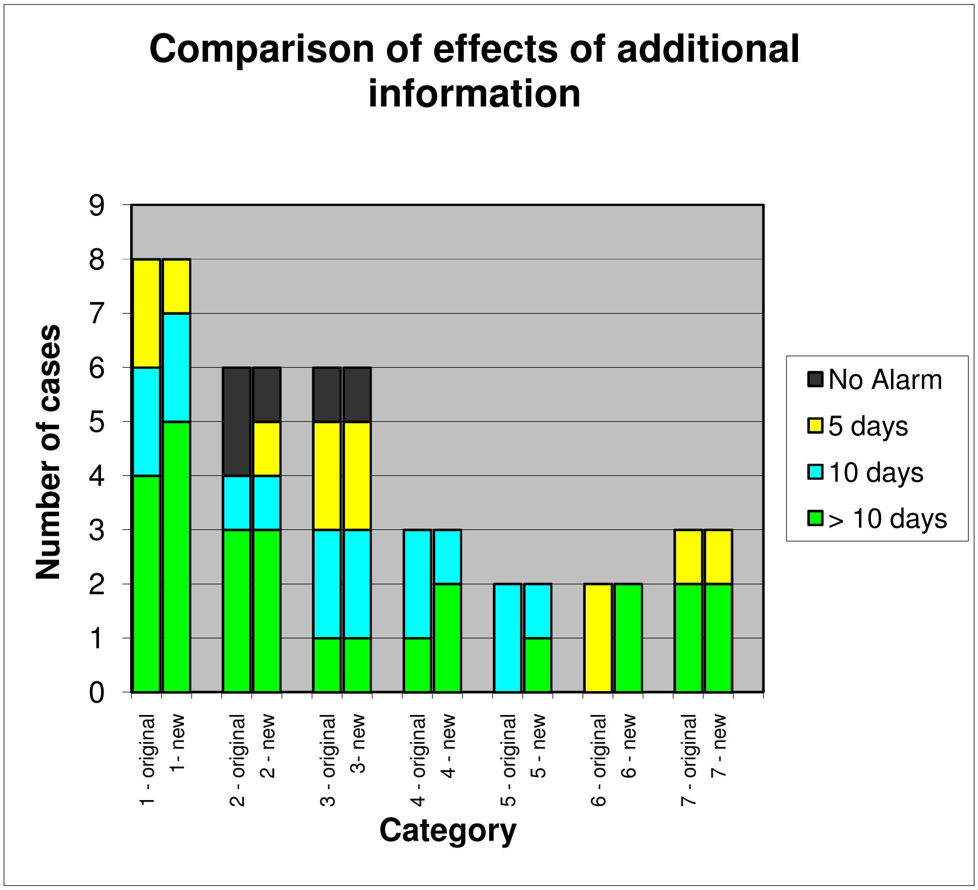


Figure 5-2: A comparison of the original and new information in the alarm system. Categories are 1- Many tasks in the same location 2 – Missing dependency 3 – Not at the same time in the same location 4 – Start-up delay in the first location 5 – Sudden slowdown of a predecessor 6 – Preceding task discontinuous and 7 – Forecast over-optimistic

5.2.4 Examples

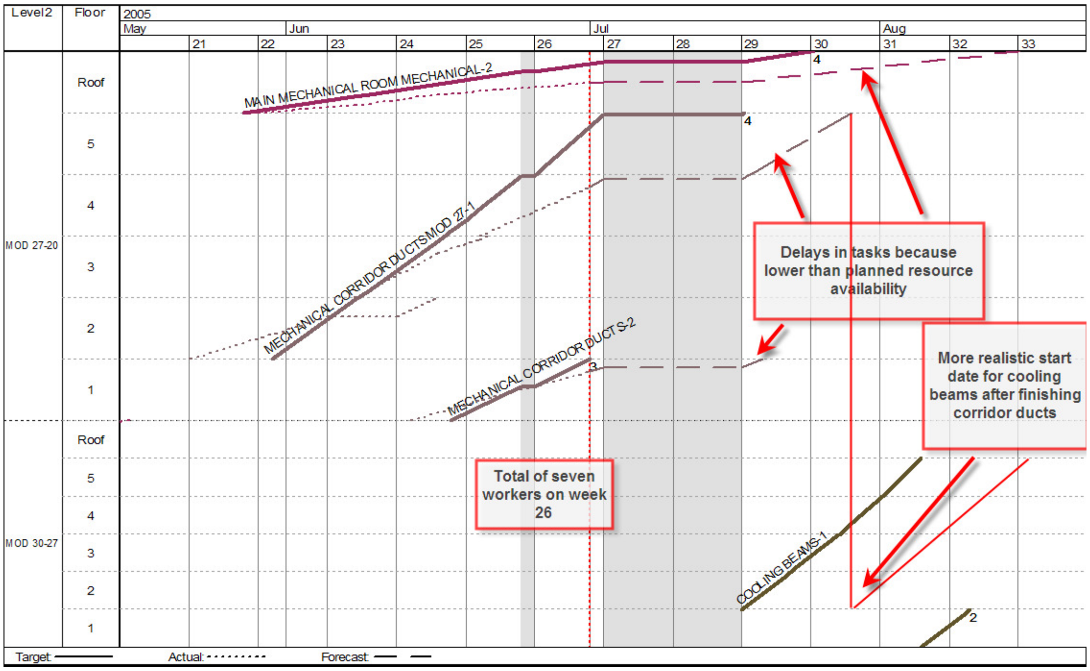
This section describes some examples in more detail.

Example 1: Resource information generates earlier alarms

Problem: Cooling beams – Cooling beam connections (Opus week 32)

This problem could have been known earlier if the resource use was discussed and updated to the forecast weekly. On week 26, all of the workers of the mechanical subcontractor were working in the main mechanical room and installing ducts in the critical second section. By using this resource information it would have been possible to know that the cooling beams could not be started without mobilizing additional resources and revising the commitment to the plumbing contractor (cooling beam connections) accordingly.

Figure 5-3 shows the ongoing tasks of the mechanical contractor and the new starting cooling beam task. The small numbers on the top location of each line show the planned manpower. Seven people were actually working in week 26 (the total of planned resources equals ten). Starting the cooling beams would require the mobilization of two additional men. Actually, the mechanical contractor was not going to increase the manpower (the actual manpower on week 29 was 6). Based on this, it is possible to know that either one of currently ongoing tasks was going to slow down below the forecast or the cooling beams would not start in week 29. More probably, the start date would be after the corridor ducts were finished in the other section, in week 31. By discussing the resource information weekly with each subcontractor, and getting commitments on resource use, an alarm could have been given three weeks before the problem.



Delays in tasks because lower than planned resource availability

More realistic start date for cooling beams after finishing corridor ducts

Total of seven workers on week 26

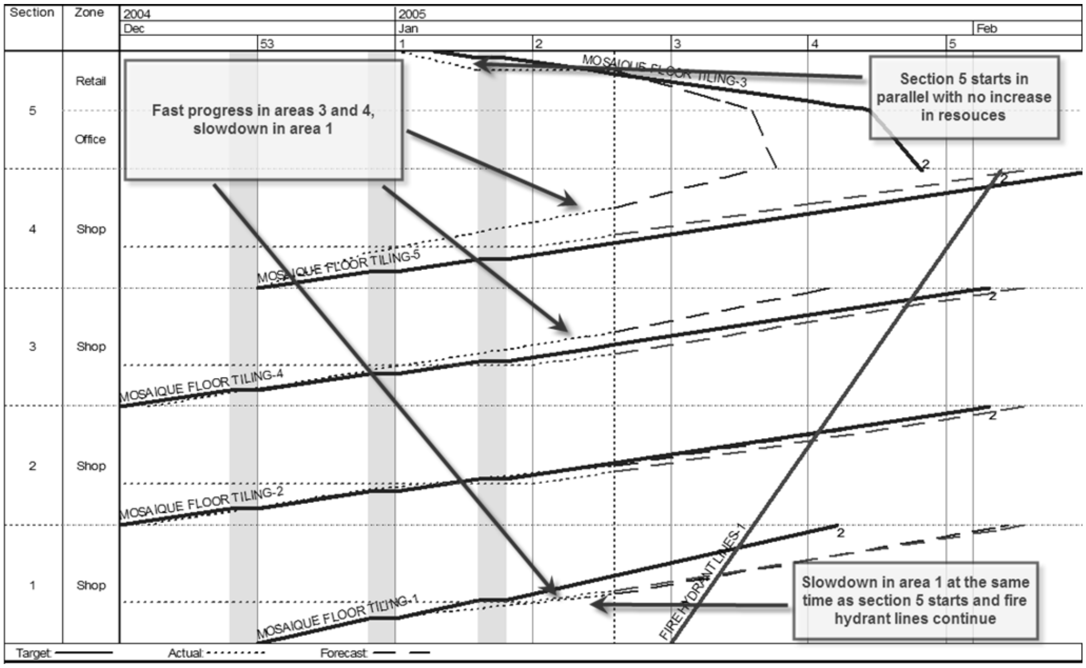
Figure 5-3: By considering the resource use and status of other tasks it would have been possible to know that the cooling beams would probably have a start date delay unless new resources were mobilized

Without considering the resource use, and by only using the information available to the original alarm system, an alarm could not be generated before the start date delay actually happened.

Example 2: Starting new locations without mobilizing new resources

Problem: Mosaic floor tiling – Plasterboard walls (Prisma, week 4) (figure 5-4)

In this case, it was not known by the production control system that section 1 would slow down. The slowdown may have happened because the mosaic floor started also on section 5, and the resources were not increased, or because the fire hydrant lines, which had been suspended previously, were continued. Even though an alarm could not be generated with the information that was available in the production control system, a discussion about the resources with the subcontractors would have shown that starting in area 5 would require the shifting of resources from one of the ongoing areas. It would then have been possible to choose which area to slow down, and by adjusting the forecast correspondingly, an alarm could have been generated earlier. Without this information, both the original and new alarm system generated the alarm just one week before the problem.



Fast progress in areas 3 and 4, slowdown in area 1

Section 5 starts in parallel with no increase in resouces

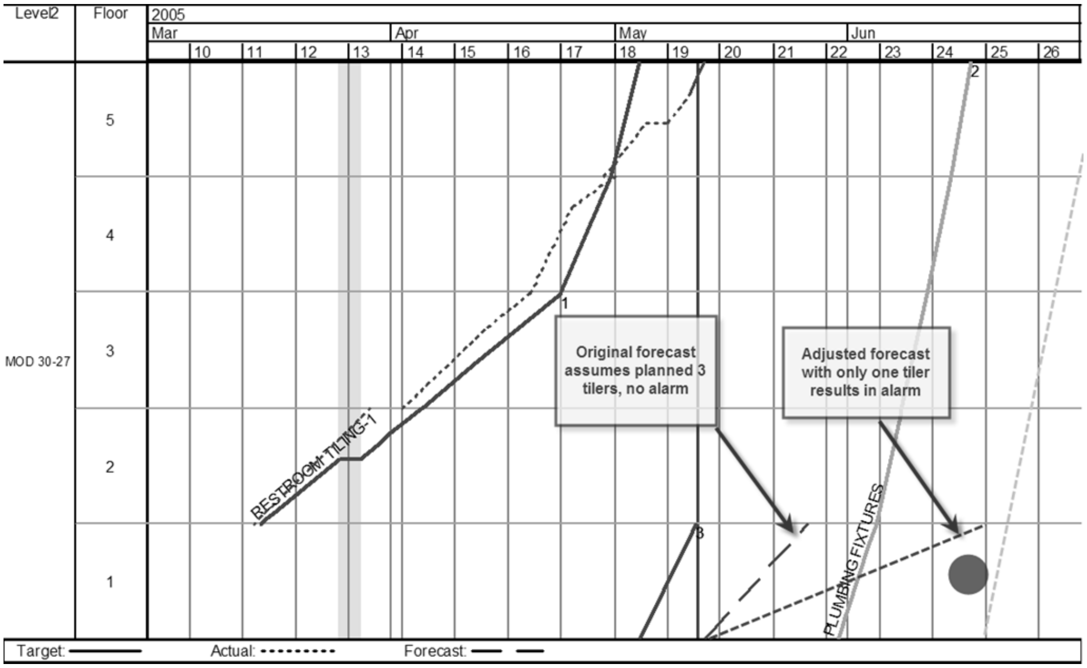
Slowdown in area 1 at the same time as section 5 starts and fire hydrant lines continue

Figure 5-4: The mosaic floor tiling task goes fast in some areas and slowly in area 1. The slowdown corresponds with the continuation of the fire hydrant lines and the starting of the mosaic floor tiling in area 5 without mobilizing new resources

Example 3: The tiling subcontractor decreases resources

Problem: Restroom tiling – Plumbing fixtures (Opus, week 22) (figure 5-5)

The original forecast system could not adjust the forecast dynamically when locations were ongoing. Therefore, an alarm was not generated until the problem happened in week 22. The new forecast system generated an alarm one week earlier, based on the same information. The alarm could have been generated already two weeks earlier, in week 19, if it had been known that only one tiler would be available. Figure 5-5 shows the forecast in week 19, assuming three tilers and assuming one tiler. If the resource availability had been discussed, it would have been known that the tiling would finish in week 24 (forecast with one tiler and actual finish week) and the plumbing fixture commitment could have been updated earlier, or new resources could have been added to the tiling task to prevent the problem.



Original forecast assumes planned 3 tilers, no alarm

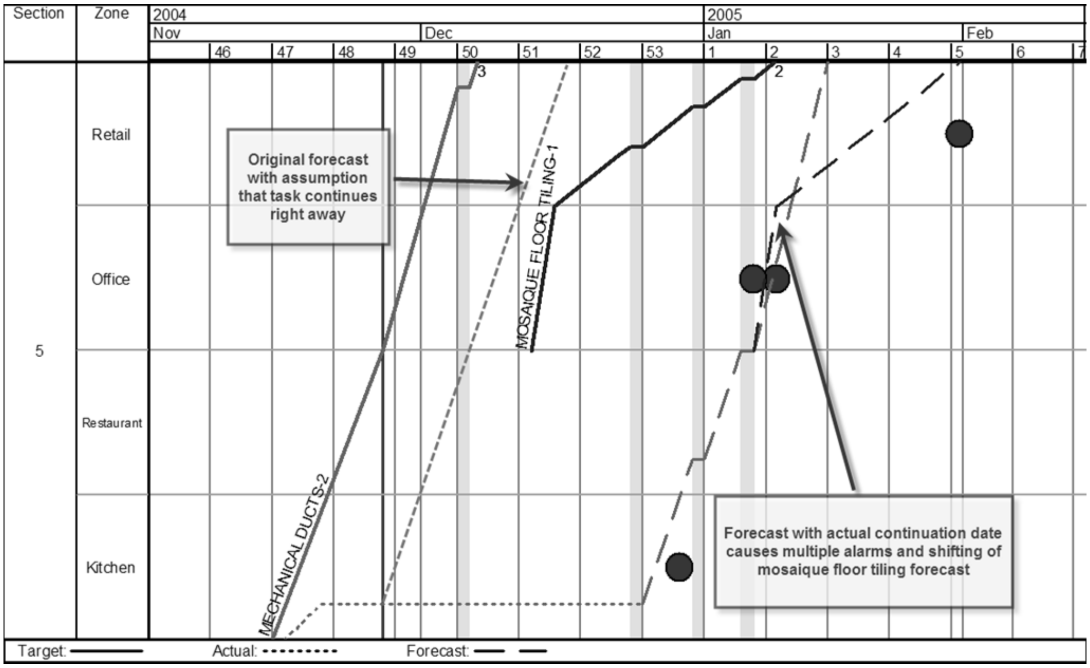
Adjusted forecast with only one tiler results in alarm

Figure 5-5: Adjusting forecasts with look-ahead resource information resulted in earlier alarms

Example 4: Decision about the continuation date results in an earlier alarm

Problem: Mechanical ducts – mosaic floor tiling (Prisma, week 51)

The original production control system gave an alarm in week 51 when it was too late and the mosaic floor tiling had to be delayed. Figure 5-6 shows the status in week 48. The original forecast assumed the continuation of the suspended mechanical ducts tasks right away, which did not result in an alarm. If the continuation date had been decided and entered into the system, the alarm would have been generated three weeks before the problem. In this case, the continuation date was known by the management, because the meeting minutes indicated that the mechanical ducts would continue after the concrete pours. If the production management had known the results of this decision, it could have been reconsidered or its effects mitigated. It will be shown in a test of the cascading production problems that this decision actually started a cascading chain of production problems which continued until the end of the project.



Original forecast with assumption that task continues right away

Forecast with actual continuation date causes multiple alarms and shifting of mosaique floor tiling forecast

Figure 5-6: Taking into account the continuation date of the mechanical ducts results in the earlier alarm.

5.2.5 Summary of the test results

The results of the alarm tests show that the new alarm system performed better than the original alarm system. It was able to correctly create alarm about issues which did not have an alarm in the original system and was able to create alarms earlier using the information available to the project team. Further improvements were shown to be possible if additional look-ahead information about the resources, the start dates of upcoming tasks and the continuation dates of any suspended tasks were entered. This requires a change of process to systematically discuss and commit to the resources and prerequisites of starting and continuing tasks.

5.3 Cascading problems and resource use

5.3.1 Introduction

In all case studies there was correlative evidence of cascading problems in the interior and MEP phases. Based on the unleveled resource profiles, a hypothesis was made that many of those problems were caused by the inability of subcontractors to quickly adjust their workforce on site based on the production requirements. This section examines one chain of cascading problems in each project and examines in more detail each production problem. The goal is to find out how many problems are internal to the model – task interference, working out-of-sequence, or resource issues; and how many problems were external to the model – starting prerequisites, procurement, and the design.

5.3.2 Method

One problem in the interior construction phase was randomly selected from each case study, and the complete chain of problems leading to and following that problem was analyzed. The random selection was done by using a numbered list of problems and Microsoft Excel's Rand() function to choose a random number between 1 and the total problem count. If the selected problem was part of a phase other than interior or MEP, a new random selection was done.

A production problem always includes two tasks: predecessor and successor tasks. These tasks were used as a starting point. All the problems relating to either the predecessor or successor task were then selected. All the new tasks relating to those problems were added to the analysis. The same method was continued for these tasks until no more tasks were found. Then, all the production problems belonging to the same chain were sorted by start date. A Flowline figure with only the tasks relating to the production problem was created. Each problem was analyzed in turn using the evidence available from the production meeting minutes, resource use, direct observation notes, and other production problems active at the same time. This evidence was used to find out the root causes of the problems.

Finally, the detail plan for one week before the start of the cascading problem chain was compared to the actual progress to find out the overall effect of delay chain for each task in the chain and the finish date of the last task in the chain.

5.3.3 Cascading problems in Prisma

5.3.3.1 Description of the cascading problem chain

In Prisma, a problem at the end of the project between the system cabling and the suspended ceiling frames was selected for analysis. The chain of problems leading to this problem started at the beginning of the interior phase when the mechanical ducts were delayed. Figure 5-7 shows a Flowline figure with the numbered red circles denoting problems. Only the tasks which are included in the chain of events are shown. Many other tasks were happening in each location, and the figure does not show the shop hall which had its own problems.

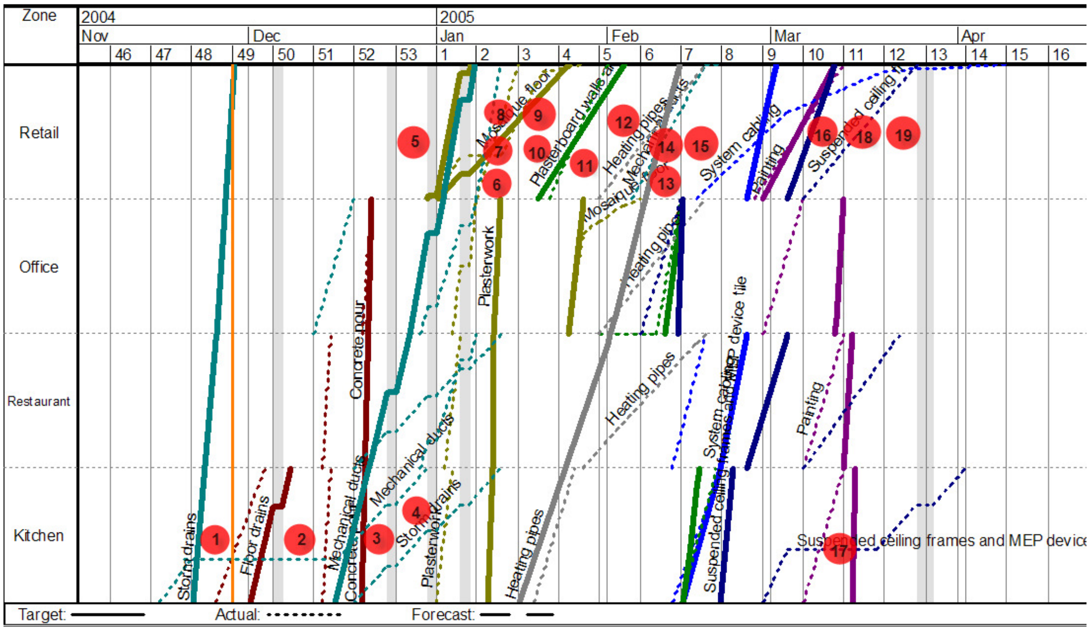


Figure 5-7: The problems in Prisma which led to problems between the suspended ceilings and the system cabling

The problems show an interesting pattern. They started from the first location in the Kitchen, and then jump up to the last location in Retail. The retail area had a high concentration of problems. The problems are described below in chronological sequence. The problem numbers below refer to the numbered circles in the Flowline diagram of figure 5-7.

Problem 1: The mechanical ducts were suspended because of the floor drains. The initial plan was to finish the mechanical ducts first. However, the mechanical duct installation in the shop hall was being done at the same time. It seems that the root cause of delay and suspension was a sharing of resources and wrong prioritization.

Problem 2: The production meeting minutes stated that the mechanical ducts would be continued after the concrete pours. As a result, the mechanical ducts continued to be suspended and the mechanical contractor had to demobilize.

Problem 3: The storm drains and mechanical ducts entered the same locations at the same time slowing each other down. The root cause of this problem seems to be a combination of the resource issue of the plumbing contractor, and the decision to continue to suspend the mechanical ducts until the floor pours (problem 2). The storm drains should have been finished before the mechanical ducts, but the plumbing subcontractor was working in the shop hall and did not have enough resources for section 5. This lack of resources was mentioned in the meeting minutes between the General Contractor and the subcontractor. At the same time, the sprinkler contractor entered the location according to their original schedule and they also suffered slowdowns (not shown in figure to decrease clutter)

Problem 4: The storm drain, mechanical duct, and sprinkler slowdowns continued. This was a continuation of problem 3.

Problem 5: The heating pipes task should have started before the mechanical ducts in the retail area. It did not start because it would not have had time to finish before the planned start of the mosaic floors.

Problems 6, 7 and 8: The mosaic floors were suspended when the plasterwork, storm drains, and sprinkler (not shown in figure) entered the retail location.

Problems 9 and 10: The delay of the mosaic floor (problems 6,7 and 8) delayed the start date of the plasterboard walls and the continuation date of the mechanical ducts

Problem 11: The plasterboard walls prevented the mechanical ducts from starting in the location. Previously, the plasterboard walls were delayed by problem 9.

Problem 12: The heating pipe task entered the retail spaces ahead of schedule, the mechanical duct continuation was delayed.

Problems 13 and 14: The installation of the mechanical ducts was slow (possibly because of the simultaneous installation of the heating pipes in the same location). The painting was originally planned to start in the retail spaces in this week, but had a start-up delay, possibly caused by the delays of the mechanical ducts and heating pipes.

Problem 15: The painting could not start in week 7, possibly because of the delays of the mechanical ducts.

Problem 16: The suspended ceiling frames started out-of-sequence in the retail spaces and this resulted in the slowdown of the system cabling. The root cause for starting the suspended ceilings out-of-sequence before completing the other locations is that the painting caused the suspension of the suspended ceiling frames in the kitchen (problem 17)

Problem 17: The painting started in the kitchen and resulted in the suspension of the installation of the suspended ceiling frames. The painting should have been finished a lot earlier, but was earlier delayed by the mechanical ducts and heating pipes (problems 14 and 15)

Problems 18 and 19: The simultaneous production of the system cabling and suspended ceilings cause slowdowns to the system cabling. This is a continuation of problem 16.

5.3.3.2 Analysis of resource issues relating to the cascading problem chain

The previous description of the problems shows that most of the issues could be related to the other problems. The original root causes of the problem series were the resource issues of the plumbing contractor and the mechanical contractor resulting in the delays of the mechanical ducts and storm drains. These resource issues are illustrated in figure 5-8, which shows all the tasks of the plumbing and mechanical contractors between weeks 47 and 53. For clarity, only one section in the shop is shown because progress in each shop section was the same. The small numbers below the timeline show the number of plumbers on site. The arrows show the assumed movement of the plumbers from task to task based on the progress data.

The storm drains started much slower than planned because the original plan would have required 5 plumbers, and the subcontractor provided two. The storm drains were suspended while the floor sewers were being done in the kitchen, and continued only after one more plumber was mobilized. All the plumbers switched to the floor drains task which was a prerequisite of pouring the concrete floor which was prioritized by the production management. The floor drains were done before their planned start date and were the cause of the suspension of the mechanical work in section 5 (this also led to the complete demobilization of the mechanical subcontractor). After the floor drains were completed, all the resources moved to install the floor sewers in the office and retail areas. The floor sewers were suspended when the floor heating was installed (a prerequisite of the concrete pours, again prioritized by the management). After finishing the floor heating, part of the resources moved to the storm drains in the office and the rest continued floor sewers in the retail area (note the slower production rate of the floor sewers because less resources were working there). After these tasks and locations were finished, the storm drains started in the kitchen and started causing problems to the mechanical ducts and the problem series that continued to the end of project.

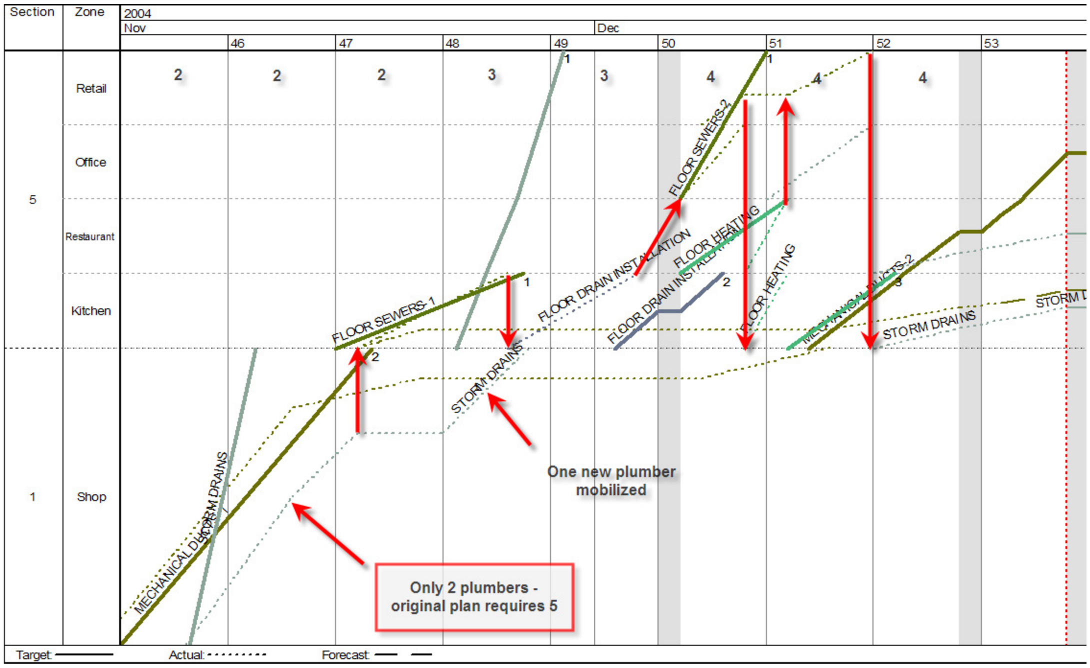


Figure 5-8: The plumbing and mechanical contractors resource use. The small numbers below the calendar weeks show the number of plumbers on site.

5.3.3.3 The effects of the cascading problem chain on schedule reliability

The actual progress was compared to the detail plan in week 46, one week before the first problem in the cascading delay chain. Most of the tasks were delayed by 3-5 weeks (table 5-1). The last tasks in the analysis finished at the same time as the building was handed over to the Owner (week 14/2005). Most of the tasks suffered unplanned discontinuities. Note that the tasks prioritized by management – the concrete pours, floor drains, mosaic floors, plasterboard walls and painting, typically have the same start-up delays and finish delays; indicating that the original durations were achieved with few discontinuities. Other tasks; such as the mechanical ducts, heating pipes and system cabling have longer durations or more discontinuities.

Table 5-1: A comparison of the start and finish weeks between the planned and actual for the tasks involved in the cascading delay chain

Task	Planned (actual) start week	Planned (actual) finish week	Start-up delay (weeks)	Finish delay (weeks)	Planned (actual) discontinuities
Mechanical ducts	47/2004 (47/2004)	50/2004 (7/2005)	0	10	0 (2)
Floor drains	49/2004 (48/2004)	50/2004 (49/2004)	-1	-1	0 (0)
Concrete pours	50/2004 (51/2004)	52/2004 (52/2004)	1	0	2 (1)
Mosaic floor	51/2004 (1/2005)	2/2005 (5/2005)	3	3	0 (1)
Heating pipes	52/2004 (3/2005)	2/2005 (7/2005)	4	5	0 (0)
Plasterboard walls	53/2004 (3/2005)	2/2005 (6/2005)	4	4	0 (0)
System cabling	1/2005 (6/2005)	4/2005 (14/2005)	5	10	0 (0)
Suspended ceiling frames	3/2005 (6/2005)	5/2005 (13/2005)	3	8	0 (1)
Painting	5/2005 (8/2005)	7/2005 (10/2005)	3	3	0 (0)

5.3.4 Cascading problems in Glomson

5.3.4.1 A description of the cascading problem chain

In Glomson, the problem between the mechanical room plumbing and the mechanical room electrical work in week 20 was randomly chosen for analysis. The mechanical rooms had cascading production problems in all of the projects. In this case, the problem chain was isolated within the mechanical room, because the start date of the mechanical room installation was defined by the procurement of machinery and the completion of the design, instead of the preceding production task.

This is a good example of cascading problems in a confined space. There are production problems every week after the trades start to work at the same time (figure 5-9). The mechanical contractor achieved the planned production rate only when the other trades were not working at the same time in the same location. The sprinkler contractor was able to achieve the planned production rate, but had numerous start-up delays in the mechanical room (the original planned start date was week 19).

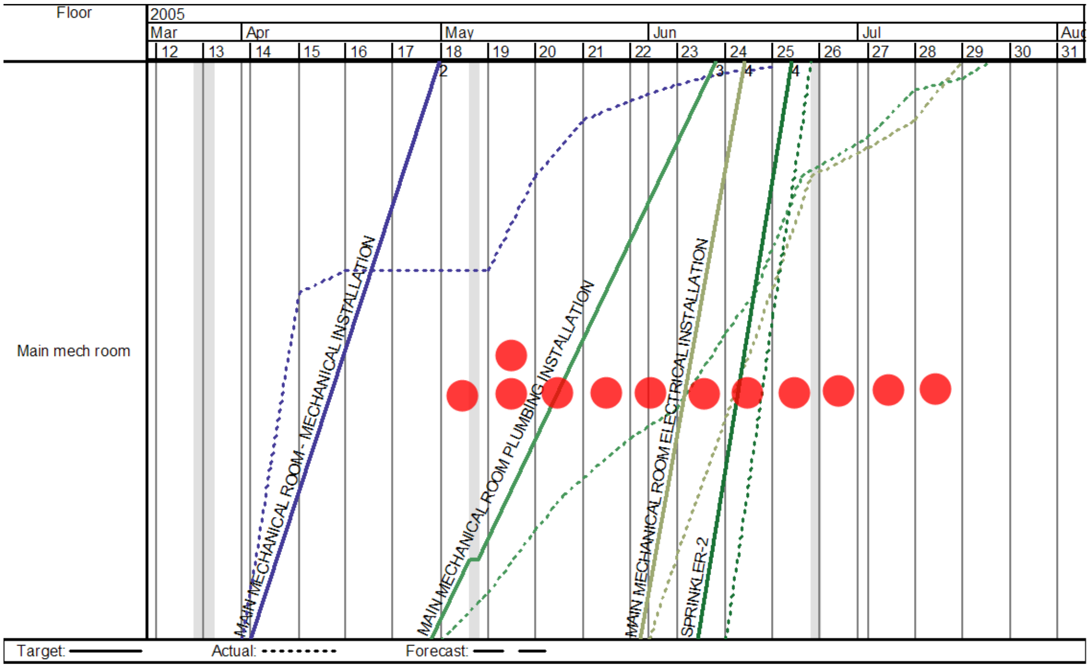


Figure 5-9: The cascading problem chain in the Glomson main mechanical room

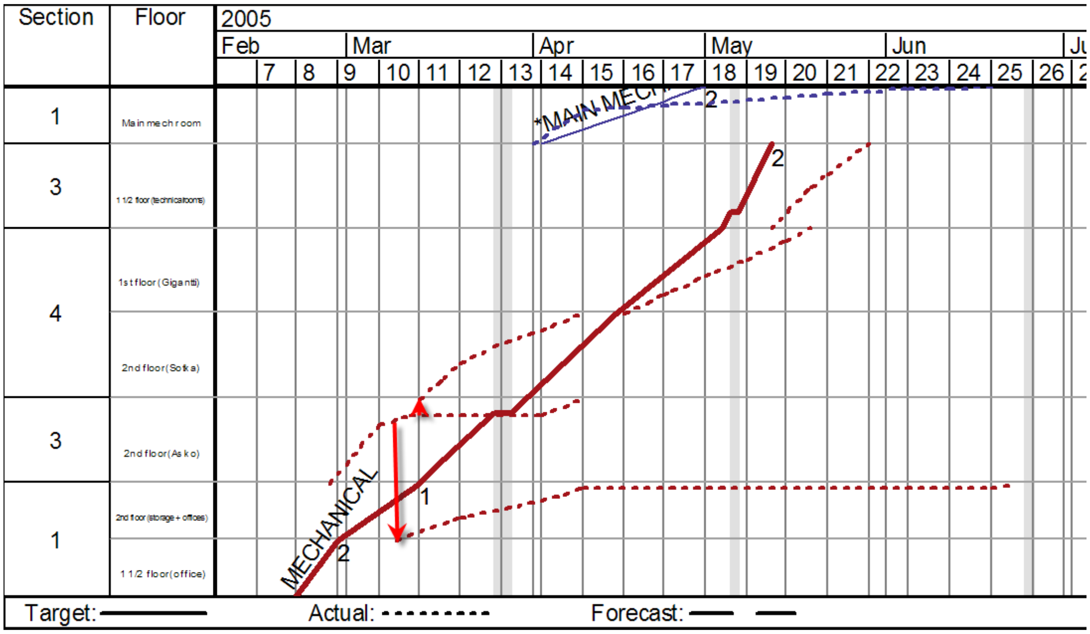


Figure 5-10 The work of the mechanical contractor in Glomson. The blue line in the top location is the Main mechanical room. Work is suspended when work is ongoing in Section 4, 1st floor

5.3.4.2 An analysis of the resource issues relating to the cascading problem chain

The cascading problems are clearly started by the suspension of the mechanical work between weeks 16 and 18. The mechanical contractor had a level resource use of two men for the entire duration of their contract. Between weeks 16 and 18, when nothing was happening in main mechanical rooms, work was ongoing in section 4, 1st floor (Figure 5-10). The figure presents some evidence that the delay in the main mechanical room and the subsequent cascading problems were caused by resource issues.

5.3.4.3 The effects of the cascading problem chain on schedule reliability

The mechanical room work was finished 3 weeks before the end of project, leaving only a short period for the testing of the mechanical room. Compared to the detail plan of week 17/2005, one week before the cascading delay chain, the final task – electrical installation - finished 2 weeks late (table 5-2). The original plan had both the mechanical and plumbing contractor out of the way when the electrical contractor was supposed to start. The delays to the mechanical and plumbing tasks were caught up by pushing the electrical contractor in earlier than planned. The electrical work was able to make good progress until the slowdowns started in week 26/2005, when the plumbing and electrical lines got too close to each other.

When the final detail plan (figure 5-9) is observed, it can be seen that the planners thought that the electrical would be able to be finished in week 24. The final plan of the sprinkler (Figure 5-9) has a finish date in week 26, which matches the original finish date of the electrical work (table 5-2). This shows that the planners had confidence until the end that the original finish date would be achieved.

Table 5-2: A comparison of the start and finish weeks between the planned and actual for the tasks involved in the cascading delay chain

Task	Planned (actual) start week	Planned (actual) finish week	Start-up delay (weeks)	Finish delay (weeks)	Planned (actual) discontinuities
Mechanical	14/2005 (14/2005)	17/2005 (25/2005)	0	8	0 (1)
Sprinkler	17/2005 (24/2005)	19/2005 (25/2005)	7	6	0 (0)
Plumbing	18/2005 (18/2005)	22/2005 (29/2005)	0	7	0 (0)
Electrical	23/2005 (22/2005)	26/2005 (28/2005)	-1	2	0 (0)

5.3.5 The cascading problems in Opus

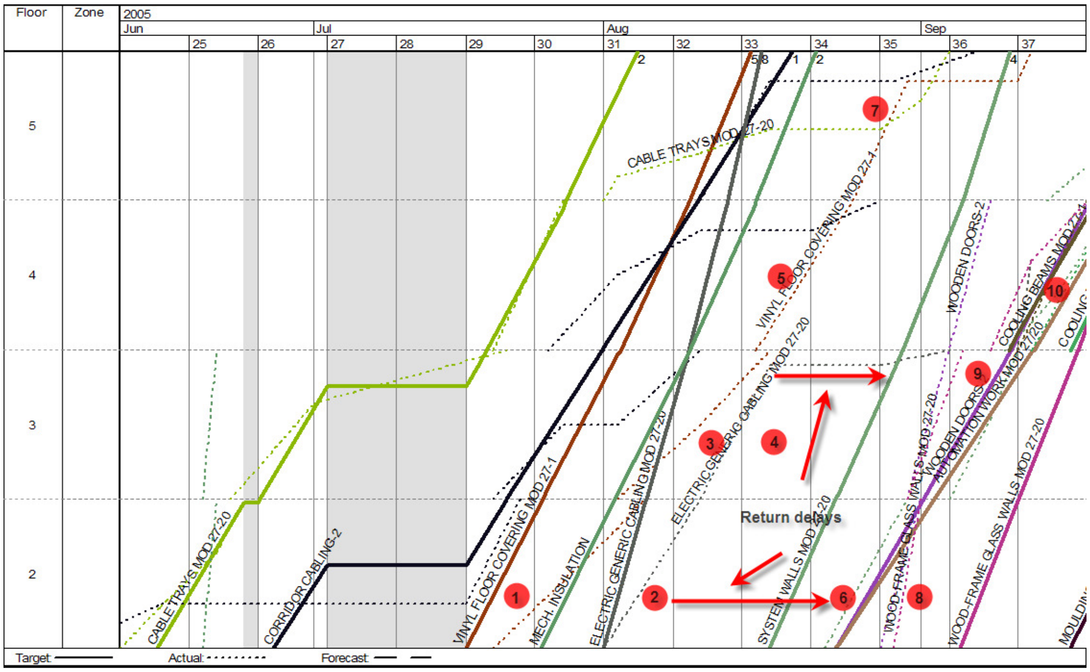


Figure 5-11: Cascading problems in Opus caused by vinyl floor covering work

5.3.5.1 A description of the cascading problem chain

The problem to be analyzed was between the generic electrical cabling and the vinyl floor covering tasks. This problem started with the vinyl floor covering, right after the two week summer holiday. Although the preceding tasks were delayed, there was enough buffer in the schedule so that their delays did not have an effect on the start date of the vinyl floor covering. The vinyl floor covering was prioritized over the other tasks, so the predecessors were also suspended when the vinyl floor covering entered the same location. The delays caused by the vinyl floor covering cascaded until the end of the project.

The problem series is presented in two figures. Figure 5-11 shows weeks 24-37 on floors 2-5, and figure 5-12 shows weeks 37-44 on floor 1. The problem series affected mostly the section between grid lines 27 and 20, so only that part of the project is shown.

The problem series started from floors 2-5 and then shifted to the 1st floor, where it continued until the end of the project. The problems shown in figure 5-11 are analyzed below.

Problem 1: The vinyl floor covering started 2 days late and went much slower than planned. The initial planned start date of the generic electric cabling was in the same week. The reason for the slow start of the vinyl floor covering was identified in the project documentation to be too small a crew (1 person instead of 3 - as planned). The generic electric cabling did not have a dependency to vinyl floor covering, which was caused by a planning error.

Problem 2: The vinyl floor covering and generic electric cabling were happening at the same time in the same location. The generic electric cabling started too slowly, possibly because it happened at the same time as the vinyl floor covering. The system walls were planned to start this week but their start date was delayed by the vinyl floor covering. The system walls did not start immediately when the vinyl floor covering was finished in the location. Instead there was a return delay of three weeks.

Problem 3: The vinyl floor covering and electric generic cabling happened together in the same location and both were going slower than planned.

Problem 4: The generic electric cabling was suspended, possibly because the vinyl floor covering was happening at the same time in the same location. The generic electric cabling did not continue immediately when the vinyl floor covering was completed in the location. Instead there was a 1.5-week return delay.

Problem 5: The vinyl floor covering entered the same location as the corridor cabling. The corridor cabling was suspended.

Problem 6: The system walls were delayed from the updated start date (problem 2). This caused a start-up delay of the wooden doors.

Problem 7: The vinyl floor covering entered the same location as the cable trays, corridor cabling and plumbing corridor pipes (not shown in figure). All three tasks were suspended.

Problem 8: A system wall start-up delay caused a start-up delay of the automation work.

Problem 9: The start-up delay of the system walls caused them to happen at the same time as the wood-framed glass walls on third floor. This caused the system walls to be suspended.

Problem 10: Many tasks entered the same location at the same time. The cooling beams started from the fourth floor instead of the second floor because of design reasons. This caused them to happen at the same time as the delayed system walls and wood-framed glass walls. The generic electric cabling was also delayed and happened at the same time. The mechanical insulation was supposed to start on 4th the floor, but suffered a delay. The generic electric cabling continued to be slower than planned.

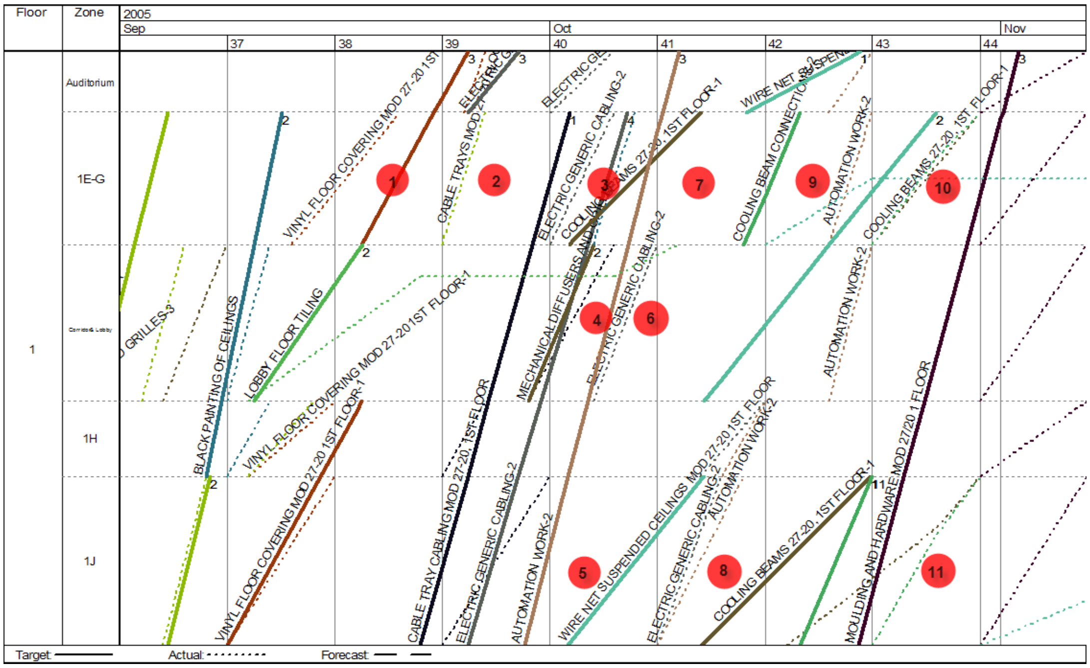


Figure 5-12: The cascading problems on the 1^{st} floor caused by the vinyl floor covering work

The problems then shifted to the 1st floor, because of delays of the cable trays, the electric generic cabling, and the vinyl floor covering on the 5th floor. All of the tasks were planned to continue next on the first floor. Note that the final suspension of the vinyl floor covering on the 5th floor (weeks 35-36 in figure 5-11) was not due to interference – the vinyl floor covering material ran out instead. Figure 5-12 shows the problems relating to the 1st floor.

Problem 1: The problems shifted to the 1st floor because the same resources continued to the first floor from the fifth floor in the cable trays (the end week on the 5th floor was 35/2005) and the vinyl floor covering tasks (end week on the 5th floor 37/3005). The cable trays were able to be finished in the Corridor area and the 1J (green lines), but had to be suspended for two weeks when the vinyl floor covering started in area 1E-G. The black painting of the ceilings was also suspended for the same reason in the same location (area 1H and the corridor and lobby were finished, blue lines). The problem happened because the vinyl floor covering started ahead of schedule in this location, instead of following the planned sequence. Also, the cable trays were produced out-of-sequence.

Problem 2: The cable trays entered location 1E-G immediately after the vinyl floor covering work was finished. As a consequence, the black painting of the ceilings continued to be suspended.

Problems 3 and 4: The electric generic cabling entered location 1E-G where the cooling beams should have started. This caused the delay of the cooling beams (however, production was still going on on the other floors, so the task was not suspended). In the corridor, the cable tray cabling and the electric generic cabling both happened at the same time which led to slowdowns.

Problem 5: The electric generic cabling started out-of-sequence from 1E-G which delayed the start date of the automation work in location 1J (technical dependency)

Problem 6: The lobby floor tiling and electric generic cabling happened at the same time and the electric generic cabling had a slowdown (The lobby floor tiling suspension was because of a lack of materials).

Problem 7: The cooling beam delay in location 1E-G caused a delay in the cooling beam connections in the same location (technical dependency)

Problem 8: The automation work and generic electric cabling happened together in location 1J, this caused a slowdown of the generic electric cabling. The delay of the automation work also caused a start-up delay of the closing wire net suspended ceilings in location 1J.

Problem 9: The wire net suspended ceilings started out-of-sequence in area 1E-G, but had to be suspended when the automation work entered the location. The delay of the cooling beams continued to delay the cooling beam connections.

Problem 10: The cooling beams and cooling beam connections started in area 1E-G, which caused the wire net suspended ceilings to be suspended.

Problem 11: The cooling beams and their connections caused the delay of wire net suspended ceilings also in area 1J.

5.3.5.2 An analysis of the resource issues relating to the cascading problem chain

In this example, the resource issues were important at the beginning of the cascading delay chain. The vinyl floor covering contractor had a one-person crew instead of three, as assumed in the plan. The task was prioritized, which led to the suspensions of other tasks. Some subcontractors who were working only on a single task of the project (the generic electric cabling and system wall subcontractors) had to demobilize and had return delays, which caused a stacking of trades, contributing to further slowdowns. The MEP contractors used continuous production in this project, having the same crew do all the cable trays for the electrician, and having the same crew install all the cooling beams for the mechanical contractor. Therefore, in this cascading delay chain, the resource issues conform to the traditional Flowline theory requiring continuous work for each work type. It may be that the high degree of repeatability in office buildings causes subcontractors to organize their crews to work continuously through the building on one work type. The suspension of the cable trays on the 1st floor (problem 1) caused the electricians to shift to the main mechanical room, which seems to have been considered a work backlog location where workers moved when they could not work elsewhere. The plumbing contractor used the plumbing fixtures as a similar work backlog task, which was accelerated when they ran out of work with the cooling beam connections.

5.3.5.3 The effects of the cascading problem chain on schedule reliability

A comparison of the planned start and finish weeks (plan of week 26/2005, one week before start of summer holiday season) to the actual start and finish weeks shows that most of the tasks were delayed 5 to 6 weeks after the cascading delay chain started (table 5-3). Many of the tasks have discontinuities of labor flow, which were the most common symptom of the cascading problem chain in this project. The closing of the wire net suspended ceilings was the last task of this delay chain, and it was delayed well into the commissioning period.

Table 5-3: Comparison of the start and finish weeks between the planned and actual for the tasks involved in the cascading delay chain [the schedule just before the summer holidays]

Task / location	Planned (actual) start week	Planned (actual) finish week	Start-up delay (weeks)	Finish delay (weeks)	Planned (actual) discontinuities
Cable trays (floors 2-5)	24/2005 (24/2005)	31/2005 (35/2005)	0	4	0 (2)
Cable trays (floor 1)	26/2005 (36/2005)	29/2005 (39/2005)	10	10	0 (1)
Vinyl Floor covering (floors 2-5)	29/2005 (29/2005)	32/2005 (37/2005)	0	5	0 (1)
Vinyl Floor covering (floor 1)	32/2005 (37/2005)	33/2005 (39/2005)	5	6	0 (0)
Generic electric cabling (floors 2-5)	29/2005 (31/2005)	32/2005 (39/2005)	2	7	0 (2)
Generic electric cabling (floor 1)	32/2005 (40/2005)	33/2005 (41/2005)	8	8	0 (0)
Cooling beams (floors 2-5)	31/2005 (37/2005)	36/2005 (41/2005)	6	5	0 (1)
Cooling beams (floor 1)	36/2005 (42/2005)	37/2005 (43/2005)	6	6	0 (0)
Cooling beam connections (floors 2-5)	31/2005 (37/2005)	36/2005 (41/2005)	6	5	0 (1)
Cooling beam connections (floor 1)	36/2005 (43/2005)	37/2005 (43/2005)	7	6	0 (0)
System walls (floor 2-5)	33/2005 (34/2005)	37/2005 (39/2005)	1	2	0 (1)
Automation work (floor 1)	38/2005 (42/2005)	39/2005 (42/2005)	4	3	0 (0)
Automation work (floors 2-5)	39/2005 (39/2005)	44/2005 (42/2005)	0	-2	0 (1)
Wire net suspended ceilings (floor 1)	40/2005 (42/2005)	41/2005 (48/2005)	2	7	0 (1)

5.3.6 Summary of the test results

The resource issues, space congestion, working out-of-sequence, and production management decisions were found to be critical contributors to the cascading problem chains. The analyzed cascading problem chains delayed the finish dates of tasks by 2 to 6 weeks, pushing them into the period reserved for commissioning in all of the projects. Because of the long end-of-project buffers, these cascading delay chains did not affect the project end dates. This presents an opportunity for significant cuts in project duration (1-1.5 months) and an increase in production reliability and associated cost savings, if the cascading production problems could be solved.

The resource issues were found to be critical in two ways. For the contractors employing multi-skilled workforce, such as the MEP contractors, the typical strategy in the case studies was to use the same pool of resources for all tasks of the project. The subcontractors did not respond to the additional resource requirements of the production schedule, but the tasks got delayed instead. For the contractors who work in a single task, demobilization and return delays were observed when the contractor suffered lower production rates as result of space congestion. Instead of coming back immediately when allowed by the predecessor, resources were remobilized 1 to 2 weeks later. This effect magnified the results of the cascading delay chains. For the MEP trades, this return delay did not happen, because they had other, less critical tasks where they could continue working. For example, the main mechanical room electrical work and the plumbing fixtures were used in this way in the Opus project.

The resource delays and working out-of-sequence, combined with the return delays and delays caused by external factors, led to space congestion. When multiple tasks happened in the same location, production rates slowed down or work completely stopped. The production management often made a decision about the prioritization of the tasks involved. This prioritization often led to more problems, because the consequences were not analyzed. The production management reacted to the delays by pushing more tasks to start according to the original schedule, which led to further space congestion and more delays. A better strategy would have been to allow the existing tasks to finish and then mobilize the new trades with higher production rates.

5.4 Test of the weekly planning functionality

5.4.1 Introduction

The reliability of the weekly planning was shown to correlate with the other schedule success metrics. However, in the actual process, the weekly planning was detached from the location-based management system. Because the weekly plans and measuring their success by metrics, such as PPC, are an effective way of communicating the production plan to the superintendents, foremen and workers, they should be integrated into the location-based control tools to link the look-ahead planning to the execution of plans. The reliability of the weekly plans based on the location-based forecast was compared to the reliability of the weekly plans planned by the project teams in the case studies. The initial hypothesis of this test was that using the forecasts would improve PPC for the ongoing tasks which have historical production rate information.

5.4.2 Method

The weekly planning functionality was tested in each project for a selected time period of the interior and MEP phases. All the MEP tasks were included and all the interior tasks which contributed to any production problems during the time period were included. If one task of a subcontractor was included, then all the tasks of the same subcontractor were included. A complete set of progress data for all the selected tasks was entered into the beta version of Control 2009 software, which implements the new forecasting system described in Chapter 4. If the original progress data had mistakes, which were corrected later in the analysis, those corrections were assumed to be available on time. For example, the suspended tasks and completion rates were assumed to be available. Because the forecast also uses the information of the detail plans, those plans were copied exactly to the new format for each week. The end result was one file for each week in each case project, concentrating on the finishes and MEP phases. Original files did not have actual resource information. This information was entered for each subcontractor based on the subcontractor meeting memos, assuming that the reported number of resources was working on each day of the week. The forecasting assumption for the future weeks was that the same amount of resources would continue working on each ongoing task. New tasks would be started, or existing tasks continued, only if the subcontractor actually mobilized new resources during the next week or if some other task was finished.

The forecasts were used to generate assignments for the weekly plans by evaluating the forecast completion rate in each location at the end of the weekly monitoring period (this was Wednesday, Thursday, or Friday, depending on project). However, the weekly plans only used increments of 10%, with a minimum completion target of 20 % in a location. If a location was planned to start, but not reach 20%, no assignment was entered for that task.

After generating the weekly plan, PPC was calculated by evaluating the status of each task and location in the following week. This PPC was compared to the PPC of the original weekly plan. Finally, the main differences were analyzed by examining the weeks where the original weekly plans performed best or worst compared to the new weekly plans and finding out the reasons.

5.4.3 Results

5.4.3.1 The performance of the forecast-based weekly planning system

The forecast-based weekly plans performed better than the original weekly plans in all of the projects (figure 5-13). In Prisma and Glomson, there were only a few weeks where the original weekly planning performed better. In Opus, the performance of the forecast-based weekly plan was almost the same as the original weekly planning process. However, there were some weeks where the forecast-based weekly plans performed a lot better and some weeks where they performed a lot worse. Most of the weeks had approximately equal PPC.

5.4.3.2 Reasons for the good performance

The better performance of the forecast-based weekly planning related to the following reasons:

- Wrong estimates of the project team relating to production rates
    - The project teams consistently planned higher targets than those based on the historical production rate leading to plan failures

- Resource issues
    - New tasks were included in the weekly plans, even though the subcontractor was not going to mobilize new resources

- Number and scope of assignments
    - The original weekly plans sometimes lumped many locations into one assignment. The forecast-based weekly plan has one assignment for each task and each location. For completing the same scope of work, this resulted in a higher PPC score

- Forgetting of assignments
    - In Glomson and Opus, some ongoing tasks were “forgotten” from the weekly plans and failed to score successful assignments

- Technical dependencies
    - Assignments were planned in the original weekly plans, although their technical predecessors were not complete

- Incorrect progress data

- In Opus, the weekly planning sometimes operated on the basis of incorrect progress data, and thus resulted in wrong assignments which failed

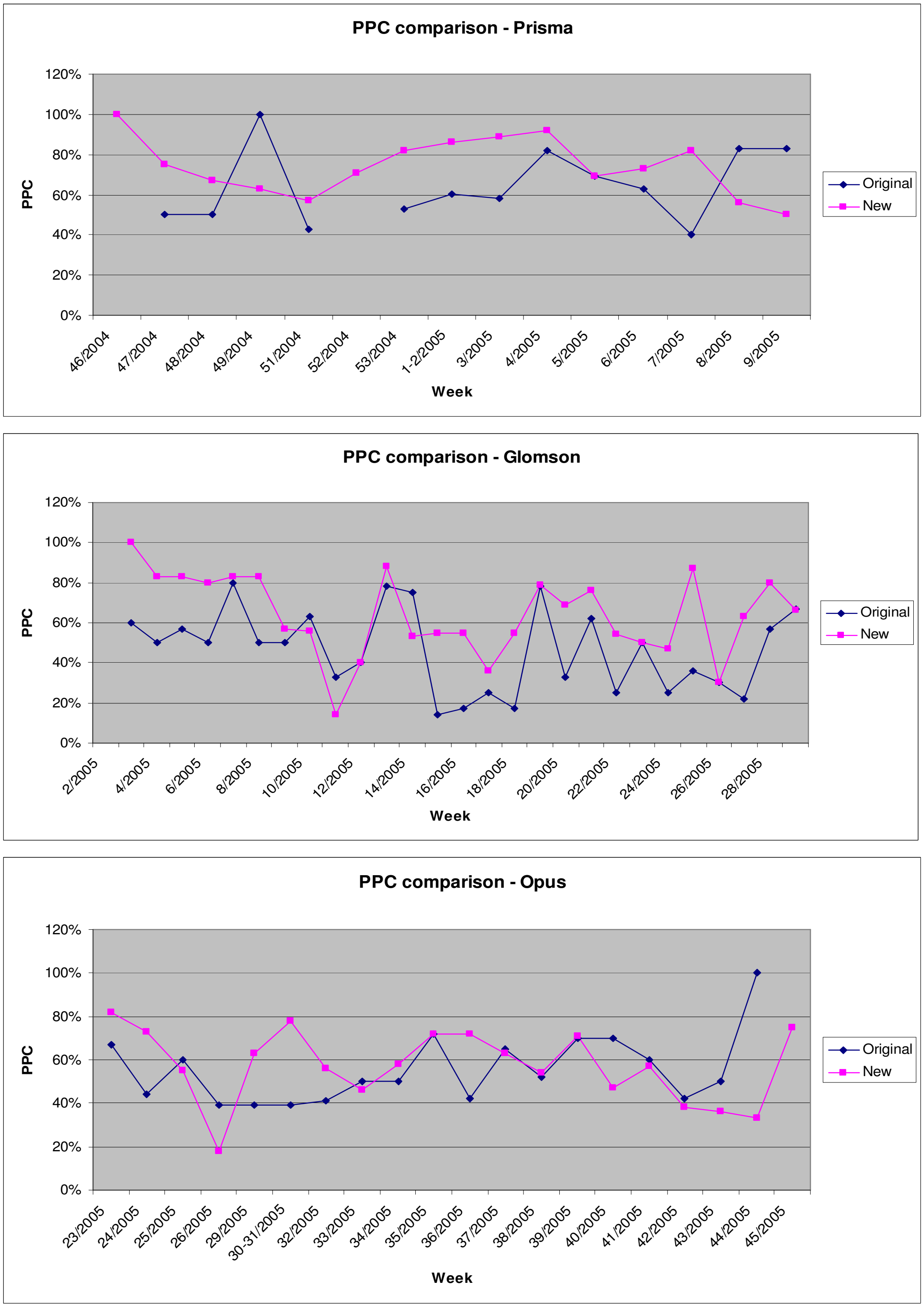


Figure 5-13: A comparison of the PPC of the original weekly plans and the weekly plans generated based on the adjusted location-based forecast

5.4.3.3 Reasons for poor performance

The reasons for the poorer performance of the forecast-based weekly planning related to the following reasons:

- Slowdowns compared to previous production
    - Multiple tasks entering the same location resulted in slowdowns
    - The Summer holiday season resulted in slowdowns in many projects
    - Tasks happening during the commissioning phase at the end of the project did not achieve their historical production rates.
    - The project team was better able to forecast these effects in their weekly plans

- Working out-of-sequence
    - Sometimes tasks started, disregarding technical dependencies
    - Often work started in the wrong location
    - The project engineer's weekly plan was aware of these changes and achieved higher PPC

- Undocumented control actions
    - Sometimes, the project team knew that the production rate would increase in the following week but did not document the control action to the production control system

- New starting locations and tasks
    - The project team was more conservative when new tasks started in new locations
    - The project team generally had better information about newly starting tasks than the production control system

- Suspended tasks which did not continue
    - The project team had better information about the continuation dates of the suspended tasks than the production control system

- Production management decisions
    - The forecast did not have information about the prioritization decisions. Sometimes the same resources did not continue in the task. Instead, resources shifted to another area and the previously ongoing task was suspended

5.4.4 Summary of the test results

The test results show that the forecasts which were adjusted with resource information and which were based on the historical production rates achieved in the project added value to the weekly planning process. They are especially useful in evaluating how much work can be done by limited resources in next week, and whether it is realistic to assume that new tasks can be started if new resources are not mobilized. A systematic weekly planning process based on forecasts makes sure that assignments are not ignored, and they are defined in a standard way based on the locations. This way PPC scores are easier to compare between the two weeks. Taking into account the technical dependencies ensures that work which does not have its predecessors complete does not enter the weekly plans.

The project teams performed better than the forecast-based weekly planning with new, starting tasks, when the tasks had been decided to be done in a different sequence and with the continuation dates of the suspended tasks. Many control actions had not been modeled in the production control system, which decreased the performance of the forecast-based weekly plans. These results show that much of the information relevant to forecasting is known by the project teams, but it is not documented in the production control system or discussed in production meetings. If all this knowledge was available in the production control system, the forecasts would offer much more accurate support to decision making.

5.5 Summary of the chapter

This chapter presented three tests relating to the key results of the case studies. It was found that alarms were critical to enable timely control actions to stop the cascading delay chains. An improved alarm system was tested, and it was found that the new alarm system created more alarms earlier than the original alarm system. With the addition of more information to the system, such as the resource use of the upcoming weeks and the start and continuation dates of tasks, the alarm system could be further improved.

The hypothesis about the cascading problem chains being caused mostly by resource issues and working out of sequence was verified by looking at the cascading problems in all of the case studies. In each case, the resource issues and out-of-sequence work were found to contribute significantly to the randomly selected cascading problem chains. These cascading problem chains were found to extend into the commissioning period of the project. The only reason why they did not affect the end date of the project was the long commissioning period, which operated as an end-of-project buffer.

An analysis of the root causes of the problems show that the problems can be controlled and prevented. Decisions need to be analyzed. For example, in many cases a decision to delay a start date in a location would have been preferable to entering the same location at the same time with other tasks, according to the schedule. If both tasks are already happening at the same time, it may make sense to prioritize locations where interference is not happening and suspend work in the congested location. Changes of resources compared to plans caused problems. Any last-minute changes in plans should be avoided and commitments to the plans should be received well in advance.

The forecast-based weekly planning system was tested, and it was found that the reliability of the weekly plans can be improved by incorporating the forecast-based data. The project teams had better knowledge of the production management decisions and upcoming tasks, but failed to evaluate the production rates or resource problems in a realistic way. Weekly plan reliability can be increased by defining the weekly plans by combining the forecast and project team information.

6. Conclusions

The most important findings relating to the research questions are summarized in this chapter. Finally, the overall conclusions are presented.

6.1 Research question 1: What is the actual production control process on site?

In the case projects, the production control processes were found to be non-systematic and different from the process that was delivered as a model to the project teams. The following sub-processes were analyzed:

1. The detail task planning process
2. The monitoring and controlling processes
3. The production meetings

6.1.1 Detail task planning process

The planning of new detail tasks followed the model process, but detail task updates started from the desired start or finish dates. The detail schedules were manipulated to achieve these dates, instead of using logic and resource availability to calculate realistic start and finish dates. This fact, together with the frequent updating of the detail schedules and a lack of commitment, were important reasons for the low reliability of the detail schedules. The reasons for the cascading delay chains can be partly attributed to this process. Frequent updates without considering their overall effects on the resources and other trades were shown to cause production problems.

6.1.2 The monitoring and controlling process

The collection of the monitoring data was the task of the project engineer. The project engineer collected the status information by either walking the site and reporting the status in the control charts, or by asking for the progress information from the subcontractors. Getting information from the subcontractors resulted in a better quality of data than concentrating the responsibility to one person. For many tasks it required expertise to evaluate the degree of completion. Typical problems with the data included the wrong percentage of completed work in locations, or assuming that the work was continuing, although in reality it was suspended. These data problems contributed to the low reliability of the detail schedules and the problems with the alarm system.

Although there was evidence that alarms led to control actions, there is no documentary evidence that they were actually discussed by the project teams. Similarly, the control action planning had only indirect evidence, for example increasing the resources to tasks which were delayed. It can be concluded that although the information about production problems was often available in the system, it was unsystematically used. Sometimes control actions were modeled by changing the detail task itself. This tended to confuse the control action with the original commitment, and often forced the planner to remove dependencies. Missing dependencies caused the alarm system to miss problems.

The weekly planning process was detached from the location-based monitoring and controlling processes. Tests about the weekly planning indicate that the project teams used information which was not entered into the production control system when planning the weekly plans. On the other hand, the information from the production control system was not used to plan better weekly plans. This, combined with the fact that there was no commitment to the weekly plans, contributed to the bad reliability of the weekly plans in all of the case projects. On the other hand, production management decisions about prioritization, the continuation dates of suspended tasks and the start dates of new tasks, were not available to the production control system, which decreased the quality of the forecasts and, in many cases, prevented timely alarms.

6.1.3 The production meetings

The key finding about the production meetings was that problems and control actions were not systematically discussed. The schedule, subcontractor issues and General Contractor issues were part of the agenda in each case project, but they tended to describe what had been done, instead of discussing any upcoming production problems. Most production problems indicated by the project data were not noticed or discussed at all. This finding means that production problems are either hidden and not known to project management; or they are considered commonplace and are not discussed in the meetings. An increased awareness of production problems and discussing them openly in the production meetings presents an opportunity to improve overall project performance.

Resource availability and prioritization were not discussed at all in the production meetings. The number of resources currently on site was reported in each project by almost every subcontractor, but there was no mention of any upcoming mobilizations or demobilizations, or which tasks to prioritize. Resource issues were found to be common root causes of cascading delay chains.

Opus was the only case project where the control charts and flowline diagrams were used in the production meetings. This had a positive effect, because Opus had the best production reliability measured by production rates compared to the plan. As a conclusion, discussing the production rates and status of each location improves the production control results.

6.2 Research question 2: How reliable are the production plans?

The production plans were not found to be reliable on the baseline, detailed or weekly level. This did not affect the project end dates because of the long end-of-project buffers (1-2 months depending on the case project). The delays were caught up by using up the end-of-project buffer and overlapping production with the commissioning activities.

The actual progress compared to the baseline schedule had significantly high differences between the planned and actual start and finish dates. The start dates were generally well controlled, but because of the discontinuities and slowdowns of production, the finish dates had long delay on average in all of the case studies. These slips in the finish dates were shown to be a result of the cascading delay chains. Controlling the start dates is evidence of push control, where tasks are started without considering the status of the production system. In many cases, delaying the start dates would have prevented location congestion and the consequent cascading delay chains. Although the detailed schedules had better reliability than the baseline schedules, there were still high variations between the planned and actual production rates and finish dates. All of the case projects had an average PPC close to 60%. Last Planner studies typically have the project teams start from a 60% level, and to try to achieve PPC over 80% (e.g. Ballard, 2000). Therefore, PPC of 60% can not be considered reliable.

6.3 Research question 3: Which factors explain the success or failure of the plans?

The main reasons for the plan failures can be classified into the following groups:

- Cascading delay chains
- Resource problems
- The detail task planning process
- A lack of control actions
- Production management decisions

Most of the plan failures were caused by the cascading delay chains. Suffering from these delays correlated with the low reliability of the metrics (production rate deviations, start date deviations, discontinuities, and finish date deviations). These delay chains were typically started by resource problems, or by working out of the planned sequence. In the analyzed case studies, these chains happened mostly in the MEP and finishes phases, and were disconnected from the other construction phases. This is interesting, because the tasks related to earthworks, foundations and the structure typically get most attention of the production management. Improving the production control of the interior work can be said to be a critical improvement opportunity for General Contractors.

Resource problems were typical for contractors employing multi-skilled labor, such as the MEP contractors. It was shown that it is not enough to consider just the continuity of work for the MEP trades, but the overall resource profile needs to be considered as well. The production plans assumed more or less resources than were available, and this caused either delays of the start dates or early starts. When one contractor starts early or is delayed, he usually ends up working in the same location as some other contractor, causing start-up delays, discontinuities, or slowdowns. There was evidence of return delays of 1.5 to 2 weeks for the contractors who had to demobilize, because they did not have other work on the project.

The detail task planning process which was used in the case studies made these problems worse. Starting from the desired start and finish dates was counter-productive, because it was not evaluated whether the other contractors would be working in the same location at the same time. Detail task updating also did not consider the resources or technical relationships which caused many plans to fail.

Control actions were often not taken, even though there was an alarm in the system. The reasons for not taking control actions are not known based on data, but they may be related to the fact that the problems were not formally discussed in the production meetings.

Many production management decisions were shown to cause cascading production problems. Prioritization decisions were not formally analyzed and often contributed to the cascading problem chains. The cascading problem chains were further aggravated by push controlling the start dates, which forced the new contractors to start in the same locations as the previously delayed contractors.

6.4 Research question 4: Was the information provided by the Location-based management system relevant for decision making?

The results support the conclusion that many of the production problems can be explained by using the location-based management system. It is possible to know of problems before they happen, and to take control actions to prevent them. Although the case studies did not have a systematic process for discussing the problems and planning control actions, there were many problems which were successfully avoided by control actions. Based on these results, it can be concluded that the production system is very fragile, but not chaotic. It is possible to use location based management tools to improve the reliability and performance. However, even small deviations are dangerous, because they start cascading chains of problems which were shown to be very difficult to stop.

Many shortcomings were also found in both the location-based management system and how it was used. There were many problems which did not provide early warnings. Many of these problems were related to the process, such as removing dependencies to achieve the desired start and finish dates. However, issues were found with the system itself, because of over-optimistic forecasts, and because it failed to use resource information in the way it was available to the projects. The lack of look-ahead functionality and the ability to adjust the forecasts reduced the relevance of the LBMS. To increase the relevance, these problems need to be addressed.

6.5 Research question 5: How should the Location-based management system and production control processes be changed to provide better information and decisions to prevent production problems?

The answers to research questions 3 and 4 lead to the conclusion that preventing cascading production problems is the natural domain of location-based management systems. In particular, production problems can be prevented by generating alarms of them sufficiently in advance, and implementing control actions to prevent them from happening. Therefore, the critical development goals of the LBMS and processes relate to generating alarms earlier.

6.5.1 Changes to the processes

Changes in the processes to achieve this goal relate to:

- Getting better and more consistent progress data by dividing responsibilities.
- Getting commitments to the detail tasks
- Confirming the start dates of tasks which have not been started, and the continuation dates of tasks which have been suspended
- Discussing resource use and planning resource-based look-ahead schedules
- Changing the production meetings to discuss any problems and control actions
- Using resource-based look-ahead to generate the weekly schedules

6.5.1.1 Getting better and more consistent progress data

Many times, alarms were not generated or weekly assignments were incorrect, because the progress data had problems. Improving the quality of the progress data can be achieved without large additional cost by distributing the responsibility to the subcontractors. This conclusion is based on the observation that when the subcontractors participated in the data collection process, the quality of the data was better.

6.5.1.2 Getting commitments to the detail tasks

Getting commitments early enough was shown to be important, because detail task updates close to actual production were shown to cause production problems. After a commitment, the schedule is locked and production is controlled by the monitoring progress and modifying the forecast is based on control actions. A committed detail task should be changed only if there is an external reason; such as a change order, a design delay or a procurement delay.

6.5.1.3 Confirming the start and continuation dates

A common reason for not generating an alarm was that the start and continuation dates for the upcoming or suspended tasks were not confirmed. Instead, the production control focused on tasks which were already delayed. By improving look-ahead planning, the alarms of upcoming problems can be generated earlier. Confirming the start and continuation dates includes discussions about the starting and continuation prerequisites and decisions about when to start and continue tasks.

6.5.1.4 Resource use

Resources were found to be a key reason for starting cascading delay chains. On the process side, the resource use of each subcontractor should be discussed weekly to make sure that the production forecast assumes the same numbers of workers as are actually available, and that the available tasks and locations are correctly prioritized. Because increasing resources is a control action, resources should be discussed together with control actions.

6.5.1.5 The production meetings

The production meetings did not meet their coordination objective in their current form. In the case studies, problems were not systematically discussed, and control actions were not planned in the production meetings. The production meetings should be changed to concentrate on problem solving instead of discussing currently ongoing tasks. This conclusion can be drawn from the large number of production problems that were identified from the LBMS data, compared to very small number of problems which were actually discussed.

6.5.1.6 Weekly schedules

The reliability of the weekly schedules was shown to correlate strongly with the reliability of the location-based schedules. The weekly schedule reliability can be increased by using adjusted forecasts to initialize a weekly assignment. The project teams were consistently unable to evaluate how much could be produced with the currently available resources, or whether any new tasks could be started without mobilizing new resources. It can be concluded that the weekly schedules should be integrated into the LBMS, instead of handling them as a separate process.

6.5.2 Changes to the production control system

Many assumptions of the location-based management systems were found to be false during this research. Many parts of the system needed a complete redesign to provide a tool for preventing cascading production problems. Key changes affected the following components:

- The forecasting system
- The alarm system
- The resource-based look-ahead

6.5.2.1 Changes to the forecasting system

The forecasting system was changed to be less optimistic and to react faster to changes in the production rate. This was shown to generate earlier alarms in tests.

6.5.2.2 Changes to the alarm system

The updated alarm system creates two types of alarms: “hard” alarms and “soft” alarms. “Soft” alarms are a new alarm type which is generated every time two tasks happen together in a location. The most common reason for failing to alarm was that system did not have a dependency between the two tasks. This change was shown to result in more alarms earlier than with the original system.

6.5.2.3 The Resource-based look-ahead

The new functionality was added to allow the planner to plan control actions and the look-ahead schedule by adjusting the forecast based on the number of resources working in each task and location during the upcoming weeks. Adjusting the forecast allows the updating of the production control system with information about subcontractor resource availability and examining what-if scenarios related to the prioritization and optimal start and continuation dates of new tasks. This was shows to generate more and earlier alarms, and to increase the predictive ability of the forecast system by improving the percentage of the plan completed in tests.

6.6 Overall conclusions

Systematic production control was found to be missing in the case studies. Production problems are not discussed, and their total effect is not evaluated. Decisions about prioritization and start and continuation dates are made without evaluating their effects. Start dates are controlled based on the original baseline schedule, without considering the current status of the production system. The resource issues of subcontractors are not considered when planning and controlling production. These issues lead to cascading production problems. Because cascading production problems exist in every project, long end-of-project buffers are needed to prevent knock-on effects to the project finish dates. By improving the production control processes, there is an opportunity to decrease these end-of-project buffers and increase productivity in the projects.

The new production control processes and system were developed, and tests show that alarms relating to production problems can be given earlier by using the new system. Timely alarms are a critical part of a production control system, because they were shown to result in control actions if given early enough. By concentrating production control on preventing production problems, cascading problem chains can be prevented from happening, or they can be stopped. This requires the use of look-ahead planning, the systematic analysis of production management decisions, open discussions about resource use and production problems with subcontractors and connecting the weekly plans to the production control system.

7. Discussion

This chapter compares the case study and test results and conclusions with the other research results in the technical literature. Then the reliability and validity of the research are discussed. Finally, the contributions to the research, implications for construction management, and any possible future research directions are presented.

7.1 A discussion of the case study results and other evidence

7.1.1 Cascading production problems, complexity and chaos

7.1.1.1 Case study findings

Every examined case study had a pattern of cascading production problems which started from the beginning of the interior work phase, and continued until the end of project. These cascading problems were caused by multiple factors. Typically, the cascading problem chains were caused by a combination of resource issues, production management decisions, and out-of-sequence work; which resulted in multiple contractors working in the same location. Having multiple contractors in the same location resulted in slowdowns and discontinuities of work, with the associated return delays. Many subcontractors shifted to another task or location when interfered with by other contractors, which was one of the reasons for frequent out-of-sequence work. Some of the problems were exacerbated by design and material related issues.

However, it was also shown that for many of the problems, alarms could be generated before they happened. A location-based management system can effectively utilize the historical progress data to create forecasts which reveal problems. In many cases, alarms triggered control actions which were successful and prevented upcoming problems before they became reality. The case study results show that cascading problems can be prevented by taking immediate action when the production control system generates an alarm. This research improved the forecasting and alarm system to generate alarms earlier, and in circumstances where the previous alarm system did not generate an alarm. It was found that by adding more information about production management decisions and resource availability, the alarm system could be further improved.

Regarding the complexity, the hypothesis that forecasts can be generated for the same subcontractor and similar production in the same project received some support. In many cases, it was possible to forecast future problems in advance. Also detailed preplanning was shown to be useful in the correlation analysis. Failing to follow a predetermined plan correlated with more problems and less predictability. However, systematic production control processes need to be implemented to follow the plan.

7.1.1.2 Other evidence

Cascading problems in production have been examined by the use of a simulation. In a simulation study, it was found that work flow variability impacts the performance of the succeeding trades and can also effect the project completion date (Tommelein et al. 1999). The paper recognizes that when the predecessor has a deviation, the successors may have to perform out-of-sequence work elsewhere.

Thomas et. al (2003) examined improving labor flow reliability for better productivity. Labor flow was defined in the same way as in location-based management. It involves allocating labor resources to tasks and work assignments, and the interaction of crews with other crews and other work. The case studies presented in the paper identified slowdowns caused by other trades. On many days, the reasons for low productivity included insufficient work to perform, or waiting for a predecessor activity. In three case studies, 4,610 work hours were inefficiently used out of 12,063 work hours. Labor flow issues were found to account for 58 % of these productivity losses. These results show that, in addition to endangering total project duration, cascading effects have real productivity and cost effects.

In Last Planner™ research, the root causes of not completing assignments are categorized into groups. Cascading problems similar to those found in this research can be argued to be represented by three groups: a lack of work-in-progress, work force issues and subcontractor delays. In a quantitative study of 105 projects, 34.77% of non-completion of work packages was related to work force issues, which was the most common reason. (Bortolazza & Formoso 2006). Another recent quantitative research in Chile with 77 projects had subcontractor issues increasing to be the largest reason of non-completion over a three year research period. (Alarcon, Diethelm, Rojo & Calderon 2005). Interestingly Alarcon et al. (2005) found that subcontractor delayswere twice as important in projects with a PPC greater than 65% and concluded that in projects with a high PPC the causes related to subcontractors become more significant.

Research in Lean Construction has also indicated that projects are complex and on the edge of chaos (Bertelsen 2003, Bertelsen & Koskela 2003). Chaos was defined by the authors as the inability to predict short-term events in the project ("chaos-in-the-small") or the inability to predict project completion ("chaos-in-the-large"). Writers argued that Last Planner™ is a good tool to deal with "chaos-in-the-small" issues, but other tools are needed for "chaos-in-the-large" issues. Even though the chaotic nature of projects has not been widely accepted, it is commonly accepted that projects are complex. The implication of this complexity claim has been that the research in Lean Construction has focused on improving the planning methods related to phase scheduling and weekly planning which occur close to production. The role of the preplanned master schedule has been limited to milestones and the scheduling of long lead time items. Kenley (2005) argued that this apparent complexity was caused by inadequate planning systems, and although construction is complex, the complexity can be managed with good planning tools. However, Kenley considered only the planning and resource aspects and ignored the uncertainties related to requirements, material deliveries, and design and process information.

One reason for the complexity of current construction projects is the need to coordinate specialty contractors with complex interdependencies (Tommelein & Ballard 1997). Specialty contractors require work to be done by others and cannot start their work before the other parties have finished theirs. Tommelein and Ballard (1997) listed multiple examples of third-party tasks outside the exclusive control of the specialty contractor. These include clarifying the scope of work through requests for information, obtaining design updates, reviewing change orders, acquiring as-built data for work done by others, obtaining approvals for shop drawings, scheduling the use of shared equipment, stake out location to off-load, stage and transport materials, and to allow workers to access their work areas and to have other specialty contractors complete prerequisite work. Because multiple specialty contractors work together their production plans become interwoven in complex ways. This complexity is difficult to model with CPM tools because of the required excessive level of detail and because of the inability to model resource interdependencies and flow (Tommelein & Ballard 1997).

It has been shown that by implementing location-based control processes, cascading delay chains can be stopped (Toikkanen 1989, Hannukkala 1991, Tuominen 1993, Kolhonen et al. 2003). However, these results were received with action research with a full-time researcher on site to guide the production management in their control decisions. In these cases, the cascading production problems were prevented by immediately reacting and correcting any deviation. Schedule forecasts were not used, but all deviations from the baseline were immediately corrected. It should be noted that these case studies were comparatively small (8,000 – 12,500 m2), and related to residential construction, and buffers between tasks were large.

7.1.1.3 A discussion of the case study and other evidence

Technical literature gives supporting evidence to the hypothesis that these cascading delay chains exist in construction projects, and have been found in multiple projects and countries, and by simulation. Although in this research, productivity effects could not be accurately calculated based on the case study data, the results of Thomas et al. (2003) support the hypothesis that waiting for other trades, and insufficient work to perform and other labor flow issues resulted in productivity losses which were more important than the other components' work flow (equipment, material, information). Also, research related to Last Planner has recognized the high proportion of issues related to resources and subcontractor delays (Bortolazza & Formoso 2006, Alarcon et al. 2005).

It has been shown by the results of this research that production problems cause downstream problems via multiple mechanisms. This contributes to the apparent complexity of the production system. Using location-based data alone was not sufficient to explain the problems. However, when a detailed analysis of resource use was added, most of the production problems could be explained. Location-based systems can be used to explain and to predict cascading delays and therefore to reduce complexity. Uncontrolled cascading delay chains can be argued to be the reason why badly controlled construction projects get chaotic ("chaos-in-the-large") (Bertelsen & Koskela 2003). They may also be the reason why the importance of subcontractor related issues increases when PPC increases (Alarcon et al 2005) because of the lack of explicit tools in Last Planner™ to forecast cascading delays. Location-based controlling helps to coordinate the use of shared equipment, the availability of locations, and the completion of prerequisite work. However, it does not directly address the other factors described by Tommelein and Ballard (1997) related to complex interrelationships between specialty contractors, such as RFIs, design updates, shop drawing approvals, as-built data and change orders.

Earlier Finnish research results show that by implementing systematic control processes, cascading delay chains can be stopped and even baseline schedules can be highly reliable, without the need for excessive end-of-project buffers (Toikkanen 1989, Hannukkala 1991, Tuominen 1993, Kolhonen et al. 2003). These case studies used action research with a full-time researcher on site participating in decision-making with the project team. The case study evidence of this research shows that the control actions were successful in many cases. However, the controlling methodology was not systematic and could not prevent cascading delay chains from happening. In order to increase productivity and schedule reliability and to decrease probability of chaos, more information needs to be collected from the site and more efforts need to be made by contractors to implement systematic controlling processes. If deviations happen, a forecast needs to be generated and corrective action implemented.

7.1.2 The controlling methodology

7.1.2.1 Case study findings

The controlling methodologies implemented in the case study projects were found to have many problems. Problems were related to recording and making commitments, discussing problems in subcontractor and Owner meetings, prioritizing tasks, and systematic decision making. There was a lack of a systematic production control process.

The case studies very rarely had documentation of the commitments made by the stakeholders of the project. Plans were constantly updated, and because of the constant changes from week to week, it was impossible to find out what the actual commitments were. Subcontractor meeting memos tended to discuss the past more than the future and instead of recording commitments, they tended to record the upcoming work in very vague terms. Most of the production problems found from the data were never discussed in the meetings. Production problems were common in all of the projects. Start-up delays were often discussed, but discontinuities or slowdowns of production rarely ended up in the meeting memos. It may be that these problem types are so typical in construction projects that subcontractors have included allowance for these problems in their bids and do not bring them up in meetings.

The case study results show that it is not enough to plan continuous Flowlines to balance the resource use of contractors employing multi-skilled labor. Resources were found to be at the core of explaining the cascading production problems. Either too few or too many resources could cause a cascading delay chain. Having more resources available than planned led to early starts and out-of-sequence work. Having fewer resources available than planned led to slow production rates, delays in the start dates of new tasks or the suspension of ongoing tasks. The combination of these effects often caused multiple subcontractors to work in the same location against the plan (one started early and another one was delayed because of resource issues).

The case study evidence shows that the cascading problem chains were made worse by push controlling the start dates of new tasks without considering the other contractors in the same area. Many production management decisions, such as task prioritization, were found to be counter-productive. The reason for this was that the real method of look-ahead planning was found to be missing in current practice. The location-based method of detail task planning was not suited to this task because it did not operate on the production data, but instead adjusted the original commitment. Changing the plan ignores the current status of production. Therefore it was suggested that look-ahead planning should be implemented by changing the forecast. Because forecasts start from the current progress, they explicitly take into account the current status of the production system. This way, location-based look-ahead planning can be implemented as a pull system.

Considering resources in the location-based control model improved the explanatory power of the model, and revealed multiple reasons for the cascading delays. Resource issues explained many slowdowns and out-of-sequence work. Better forecasts were able to be calculated by taking into account the estimated resource availability of the upcoming weeks and other look-ahead information such as production management decisions, and the starting and continuing prerequisites of new and suspended tasks. All management decisions; such as task sequence, task prioritization, starting new tasks, suspending ongoing tasks, continuing suspended tasks, and the use of resources, can and should be analyzed systematically.

7.1.2.2 Other evidence

In CPM control methodology, plans are updated to correspond with the actual progress and the rest of the project is re-planned to find ways to achieve the original contract duration (Galloway 2006). Typically this is done by adjusting the logic or activity durations. The actual planning process happens mostly in meetings (Cohenza-Zall, Laufer, Shapira & Howell 1994). Cohenza-Zall et al. found in their research that planning is mostly informal, the relevant information is not available in the meetings, and no linkage is made to the previous planning stages. Look-ahead plans are typically extracts from the master or phase schedule, where detail is added for the upcoming three weeks. (Ballard 2000). Total float and criticality are used to prioritize tasks. It is common to update the schedule monthly and use the resulting schedule to prioritize tasks during the next month (Galloway 2006).

CPM literature has long recognized the importance of resources in scheduling. A basic CPM model assumes unlimited resources and considers only handoffs between the activities (Lu & Li 2003). Many methods to achieve resource-leveling have been discussed in literature (e.g. Hegazy 1999, Lu & Li 2003, Chua & Shen 2005). However, a minority (30 %) of contractors were found to consider resource loading useful in a survey study (Galloway 2006). A direct observation of the contractors' schedules indicates that resource loading is extremely rare. Instead, crew logic is typically added to the networks (Woolf 2007). This results in overly complex schedules which do not achieve a continuous flow (Kenley 2005). Methods such as critical chain (Eliyahu 1997) have tried to address these issues by a new concept of critical chain which is the longest chain of dependent steps. Dependencies can arise from resources or other reasons (p. 215). Resource sequence optimization methods are criticized by Eliyahu (pp. 216-217) because they assume that durations are deterministic.

Papers related to schedule analysis in the event of claims have recognized the importance of resource flow for cascading delay chains. For example, Ibbs and Nguyen (2007) developed a resource-based schedule analysis method. They recognized that delays both change critical path, but also disrupt the planned resource allocation. Upstream delays causing a resource allocation issue to downstream work could trigger cascading delays which may cause project delays.

The Last Planner System™ emphasizes the multi-level planning process, recording commitments, and tracking their reliability. The master schedule defines milestones for the phase schedules which are planned together with the subcontractors. Before the start of an operation, a First Run Study is done to create a detailed plan of how the work will be completed and to serve as a control document for the operation. (Howell & Ballard 1999). Look-ahead planning explodes the phase schedule activities to the assignments which are sound. Assignments are moved to the next week of the look-ahead window only if it is assumed that they can be made ready on time. Look-ahead planning defines priorities for making tasks ready. Finally, assignments are allocated to the weekly plans if they can be made ready on time. In addition to the weekly plan, there is a workable backlog which contains the assignments that have been made ready, but are not part of the weekly plan. This workable backlog is by definition lower priority than the weekly plan. In the following week, the reliability of the weekly plan is assessed to calculate PPC. In controlling, Last Planner emphasizes finding the root causes of plan failures and learning from them to improve plan reliability. (Ballard 2000) Look-ahead planning has been considered a critical part of production control in papers about Last Planner (Ballard & Howell 1998).

The importance of resource issues and resource leveling has long been recognized in Lean Construction literature. Resources are first planned during the phase scheduling and First Run Studies (Howell & Ballard 1999). A First Run Study may also include a plan for a Continous Flow Process, which can utilize location-based tools (Ballard & Tommelein 1999). On the assignment level, The Last Planner System™ highlights the importance of pulling in resources when needed (e.g. Ballard & Howell 1998, Ballard 2000). A property of sound assignment in the Last Planner System™ is sizing capacity to load. Last Planner papers typically have figures relating to the look-ahead plans of the upcoming weeks with the resource numbers for each activity shown. A typical controlling process includes evaluation by the foreman of the available resources and the available workload. The foreman notes any work remaining after all the available resources have been allocated or any resource remaining after all work has been allocated. If work is left over, it goes to the workable backlog. If manpower is left over, the foreman asks for instructions from his supervisor. (Ballard & Howell 1998).

Lean Construction relies on pull controlling. Pull can be defined as taking into account the current state of the production system when making decisions about whether to allow more work-in-progress to the system. In contrast, push systems use external information, such as the production plans to push work into system without considering the current state of the production system (Hopp and Spearman 1996, pp. 360-362). It has been argued that the Last Planner System™ is a pull system, because it allows work into the system only when it has been made ready (Ballard 2000).

Location-based controlling systems concentrate on controlling production rates and completing locations and preventing a starvation of work (Kiiras 1989, Kankainen & Sandvik 1993). Resources should be able to flow continuously from location to location without interference. Location-based controlling systems stress completely finishing locations before moving to the next location. This establishes a pattern of work which is easy to follow. Out-of-sequence work can be prevented by tying the payment schedule to the completion of locations. (Seppänen & Kenley 2005b, Pekanpalo 2004). This effectively prioritizes a make-ready process based on the production sequence of locations. Howell, Ballard, Koskela and Tommelein (2004) argue that maintaining a steady production rate is not enough for work-flow reliability. Work flow can be said to be reliable only if the specific work promised to downstream has been completed. If capacity is shifted to alternative tasks in order to make progress, the planned sequence is destroyed, causing further problems to reliability (Howell et al. 2004). It can be argued that location-based systems and Lean Construction try to achieve the same goal here. Location-based systems create commitments based on task and location in order to better integrate the data and create forecasts, while the Last Planner System™, as a social process, has a more flexible view of the specific work promised to downstream.

On the surface, location-based methods seem to push work into the system based on a predetermined plan. This was actually the case in the Finnish action research, where any deviations from the baseline were immediately corrected. However, controlling the schedule using the baseline was implemented to prevent two crews from colliding with each other, which is a shared goal with pull systems. Task planning is a methodology developed in Finland for securing the completion of production from the schedule, cost, safety, and quality standpoints, according to the baseline schedule or budget (Junnonen 1998, Junnonen & Seppänen 2004). Task planning optimally begins even before the subcontractors have been selected for the project and establishes targets for production rates, unit costs, and quality requirements. The initial task planning results are used in requesting proposals. The task plans are updated in the subcontractor negotiations and in the start-up meeting. The production control of task planning concentrates on production rates and making work ready. If there are deviations, they are solved in quality circles together with the workers (Junnonen 1998).

Recently, research has been carried out into subcontractor decision making with regard to resources. A subcontractor tries to maximize the utilization of his resources over multiple projects. If production is more reliable in a project, subcontractors have the motivation to allocate more resources, because they can maximize profits that way (Sacks 2004). Resource allocation can be seen as a game theoretical problem, where the general contractor has the options to require too much, too little, or the right amount of resources, and the subcontractor can allocate too much, too little, or the right amount of resources. It was shown that under unreliable production, the general contractor is motivated to demand too many resources, and the subcontractor is motivated to supply too few resources. (Sacks & Harel 2006).

Tommelein and Ballard (1997) argue that in recent years, general contractors have commonly adopted a hands-off approach to specialty contractor coordination. Instead of performing the function of specialty contractor coordinator, the general contractors act as contract brokers and leave the specialty subcontractors to fend for themselves. They advocate the use of detailed production planning, including the detailed planning of process interdependencies, shared resources, and working with subcontractors to develop the plans in regular planning meetings.

7.1.2.3 Discussion of the case study and other evidence

All controlling methodologies can be said to have some good components, but to be lacking in others. Table 7-1 compares and contrasts the strengths and weaknesses of the methods. The Last Planner System™ and location-based systems can be argued to be production control systems, while CPM is more a project control system and ignores production. Although Last Planner is easy to implement and effective, it ignores labor flow and ignores the fact that construction production happens in locations.[1] Location-based management has been, this far, implemented with a push methodology, and it is little used outside Finland. However, its effectiveness has been shown using action research.

The argument for the push and pull production systems is interesting. Applying the Lean Manufacturing terminology of pull and push into construction requires finding the appropriate analogies between manufacturing and construction. In manufacturing, the product moves through stationary workstations. In construction, labor flows through stationary locations finishing work. The benefit of a pull system comes from limiting work-in-progress, thereby limiting congestion (Hopp and Spearman 1996, p 358).

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[1] Even though the Last Planner System™ does not explicitly consider labor flow, the need for continuous flow processes has been identified in Lean Construction community (Ballard & Tommelein 1999). However, Lean Construction is not a production control system but a production philosophy – both location-based planning and the Last Planner System™ subscribe to the ideals of Lean Construction

Table 7-1: A comparison of control methods

Method	Strengths	Weaknesses
Activity-based (CPM)	• Widely used • Forces management to rethink the rest of the project by month • Criticality and float are simple measures for prioritization	• Logic abuse is common • Push control methodology • Does not consider commitment or prerequisites of production • Critical path shifts from update to update • Project control, not production control system
Last Planner™	• Easy to understand • Promotes continuous improvement • Proven effectiveness (action research) • Proactive control • Commitments and prerequisites of production explicit • Pull-controlling methodology	• Does not explicitly consider labor flow • Does not force location sequence • No explicit tools to size capacity to load • Only easy parts implemented when researcher not on site (weekly planning, PPC measurement)
Location-based (according to Finnish action research studies)	• Production, labor flow and sizing capacity to load explicit • Immediate reaction to deviations • Proven effectiveness (action research) • Task planning incorporates controlling of prerequisites and proactive planning	• Push control methodology • Only easy parts implemented when researcher not on site (planning, control charts) • Little used outside of Finland

In construction, work-in-progress can be argued to be a function of the number of crews and the locations being worked on at the same time. An example of push control would be to start new crews or subcontractors based on the baseline schedule requirements, or to increase the production rate, just because a subcontractor is delayed, without considering the current state of the production system. The tendency of the case projects to practice push controlling may be a symptom of the general contractors working as contract brokers instead of taking on the role of specialty contractor coordination. (Tommelein & Ballard 1997). Traditional control methods based on optimizing individual activities, lead to problems as managers optimize their activity with little concern for the problems this causes others (Koskela et al. 2002: 216). An example of pull control would be to start new crews only when the production control data shows that there are free locations for them. Constant work-in-progress is difficult to implement in construction because different locations typically have different quantities and some crews flow only through part of the project. Location-based controlling can be used as a pull system with the implementation of a resource-based look-ahead system. The progress stage of the information describes the current state of the production system. The forecasts describe what will happen if the original plan is followed with the actual production rates and resources. Alarms indicate space congestion and upcoming problems. Look-ahead planning adjusts the forecast by prioritizing the use of the available resources and preventing new resources from entering the system if it is congested. In addition to this, the other prerequisites of production need to be managed by the use of checklists to ensure that look-ahead can be implemented.

Using the look-ahead achieves the same goal as the earlier push controlling methods in the Finnish action research with the pull methods. Controlling to the original baseline should be done only if there are enough empty locations in front of the crews to accommodate the additional manpower, or to start new tasks. Because the forecasts and look-ahead plans were not available to the Finnish case studies, production had to be pushed using the original baseline to be able to prevent clashes (Jouko Kankainen, personal communication). Now conflicts can be prevented by using the forecasts and alarms and the same goal can be achieved with a pull system.

It can be concluded that combining the work flow and resource flow issues into one system would combine the strengths of both methods, and eliminate some of the weaknesses. Both systems share the same goal: the reliable hand-off of specific work to succeeding specialists. This commitment is defined by the use of tasks and locations in location-based management, but is flexible in Last Planner System™. The case study results confirmed the assumption of the Last Planner System™ that smoothing the production rate is not sufficient to obtain good production control results, also the specific work to be done needs to be completed (Howell et. al 2004). This received support because implementing work in the wrong sequence correlated strongly with downstream production problems. Location-based management does not explicitly consider all the prerequisites of production, but provides powerful tools for managing resource flow and look-ahead planning. The Last Planner System™ does not explicitly consider resource flow, but has a straightforward plan reliability metric which was shown to correlate with other production metrics and is easy to implement. In this research it was shown that basing assignments on forecasts which are based on the historical production rates resulted in better PPC than the original weekly plans that the project teams made. The main reasons for the better performance of the automated forecasts were related to the incorrect estimates of the project team relating to the production rates and resources (refer to section 5.4) . By improving predictability, the likelihood of the subcontractors allocating resources to the project is improved (Harel & Sacks 2006). Location-based management can provide explicit tools for Last Planners to size capacity to load by combining the foreman and supervisor experience to objective information about past productivity rates. It can contribute to the social process by showing potential problems in resources and capacity before commitments are made. It should be noted that location-based principles have already been used in planning Continuous Flow Processes (Ballard & Tommelein 1999), and First Run Studies (Howell & Ballard 1999) have almost identical content to task planning (Junnonen 1998).

7.1.3 Forecasts and alarms

7.1.3.1 The case study evidence

The case study results show that although the general principles of location-based controlling were sound, the details of the system need to be adjusted and new tools developed. In particular, the forecasting and alarm system had problems which needed to be fixed to result in a better system.

It was found that to enable more and earlier alarms, the forecasts should be adjusted based on the prerequisite information (starting new locations or continuing suspended locations), resource information (availability of resources), and production management decisions. In addition, the forecasts should be calculated in real time immediately after the start of the task, instead of waiting for the locations to be completed in order to give earlier alarms. By redefining look-ahead planning as adjusting the forecast based on prerequisites, resource information and production management decisions, these goals could be achieved.

The alarm system generated alarms when the predecessor’s forecast caused the successor’s forecast to become discontinuous. This definition would have worked if all the tasks could be put in a fixed sequence. However, it was found in the case studies that many sequences could be altered freely. Even though tasks may not have a technical dependency, they can interfere with each other if they happen together in the same location. Because the plans tend to include only the technically mandatory relationships and relationships which fix conflicts which are apparent in planning stage, many unexpected conflicts can happen during implementation. Successors can start before predecessors, or totally unrelated tasks can happen simultaneously and cause problems. To solve these issues, a new kind of alarm was added to the system to visualize that two tasks were happening in the same location. It is then the task of the production management to find out if there is enough space in the location to have full productivity for both crews.

The tests in this research showed that the new forecasting and alarming system resulted in earlier alarms.

7.1.3.2 Other evidence

Schedule forecasts and alarms can be argued to be features of a location-based management system. Although experienced CPM practitioners often observe the actual performance of a subcontractor and update the durations of upcoming locations manually (Woolf 2007), this type of forecasting is a manual process. In critical chain method, the subcontractors or resources are asked to give weekly forecasts of the remaining durations of ongoing tasks (Eliyahu 1997: 166) and they are notified of the upcoming work on the critical path; first 10 days before the start of work, then three days before; and finally on the day before the start of work (p. 182-183). In the Last Planner System™ the forecasting of production problems and getting advance warning of problems happens principally through a social process, by monitoring the reasons for plan failure and improving forecasts if they are reasons for non-completion. (Ballard, Tommelein, Koskela & Howell 2002: 233). It is critical to collect information from any upstream production processes and anticipate the future (Howell & Ballard 1996). Forecast information is needed at different times for different decisions; for example distant flows might require a 12-week lead time, and labor could be adjusted in four weeks, while crew planning decisions can be made one week in advance (Howell & Ballard 1996). Many projects track productivity separately from the schedule (direct observation of projects reveals Excel spreadsheets for productivity analysis). Automated forecasting based on production rates and the prevention of upcoming interferences have not been (at least generally) discussed in technical literature.

Production rate forecasts have been part of location-based controlling techniques from the beginning (Kankainen & Sandvik 1993). However, these forecasts have been simplistic and just a graphical extrapolation based on actual production and finding the effects of a deviation to an immediate predecessor and successor. To the author's knowledge, complex forecasts taking into account dependencies, deviations from plans, different quantities, and resources in locations, have not been developed previously.

It has been recognized in literature that logic is not strict and there are different types of dependencies. There have been many attempts to classify the logic into categories. Kähkönen (1993) created a model for automating dependency creation based on location and dependency types. He recognized that logic can be unconditional or conditional. Only unconditional logic requires a fixed sequence. Conditional logic allows the planner to choose the sequence of tasks (Kähkönen 1993: 134-135). In other research projects, logic has been classified to enabling and impeding dependencies, and algorithms have been developed to automate rescheduling based on the dependency type (Koo, Fischer & Kunz 2007).

It has also been recognized that space congestion is a problem which affects productivity. Thomas, Riley and Sinha (2006) examined the productivity effects of space congestion and found out that labor inefficiency related to congestion was 30% in a case study. Riley and Sanvido (1995) categorized locations to 12 categories to show space congestion. These categories could be used to identify interference and to define patterns. The authors stressed the importance of following similar work patterns in each zone category to minimize interference.

7.1.3.3 A Discussion of the case study and other evidence

This research has validated that problems found in other literature can be forecast by the use of location-based data. The importance of space congestion to productivity has been discussed in technical literature (Riley & Sanvido 1995, Thomas et al 2006). Similarly, many authors have found that dependencies are not always mandatory, fixed dependencies can be categorized in multiple ways and changed during implementation (Kähkönen 1993, Koo et al 2007).

This research developed an improved forecasting method which was shown to better predict and generate alarms for space congestion. The new forecasts recognize that planners do not enter all the required dependencies to their plans, and that dependencies can be changed. Therefore, alarms are generated always when forecasts of two tasks enter the same location. Production management can then make a decision to react to the alarm or decide that the tasks can happen in the same location without interference. Although alarms and forecasts have been created by the Last Planners themselves, the use of a mathematical procedure to generate forecasts based on objective starting data and resource information, should improve controlling results also in projects implementing the Last Planner System™. The research findings show that subcontractor management increases in importance when PPC increases (Alarcon et al 2005). This indicates that forecasts and alarms may be the most difficult elements to improve using only a social process. If Location-based management is combined with Last Planner, the forecast and alarm information can be used in validating the soundness of assignments, together with other constraint information. Accurate forecasts are required to be able to make decisions sufficiently early and to staff according to the available workflow, instead of the standard decision to increase staffing when a schedule falls behind (Howell & Ballard 1996)

7.2 Reliability and validity

A case study research can be evaluated based on its reliability and validity (Yin 2003).

The reliability of the results was increased by including the three case studies, which all showed similar results. Although three is a small number of case studies, the reliability was increased by a statistical analysis of the status of the tasks in each location each week, resulting in a large quantity of data which increases reliability. The project teams self-reported their progress, and some errors were found in the progress data. However, because the analysis was dynamic, it was possible to fix the errors of the previous week based on information in the future. The amount of data pointing in the same direction was large, which further increased reliability. Production problems had to be inferred from the data because there was no mention of many problems in the supporting documentation. To evaluate the effect of this fact on reliability, the results were divided into certain, probable, and possible. Even though most of the problems were categorized "possible", there were enough probable and certain results that conclusions could be drawn from data with confidence.

Construct validity was improved by using multiple sources of information: project files, production meeting minutes, and direct observation on site. Internal validity was improved by using multiple analysis techniques: statistical correlation analysis, dynamic analysis of changes, and explanation building using the Flowline figures and resource information. The case study findings were compared to the findings in literature. Similar issues were found in the other literature, so the results generalized well. The external validity was improved by including multiple case studies, which represented well the current Finnish commercial construction. In three projects, there were three different General Contractors working in a standard contractual arrangement with the Owner. Even though one case study had an internal Owner, the contractual arrangement was standard. The project durations were short, which is a typical feature of the current Finnish construction industry. The case study projects included an office building, a shopping center with a large open space, and a retail park with multiple smaller retail stores.

The results generalize well to the Finnish building construction industry, and because of similar findings in the literature from other countries, it can be argued that the problems identified in this research are universal problems in the construction industry (at least in industrialized Western countries) and similar methods and processes can be applied globally. However, in all cases, projects were managed using a push methodology of control. The results may not generalize to projects where pull methodologies (such as Last Planner) are used.

The limitations of the case study research include the following:

- Actual resources could not be evaluated daily or allocated to tasks and locations which makes productivity analysis impossible
- Only Finnish building construction cases were used, which may decrease generalizability of results to international level and other types of construction.
- The case studies were comparatively small and simple. In more complex projects, issues related to design and change orders may be bigger factors affecting complexity
- Only crew interference -related issues were considered when examining the cascading delay chains. Although all the examined cascades were caused by resource management issues, there may be other delay chains caused by other factors.
- Because there was little evidence of real production control in these projects, conclusions can not be drawn about the overall benefits of location-based management. However, the previous action research case studies in Finland have shown that by the strong production control of individual tasks, the schedule reliability of the whole project can be improved (e.g. Toikkanen 1989, Hannukkala 1991, Tuominen 1993) .

7.3 Contributions to knowledge

This research has defined a method for the collection of production data from sites using location-based methods. Analysis of this data revealed reasons for the cascading delay chains - and proposed processes to prevent them. The key issue of subcontractor resource management was found to be the core reason for cascading delay chains which contribute to the apparent complexity of the construction projects. Although this in itself is not a new finding, this research provides new data to quantify the effects and analyze their root causes by using a location-based resource model. Methods were developed for calculating forecasts based on the actual production and resource availability. Look-ahead planning was redefined as adjusting the forecast to make it a pull controlling system. Ways to combine the ideas of the Last Planner System™ of production control with location-based management systems were proposed.

Using the location-based methods, it is easy to collect large amounts of data from construction projects in a consistent way. Data collection methods were developed as part of this research. Problems related with the reliability of self-reported data were discovered and discussed. Similar methods can be used to replicate the findings in other countries.

This research contributed new ideas to the discussion of complexity and chaos in projects. Cascading delay chains were found to contribute to the apparent complexity of construction projects. Working out-of-sequence and having more or less resources on site than needed were found to be key issues causing cascading delay chains.

This research interpreted pull controlling to mean minimizing work-in-progress by allowing more crews to the system only if there are free locations for the crews. This interpretation has not been previously generally discussed in technical literature.

Schedule forecasting methods have not been discussed a great deal in technical literature. The initial forecasting model was tested and improvements were made to those parts of the system which prevented forecasting problems on time. By adding look-ahead information, resource availability information, and using historical productivity information in a different way, it became possible to forecast many production problems over two weeks before they happened.

The case study projects implemented weekly planning and PPC measurement, but did not implement the Last Planner System. It was found that PPC correlated with other production variables. The important role of commitments and look-ahead planning were confirmed. Because the findings related to Last Planner and location-based management are well aligned, it was suggested that location-based methods provide tools to support the Last Planner production control processes. Methods were found to be complementary, instead of overlapping.

7.4 Implications to Construction Management

A key conclusion of this research was that it is not enough to implement location-based planning and controlling tools without implementing the supporting production control processes. The natural way of controlling projects in today's industry seems to be push control. Crews are mobilized according to the baseline schedule without considering the current state of the system. Controlling happens only when a subcontractor is delayed from the original baseline or detail schedule. Production problems are not openly discussed. The production meetings concentrate on describing past progress instead of planning how to prevent future problems. Prioritization and resource decisions are made informally without considering the production control system information. Instead of taking preventative action when upcoming problems are detected, the management tends to react to issues *after* the problem has already happened.

Based on the results of this research, the author has started the proper implementation of a location-based management system in multiple projects, both in Finland and in the USA. The initial results show that getting subcontractor involvement in the planning and open resource discussions are well received in the construction projects. However, the push control mentality is difficult to change. Everything goes well when the researcher is on site, but a return to push control starts immediately when the researcher leaves the site. This may explain the success of the action research case studies both in Finland and in the Last Planner™ research.

To ensure proper implementation, project teams need to get proper management or consultant support. A typical problem in the industry is that planning software is given to the project teams, and after software training they are expected to bring in the promised benefits of location-based management. However, training should not concentrate on the software but the pull control processes. Because the old ways are deeply entrenched in the mentality of project managers, they need continuous support from the company champions or external consultants to change their way of working. Otherwise the old processes are implemented with a new planning software and the full benefits are not gained.

The encouraging result of this research is that it is possible to know of many production problems over two weeks before they happen. Therefore, the complexity of construction related to interference between subcontractors can be managed, and it is possible to prevent cascading delays and production conflicts. However, this requires a different kind of attitude from project managers concentrating on systematic, proactive control instead of firefighting.

A practical contribution of this research was the implementation of the improved forecast and look-ahead system in the software package, Vico Software Control 2009. Most of the findings of this research have been incorporated into the new version of Control to make it possible for construction companies to implement the proposed processes.

7.5 Need for further research

There are multiple ways research can continue based on this research. The method for collecting and analyzing location-based data can be implemented in more case studies of higher complexity in different countries to replicate the findings. New forecast and alarm systems and proposed production control processes should be implemented in case studies with action research to find out how much improvement can be gained over the traditional processes and to further improve the processes. The productivity effects of interference should be added to the analysis to find out the productivity and cost benefits of implementation. An especially interesting research topic would be to implement the Last Planner System™ and location-based management in the same project to observe how much improvement location-based management can bring to Last Planner projects and vice versa. The findings of this research should be incorporated into developing the theory of production in the field of construction. Forecast could be further improved by distinguishing between conditional and unconditional dependencies (Kähkönen 1993). The overall solution should be extended to discuss the commercial terms between the parties and to be part of a more inclusive systems view which considers other factors such as design information and a lack of materials.

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A) Case study I: Kirkkonummi Prisma

A.1 Project description

Prisma is a Finnish retail chain. The case project was an expansion of 6,000 m^2 to an existing Prisma store in Kirkkonummi. The structure was pre-cast concrete and had a pre-cast façade. One side of the building had a curtain wall system. The project was composed of a shop hall area of 4,200 m^2, an air raid shelter / office area, and retail areas for small entrepreneurs, including a restaurant. There was a mechanical room on the roof and a rooftop parking area. The project was divided into five structurally independent sections of similar size. The first section had an air raid shelter. Part of the first and all of the fifth section had two floors. The other sections were the shop hall area and had only one floor. In addition to the expansion, there was some work to be done on the existing structure. This work was not included in the case study.

Also, the finishes and MEP were planned using the structural breakdown of the five sections and two floors. All the shop hall areas were identical. Sections one and five included offices, retail spaces, a restaurant, and a kitchen. The floor covering material of most of the locations was mosaic floor tiling. The kitchen and restaurant had special floor tiling. The shop hall ceiling was painted and the overhead ducts, pipes, and cable trays were visible. The fifth section had suspended ceilings in the retail spaces and offices. Sections 1 and 5 had interior walls, mostly plasterboard, but most of the kitchen walls were masonry.

The General Contractor of the project was Skanska Talonrakennus Oy. The project contract duration was from the beginning of August 2004 to the end of April 2005. The nine-month duration was considered tight. Otherwise the project was considered easy to plan and control in terms of its schedule. The project had an experienced team which had built many similar projects in the past.

A.2 Available starting data

When the location-based baseline schedule was planned, most of the procurement activities had not started. There was virtually no design of the mechanical, electrical and plumbing (MEP) systems. The master schedule had been planned using a bar chart based on similar projects in the past. The original schedule did not have any quantity or resource information, and did not consider crew continuity. However, the list of tasks and their sequence was comprehensive. The project team had never been exposed to location-based planning before.

The cost estimate of the project was on a rough level of detail and did not have quantities by location. There was no time to estimate the quantities again for the location-based system, so approximated percentages had to be used to roughly distribute the quantities to locations. There were no productivity rates available in the cost estimate because most of the work was subcontracted. Therefore general productivity rates had to be used for resource loading. The MEP work did not have any quantities available, and the MEP design was still ongoing when the master schedule was planned, so everything related to MEP was based on experience of similar previous projects. Consequently the original MEP schedule was created on a rough level of detail.

Some quantities were estimated by location by a project engineer. The quantities were estimated for the pre-cast structure for each element type, interior walls, floor covering, suspended ceilings, and wall finishes.

A.3 Schedule planning process

The project engineer was responsible for scheduling. He did not have prior experience of location-based scheduling. He had finished a traditional bar chart schedule which had been approved by the client. This had the effect of biasing the scheduling. Quantities, productivity rates and resources were used to plan durations, but the number of crews was changed so that the durations closely matched the original ones, instead of being able to optimize the schedule. This was necessary because the bar chart schedule had already been committed to.

In addition to the project engineer, the scheduling team included Skanska’s main user of location-based planning software and the researcher. The site manager and other project team members were not involved in the scheduling. Because our communications were only with the project engineerand mostly off site, it is unclear how well the rest of the team learned the system during the project. In this project, the project engineer did not want to use the planning software, so all the scheduling was done in the weekly meetings. The planning software was used by Skanska’s main user or by the researcher.

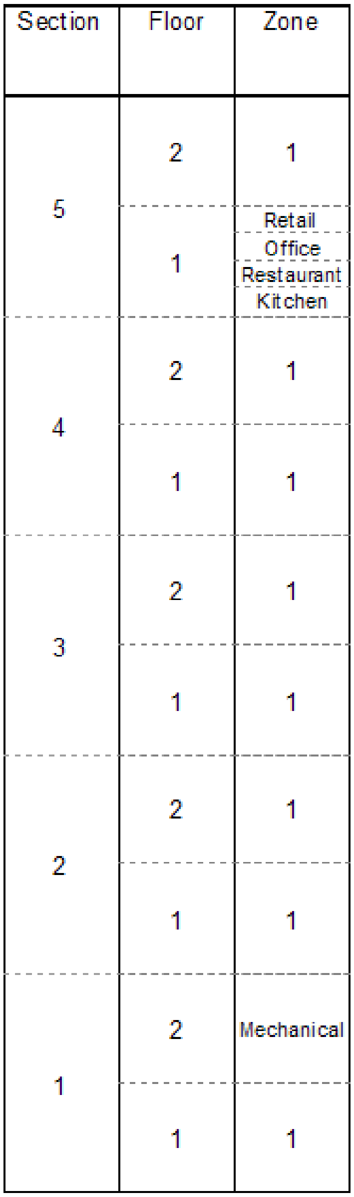
Because the bar chart schedule had been approved, only one main alternative was evaluated. Because the bar chart was not location-based, it was possible to add more detail to the locations and explore when the crews should be working in each area. The main benefit of the location-based planning was to reveal the criticality of section 5 with small spaces, which had not been fully appreciated by the project team before.

In the final baseline schedule, work was clearly divided into two main areas: the shop hall and the fifth section. Most of the production rates were synchronized, if possible, within the constraints of the approved baseline schedule dates. This was often possible because the original baseline schedule did not separate the shop hall and small retail spaces. Because resources were overlapping in these two areas, it was possible to adjust the production rate and still achieve the same start and finish dates. With the exception of the MEP work, all the task durations were based on the quantities and productivity rates from the Finnish productivity database, which has been created as a joint effort of the industry (Mäki & Koskenvesa 2002).

A.3.1 Location Breakdown Structure

The Location Breakdown Structure of the project was defined on three hierarchy levels. There were five sections which were numbered from one to five. Each section was subdivided into two floors. Section five was further subdivided into the kitchen, restaurant, office, and retail spaces. The locations of section five were small (100 to 500 m^2). The shop hall locations were approximately 1,000 m^2 each.

Using the location breakdown structure of the structure for the finishes trades caused problems, especially in the shop hall area where the natural flow of work was different than the location breakdown. Figure A.1 shows the location breakdown structure of the project.



Section	Floor	Zone
5	2	1
	1	Retail Office Restaurant Kitchen
4	2	1
	1	1
3	2	1
	1	1
2	2	1
	1	1
1	2	Mechanical
	1	1

Figure A-1: The Location Breakdown Structure of Prisma

A.3.2 Task list

The level of detail for the baseline schedule was moderate for the construction work, except for the earthworks and foundations, which had been finished before the scheduling started. For the MEP trades, the level of detail was very low. This was the result of not having completed the MEP design and not knowing who the subcontractors were to be.

The task list of Prisma is shown in table A-1 below.

Table A-1: Task list of Prisma

SYSTEM	TASKS
Earthworks / Foundations	Air raid Shelter
Structure, Roofing, Facade	Pre-cast concrete structure and facade, Exterior walls, Roofing, Installation of the trolley shelter, Curtain wall, Mechanical room steel structure
Finishes	Concrete floor topping, Masonry walls, Plasterboard walls and framing for gypsum board ceilings, Elastomer floor finishing, Mosaic floor tiling, Plasterwork, Painting first coat, Painting final coat, Painting of shop hall ceiling, Wall tiling, Floor tiling, Vinyl floor covering, Metal doors, Shopfront glass walls, Suspended ceiling frames, Molding, Closing suspended ceilings, Kitchen equipment, Final cleaning
Plumbing	Overhead plumbing and mechanical ducts and pipes, Floor drain installation, Plumbing and sprinkler in mechanical room, Installation of kitchen equipment
Mechanical	Overhead plumbing and mechanical ducts and pipes, Mechanical installation in mechanical room
Electrical	Cable trays, System cabling, Electrical and automation in mechanical room, Lighting fixtures, Installation of kitchen equipment
Automation	Electrical and automation work in main mechanical rooms
Commissioning	Tests, Measurement and tuning, Self-Commissioning, Installation of shop furniture (client)

A.3.3 Resources and productivity rates

The productivity rates and crews were taken from the Finnish generic productivity database (Mäki & Koskenvesa 2002). The number of required crews was changed to achieve the approved baseline dates and in some cases to align the schedule. In this project, the structure was comparatively fast. The bottleneck trades seemed to be related to the MEP, although this was impossible to determine because of the lack of information. The slopes of the finishes were aligned with the long durations of the MEP tasks. Resources were found to be overlapping in the shop area and in the fifth section.

A.3.4 Dependencies, lags, and buffers

On the baseline level all the tasks had dependencies, and the dependency network was complete. Because the start and finish dates of tasks were defined by the contract, the buffers were not a result of the decision making, but happened when a task start date in the approved schedule was later than the earliest start date calculated by the dependencies. Because the buffers had not been considered when designing the approved bar chart schedule, most of the tasks did not have any buffers. On the other hand, some of the tasks had buffers of two weeks or more (for example, the Plasterwork 14 days; the Wall tiling, 10 days; the Lighting fixtures, 16 days). There was a large one-month, end-of-project buffer reserved for commissioning activities. The resulting master schedule in Flowline format is presented in figure A-2.

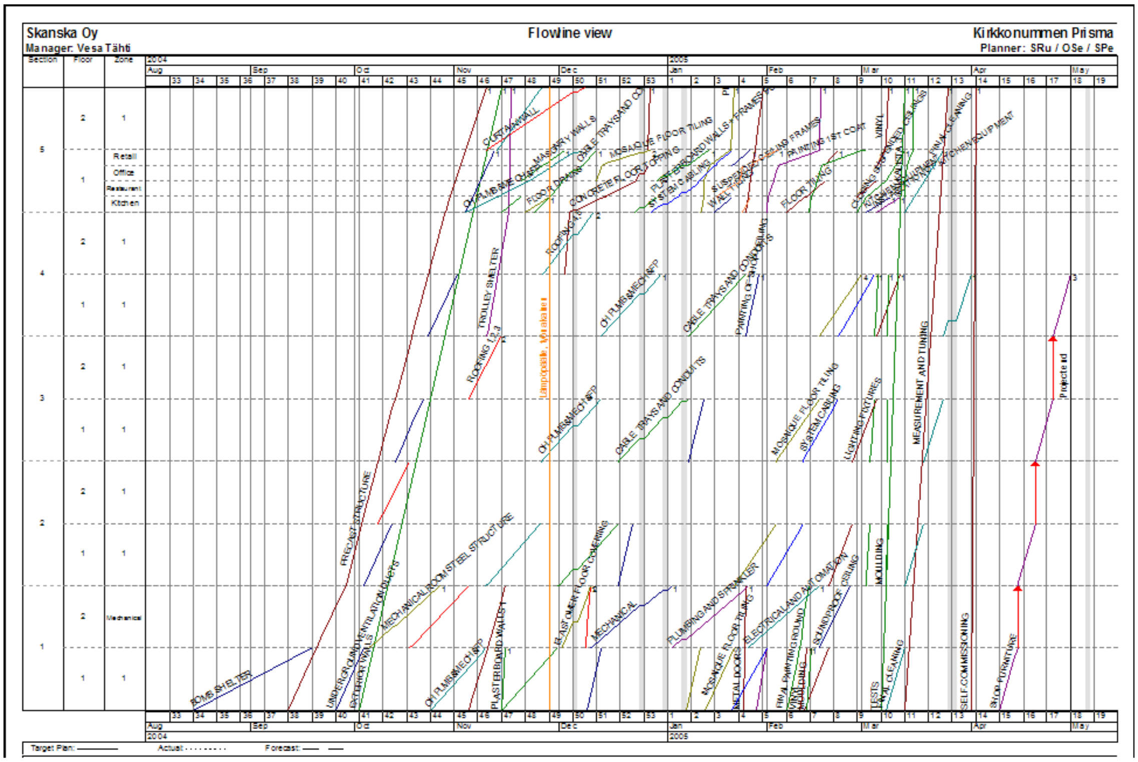


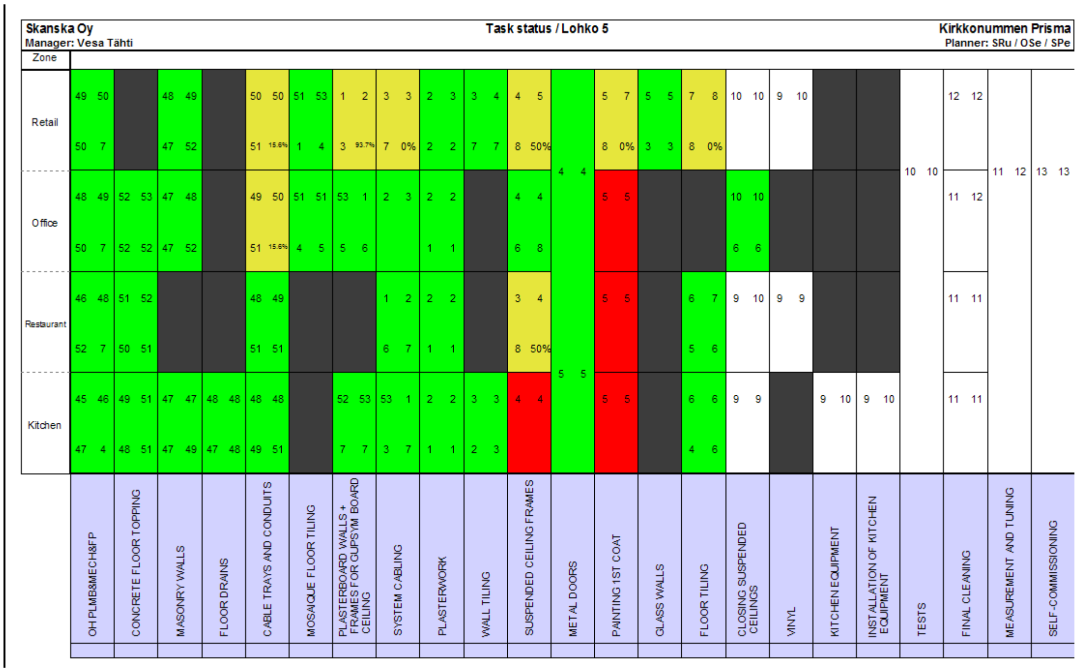
Figure A-2: Master schedule of the Prisma project

A.4 Schedule controlling process

A.4.1 Monitoring process

The status was monitored weekly by the project engineer, aided by the subcontractors. The project engineer prepared a Microsoft Word document weekly with the progress information and look-ahead information for each task. These data were entered by the researcher into the system in a weekly meeting. In the event of deviations, the reason of deviation was often known and recorded for the start-up delays and discontinuities. Slowdowns were often not noticed and were rarely documented. Also, the deviations of the MEP contractors were usually not recorded, with the exception of the works in the main mechanical room, and the tasks which had mandatory dependencies to the construction work (such as the floor drains or floor heating).

Control charts were used in the weekly progress meetings to discuss the deviations. Progress was compared against the baseline and detailed schedules. The red and yellow squares meant deviations, and were discussed to find out their reasons.



Skanska Oy **Task status / Lohko 5** **Kirkkonummen Prisma**
Manager: Vesa Tähti Planner: SRu / OSe / SPe

Zone	OH PLMB&MECH&FP	CONCRETE FLOOR TOPPING	MASONRY WALLS	FLOOR DRAINS	CABLE TRAYS AND CONDUITS	MOSAIQUE FLOOR TILING	PLASTERBOARD WALLS + FRAMES FOR GUPSYM BOARD CEILING	SYSTEM CABLING	PLASTERWORK	WALL TILING	SUSPENDED CEILING FRAMES	METAL DOORS	PAINTING 1ST COAT	GLASS WALLS	FLOOR TILING	CLOSING SUSPENDED CEILINGS	VINYL	KITCHEN EQUIPMENT	INSTALLATION OF KITCHEN EQUIPMENT	TESTS	FINAL CLEANING	MEASUREMENT AND TUNING	SELF-COMMISSIONING
Retail	49 50 50 7		48 49 47 52		50 50 51 15.6%	51 53 1 4	1 2 3 93.7%	3 3 7 0%	2 3 2 2	3 4 7 7	4 5 8 50%	4 4	5 7 8 0%	5 5 3 3	7 8 8 0%	10 10	9 10			10 10	12 12	11 12	13 13
Office	48 49 50 7	52 53 52 52	47 48 47 52		49 50 51 15.6%	51 51 4 5	53 1 5 6	2 3	2 2 1 1		4 4 6 8		5 5			10 10 6 6					11 12		
Restaurant	46 48 52 7	51 52 50 51			48 49 51 51			1 2 6 7	2 2 1 1		3 4 8 50%	5 5	5 5		6 7 5 6	9 10	9 9				11 11		
Kitchen	45 46 47 4	49 51 48 51	47 47 47 49	48 48 47 48	48 48 49 51		52 53 7 7	53 1 3 7	2 2 1 1	3 3 2 3	4 4		5 5		6 6 4 6	9 9		9 10	9 10		11 11		

Figure A-3: Example control chart of section 5 on week 9 (comparison to baseline schedule)

The actual start and finish dates of tasks in the locations were entered. If a location was ongoing for several weeks, the completion rate was used. The completion rates were based on the subcontractors' reports. If the completion rate of the previous week was the same as the completion rate of the current week, the task was considered suspended for the week. In this project, there were few apparent errors with the progress data. Using the subcontractor completion rates with blind checks worked very well. The actual resources were not recorded for the tasks, but they were reported by the subcontractors in the site meeting memos.

A.4.2 Views used

The schedules were reported and monitored by using the filtered Flowline and control chart views. These views were mostly used in the weekly scheduling meetings, but sometimes printed out and the given to subcontractors for their comments. These print-outs were not consistently used in communication.

In this project, views were created for the structure, roofing, section 5, and the shop hall. The subcontractor views were created for the MEP and related work stages and pours. The subcontractor views were not used consistently in this project. Only the MEP view was regularly printed out and edited based on subcontractor comments.

A.4.3 Production meetings

The subcontractor production meetings were held biweekly starting at the end of November 2004. The MEP contractors, General Contractor and the Owner's representative participated in these meetings. They were analyzed by the use of memos.

The ongoing tasks for every MEP subcontractor were described. In addition the total number of resources on site, the need for design specifications, and sometimes look-ahead information for the upcoming tasks were described. The look-ahead information was mainly given for construction tasks, probably the reason for this was to notify the MEP contractors of the upcoming construction work, which potentially could have an effect on the MEP work.

The deviations of the MEP tasks were documented in these memos. If there were major deviations, a separate schedule meeting was held with the responsible subcontractor. In these schedule meetings, the control actions were often discussed and more resources were requested from the subcontractors. Because the problems were well documented, this case study has the highest percentage of certain deviations. However, the problem descriptions usually did not talk about the interference the between subcontractors, but only about the subcontractor being late in an area.

The design status was reported by concentrating on the problems in the design and coordination issues. The focus was on the current missing design specifications or coordination issues. There is little evidence of looking forward to describe which design specifications would be needed in the future. The needed dates for the design were not documented.

Safety was documented by describing the result of safety measurements, and detailing any work-related accidents and near accidents.

Additionally, general contractor and subcontractor issues were addressed. These normally related to change orders, material deliveries, and quality issues.

A.4.4 Detailed task planning process

Detail task planning started in the structural phase in September 2004. The detail tasks were planned and updated weekly by the researcher in the scheduling meetings with the Project Engineer. More detail was added to the baseline tasks in the structural and roofing phases, and especially for the MEP tasks. Because the work in section 5 and shop hall was overlapping so that the same work was ongoing in both locations at the same time, each work type was analyzed as one detail task.

In many cases the detail tasks of multiple subcontractors were planned under the same baseline task. For example, the concrete floor topping baseline task included also the floor heating by the plumbing subcontractor as a detail task. This left out many alarms, because the alarm system assumed that alarms were not needed within the same baseline task.

In some cases, work was not there in the baseline schedule. This resulted in illogical task assignments. For example, the concrete floor topping baseline task in the technical room was exploded to include the plasterboard walls of the technical room, plasterwork, and painting. In these cases, these detail tasks were considered together with the other detail tasks of the same trade, instead of as part of the concrete floor topping (for example, the plasterboard walls with other plasterboard walls).

Table A-2 shows all the baseline tasks which were exploded to more than 1 detail task.

Table A-2: Level of detail of detail tasks

Baseline task	Detail tasks
Pre-cast concrete structure	Columns and beams; Walls; Slabs
Roofing	Initial pour on roof; Waterproofing; Thermal insulation: Eaves; Surface Slab
Curtain wall	Curtain wall frame; Curtain wall glazing; Wooden windows
Concrete floor topping	Concrete floor topping; Floor heating
Plasterboard walls	Drywall and framing for gypsum board suspended ceilings; Restroom suspended ceilings
Floor tiling	Floor tiling; Joints
Suspended ceiling frames	Suspended ceiling frames; Sprinkler drops in suspended ceilings
Elastomer floor finishing	Elastomer floor finishing; Fireproofing

Bottom floor ventilation and sewers	Bottom floor ventilation; Sewers
Overhead plumbing and mechanical ducts and pipes	Mechanical ducts; Storm drains; Fire hydrant lines; Sprinkler pipes; Floor sewers; Heating and water pipes
Plumbing and sprinkler in mechanical room	Plumbing in the mechanical room; The sprinkler in the mechanical room
Cable trays	Strong power cable trays; Strong power cabling; Electrical conduits
System cabling	Restaurant switchboard; System cabling
Electrical and automation in mechanical room	Main switchboard; Distribution switchboards; Electrical and automation installations
Lighting fixtures	Lighting fixtures; Lighting installation

The detail tasks were planned by task or phase. For example, the structure was planned as its own entity, roofing as one entity, concrete floor finishing as one entity, and then all the MEP and related tasks as one entity. Because of this approach, the schedule reached its final level of detail at the end of October 2004. After this, updates were only made to the existing schedule.

The subcontractors were involved in the planning of each of the major planning entities. Quantities were checked and the schedules underwent multiple iterations. However, even though quantities were requested from the MEP subcontractors, they did not provide the quantity information but just the duration. As a result, all the MEP tasks were scheduled without quantities and resources. The lack of resource information created problems, because all the subcontractors had a level use of resources throughout the project, but the schedule implicitly assumed changes in the resource requirements.

The dependencies between tasks were initially decided by the project engineer, and the resulting schedule was commented on by the subcontractors. However, the subcontractors did not understand the location-based scheduling and Flowline print-outs well enough to understand the actual flow of work. Major problems and deviations happened when the location-breakdown structure of the structural trades was imposed on the MEP trades. However, the MEP ducts and pipes flowed in the opposite direction. This caused the shop hall to have all the locations going on at the same time, as shown in figure A-4 (comparison to original baseline). Because the same location breakdown was given by the General Contractor, who did not understand the MEP subcontractor requirements, the location-based baseline schedule became irrelevant for the actual production in the shop hall area.

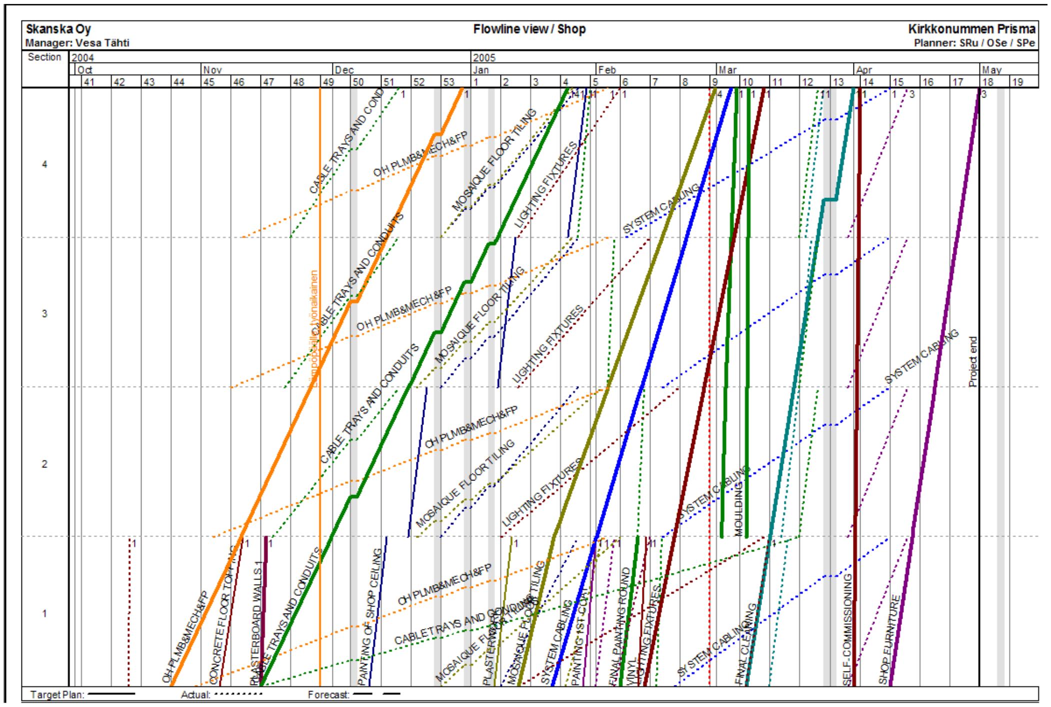


Figure A-4: Because of the wrong location breakdown structure, all the tasks seemed to happen at the same time in all locations

Detail task updating was based on a weekly document prepared by the project engineer. The document was based on discussions with the team and the main subcontractors. For each task, the document reported the completion rate in every location and the subcontractor's forecast of the finish date. The document also had look-ahead information for starting tasks; for example, specifying the start dates for upcoming locations or tasks.

Detail task updating started by checking that the detail tasks corresponded with the dates in the document. These changes were updated to the schedule. If tasks could not logically start on the specified date because of the dependencies to other tasks, these dependencies were discussed and wrong dependencies were removed. This approach resulted in the removal of many dependencies. Also, resources were not considered when shifting the start dates of tasks. Because of the lack of dependencies and resource information, this approach decreased the reliability of the detail task schedules. However, it resulted in removing over-optimistic assumptions of the start dates, because often tasks could not be started when specified in the schedule. The general trend of the updates was to push tasks in section 5 with small spaces forward to later dates, and to move tasks in the shop floor earlier in time, because there was room for them to start earlier.

After all the changes in the document had been incorporated into the schedule, the next four weeks were reviewed in detail. This process often revealed tasks which were supposed to start during the look-ahead period according to schedule, but were not known by the project engineer. These tasks were normally updated in the following week after investigation on site.

In this project, the detail task updating continued until the middle of March 2005. In the final two months, the detail tasks were not updated.

A.4.5 Control actions

The control actions were sometimes modeled in the schedule. Typically, tasks which could not start because a predecessor was not finished were updated to start later. Sometimes, the sequence was changed so that the task could start on the planned date in another location. Dependencies were often removed as a reaction to alarms. These removals involved an investigation of the issue and if the dependency was valid or not. Resources were not considered in the schedule. However, in the schedule meetings, more resources were demanded from the delayed subcontractors.

A.4.6 Weekly plan process

Weekly plans were generated as the end result of the updated detail schedule and control actions. The project engineer's weekly status document was used to set the weekly plan objectives. Therefore, the weekly plans were strongly based on what the project engineer thought it was possible to do. The status of the weekly plans was checked every week and PPC was reported back to the project engineer. Some interest in getting a better PPC result was observed.

A.5 Reliability of the baseline schedule

The results of the numerical variables described in chapter 3 show that the baseline schedule was not implemented very well in this project. Table A-3 shows the results for the numerical variables over 40 baseline tasks in the project. The results are presented using minimum, 25% quartile, median, 75% quartile, and maximum, in addition to mean and standard deviation, because the distributions are skewed.

Table A-3: minimum, average, maximum and standard deviation of selected numerical variables.

VARIABLE	MIN	25%	Median	75%	MAX	Mean	STD
Planned split points	0.00	0.00	0.00	0.25	4.00	0.38	0.81
Actual split points	0.00	0.00	1.00	1.00	4.00	0.87	0.95
Quantity deviation	0.60	1.00	1.00	1.00	1.75	1.06	0.22
Production rate deviation	0.30	0.62	0.80	1.24	5.00	1.21	1.14
Start date deviation	-24.00	-3.50	1.00	8.50	45.00	2.70	14.10
Finish date deviation	-15.00	1.00	14.00	22.00	53.00	13.72	15.01
PPC	20%	50%	71%	100%	100%	69%	25%

The results of table A-3 show that there were, on average, more discontinuities than planned. Although the median task was planned to be totally continuous, it actually had one work break. However, the fact that 75% of tasks had just one discontinuity or less, shows that breaking the flow was not a major problem in this project.

The actual quantities were, for most tasks, the same as in the baseline. However, there are some outlier tasks with lower or higher quantities. The exterior walls had a much lower quantity (60%) because part of the quantity was shifted to the pre-cast concrete structure task. This also caused a deviation in the structural quantities of 170%. Most of the other quantities were close to those planned.

The production rate deviation had a large range. There were some outlier tasks with very fast production rates and very low production rates. The much faster task was the kitchen equipment. This was clearly a planning error, because the task scope included just the delivery of the equipment, and it had been planned to take five days. The actual duration was one day. Tests of the mechanical equipment similarly had five days reserved, but the actual duration was one day. Of the quantity-based tasks, the final coat of painting had a 3.8 times higher production rate than planned. The concrete floor finishing had a production rate which was 3.5 times higher than planned. At the low production rate end, the elastomer floor finishing had 0.3 times planned production rate. This was caused by quality issues related to the floor getting wet because the roof was not finished and the consequent rework. Most of the tasks were close to the median, about 20 % slower than planned.

Consistent with earlier research by the author (Seppänen & Kankainen 2004) the start dates were much better controlled the than finish dates – the average delay of the start of an activity compared to the baseline was 2.9 days (median 1 day) and the average finish date delay was 13.7 days (median 14 days). High standard deviations and the range of the start date and finish date deviations indicate that there was high variability depending on the task. Examples of tasks which were significantly delayed were the HVAC installations in the main mechanical room (40 work days) and the installation of the drywall and gypsum board ceiling frames (53 work days). In both cases, most of the work had been done earlier, but some part of the scope could not be completed. Examples of tasks which finished early included the mosaic floor tiling which was finished 15 days before the baseline finish date. The mosaic tiling started six days late but had a 40 % higher production rate than planned.

PPC of the baseline tasks varied from 20 % to 100 %, with the median task having 69 % PPC (mean 71%). Very high PPC tasks were concentrated near the beginning (foundations) and end of the schedule (tests, self-commissioning activities, final cleaning) and low PPC tasks were mostly related to the roofing, finishes and MEP. The HVAC installation in the main mechanical room had a PPC of 20%.

Overall, the results show that the baseline schedule was not well implemented. Start dates were well controlled, but the large range of the finish date deviation shows that the baseline had little relevance for actual project implementation. Results indicate that tasks were forced to start on time according to the original baseline even though there were no prerequisites to productively finish them on time, which caused slowdowns of 20 % for the median task and an average delay of 13.7 days.

Table A-4: Baseline results

Variable	%
Planned Continuity	75%
Actual continuity	40%
Actual Location sequence	55%
Deviation: Start-up delay	33%
Deviation: Discontinuity	48%
Deviation: Slowdown	50%
Downstream:Start-up delay	38%
Downstream. Discontinuity	35%
Downstream: Production rate	35%

75 % of the tasks were planned to be continuous without breaks. However, only 40 % of the tasks were able to be implemented continuously. Because tasks only had one break on average, the productivity effects of mobilization and demobilization were limited in this project. The planned location sequence was implemented only for 55 % of the activities. During the detail task planning, the planned sequences tended to change every week based on the situation in the field. This may mean that instead of controlling production using the locations, the General Contractor let the subcontractors work in any area of their choosing.

Discontinuities of production and slowdowns were the most common deviation type, with 50 % of tasks being unable to achieve 80% of the planned production rate and 48 % of tasks having more actual than planned discontinuities. 33 % of tasks started more than one week late compared to the baseline. These figures show that the baseline was either not controlled very well or there were planning mistakes.

However, relatively few tasks caused problems to other tasks. Start-up delays were caused by 38 % of tasks. Discontinuities and production rate slowdowns were caused by 35 % of tasks. However, the same task could cause a lot of problems. For example, the “overhead plumbing and mechanical ducts and pipes” task caused production rate problems 16 times and discontinuities 9 times.

A correlation analysis was run for the baseline schedule data. The significant correlations are shown in table A-5.

Table A-5: Significant correlations of the baseline schedule data

Planned continuity - Start date deviation	**-0.39****
Production rate - finish date deviation	*-0.332**
Finish date deviation - PPC	**-0.5****
Start date deviation - finish date deviation	***0.441*****
Slowdown - finish date deviation	*0.367**
Discontinuity - DS discontinuity	**0.446****
Discontinuity - DS production rate	**0.61****
Slowdown - DS Start-up delay	**0.501****
Slowdown - DS Discontinuity	**0.613****
Slowdown - DS Slowdown	**0.921****

Many of these correlations are important for understanding the current practice of production control. Planned continuity was negatively correlated with the delay of start date, which may mean that tasks which were planned to be continuous by delaying their start date were actually started as early as possible. This was confirmed by observation on site. Tasks which had a delayed start date because of continuity constraints were often started as soon as there was a location free for work to start. Importantly, PPC was related negatively to the finish date deviation. Tasks with high PPC tended to finish according to the baseline. The result may be interpreted in two ways: achieving a high PPC improves the production of the task and allows it to finish sooner, or finishing according to the baseline improves PPC, possibly because the assignments are defined based on the baseline targets. The finish date delay correlated also with experiencing slowdowns caused by other tasks and naturally the start date delay. Experiencing discontinuities and slowdowns often caused cascading downstream effects to other tasks, which means that the buffers in the project were insufficient. The very high correlation of slowdowns and downstream slowdowns shows that almost all the tasks with experienced slowdowns also caused slowdowns to succeeding tasks.

These results give evidence that production problems caused by preceding tasks contribute to the schedule failure of the succeeding tasks. The aim of a production control system should be to decrease these interrelationships by better planning, buffering tasks from variability, and controlling tasks to prevent them from affecting each other.

A.6 Reliability of detailed schedules

Detail schedules are planned with better data just before implementation of a task. They should capture the mutual commitment of the GC and the subcontractors. Therefore, they should be more reliable than the original baseline schedule which is done with incomplete information and design.

The reliability of the detail task planning process was evaluated by comparing the progress data to the detail task schedule of the week before the detail task started. The actual method of selecting the comparison date has been described in the Method sections (Chapter 3). Any updates after the start of production were ignored in this comparison. The variables used in the analysis were the same as with the baseline tasks. Table A-6 shows the results of the numerical variables.

Table A-6: Reliability results of detail tasks

VARIABLE	MIN	25%	Median	75%	MAX	Mean	STD
Planned discontinuities	0.00	0.00	0.00	1.00	9.00	0.66	1.45
Actual discontinuities	0.00	0.00	1.00	1.00	3.00	0.74	0.85
Quantity deviation	0.34	1.00	1.00	1.00	6.54	1.05	0.73
Production rate deviation	0.24	0.62	0.88	1.31	6.00	1.32	1.28
Start date deviation	-33.00	0.00	0.00	5.75	34.00	3.34	10.61
Finish date deviation	-29.00	0.00	9.00	16.00	41.00	9.44	13.79
PPC	0%	45%	67%	96%	100%	64%	27%

The data show remarkably similar results for the detail schedules as for the baseline schedules. The median task had a production rate of 88 % of that planned, compared to 80 % in the baseline. Extreme cases were even more pronounced on the detail task level, with the highest production rate of 600% of that planned, and the lowest being 24 % of planned. The start dates were better controlled, which is to be expected, because the comparison date was one week before the actual start. Therefore most tasks started exactly on time. Finish dates were delayed by 9 days on average (mean 9.44, median 9 days), compared to 14 on the baseline level. This is not a very big improvement over the baseline. As a conclusion, the detail task planning process was as badly flawed as the baseline planning process, despite much better information and cooperation with the subcontractors. The schedules were more indicative of what should be done than what actually could be done, and therefore had limited value. Subcontractor resource availability and other constraints should be considered in planning detail plans and there should be an explicit commitment to the detail plan objectives. In this project, the detail tasks were planned based on discussions with the subcontractors, but the commitment was not systematically captured.

Table A-7: results of the detail tasks

Variable	%
Planned Continuity	69%
Actual continuity	48%
Actual Location sequence	61%
Deviation: Start-up delay	26%
Deviation: Discontinuity	35%
Deviation: Slowdown	44%
Downstream:Start-up delay	29%
Downstream. Discontinuity	27%
Downstream: Production rate	31%

On the detail task level, the discontinuities were not so big a problem. Continuous work was planned for 69 % of the detail tasks (75 % in baseline), and 48 % of the detail tasks were actually continuous (40 % of baseline tasks). Unplanned discontinuities happened for 35 % of tasks (48 % in baseline). 61 % of tasks followed the planned sequence. This reflects the poor reliability of the detail task planning process, because plans were created one week before the start of the work.

Table A-8: Significant correlations of detail task variables

Quantity based - slowdown	*-0.259**
Quantity based - DS slowdown	**-0.36****
Actual continuity - production rate	*0.289**
Start date deviation - actual discontinuities	*-0.318**
Start date deviation - finish date deviation	**0.408****
PPC - finish date deviation	**-0.429****
Production rate - finish date deviation	**-0.426****
Finish date deviation - DS slowdown	**0.386****
Slowdown - DS slowdown	**0.726****

Table A-8 above shows the significant correlations from the detail task numerical variables. Importantly, tasks based on quantities had a negative correlation to both experiencing and causing slowdowns. To prevent cascading production problems, quantity information should be collected for each task at the latest in the detail task and commitment phases.

Continuously performed tasks were often performed a with higher production rate. This gives some evidence of the productivity improvement caused by continuous work, as predicted by the location-based planning theory.

Starting later correlated with less actual discontinuities. This is in line with the location-based planning theory which delays start dates to achieve continuity.

The start date delay correlated strongly with the finish date delay, which indicates that the start dates were delayed often so much that they could not be recovered by control actions. Typically detail tasks have shorter durations than baseline tasks, which explains this correlation: any deviation in the start date is more likely to result in a deviation to the end date.

Similarly to the baseline results, the finish date deviation also correlated strongly negatively with PPC, i.e. the tasks with higher PPCs tended to finish earlier compared to the planned finish date. However, it is impossible to define cause-and-effect based on the correlation information. Similarly to the baseline level results, also on this level of detail the slowdowns suffered by the task and the downstream effects caused by the task were heavily correlated.

A.7 Analysis of weekly plan reliability

The weekly plan reliability was analyzed by use of PPC. Previous sections have described the PPC averages for both the baseline and detail tasks to find correlations to the other variables. Figure A-5 shows PPC as a function of time.

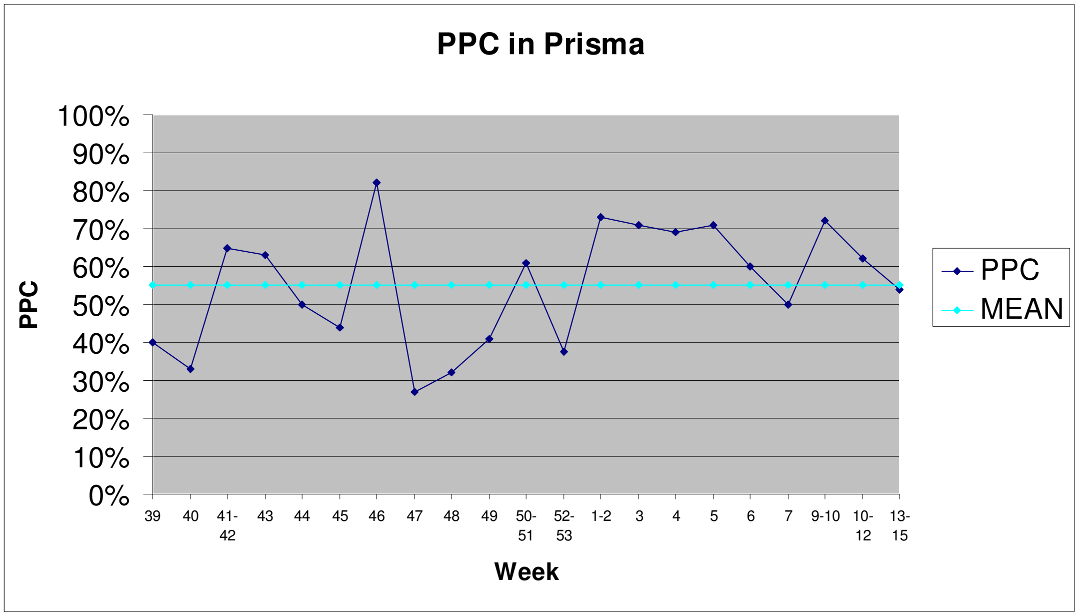


Figure A-5: PPC as a function of time in Prisma

The average weekly PPC was 55 %. There are some bad weeks which decrease the PPC between weeks 47 and 53, then PPC increases to 70 % and keeps steady for four weeks. At the end of the project, there is another dip back to the average levels. 55 % PPC is not a good result. In the previous research, PPC has started at a 50 – 60% level, but has gradually improved to 80 % and over (e.g., Ballard 2000). However, the goal of those research efforts has been to optimize PPC. In this research, PPC was measured and communicated to the project team, but it was not the goal of the research to intervene in any way. Instead the goal was to observe how high or low PPC affects the other variables used in the study.

A.8 Analysis of problem tasks

In the previous sections, both the baseline schedule and detailed schedules were found to be unreliable. In this project the baseline plan had little buffers, MEP tasks were not based on quantities and were on a very rough level of detail and the Location Breakdown Structure was not suitable for the MEP and finishes tasks in the shop hall area. The schedule of the shop hall was relaxed and many tasks could start ahead of the baseline there, but the schedule of section 5 was tight and had small locations.

A total of 124 production problems were identified from the project data. Because there were 62 detail tasks, an average task caused 2 problems to the other tasks during implementation. However, this distribution was skewed. The worst tasks caused 11 problems to the other tasks and many tasks did not cause any problems. Of these 124 problems, 36 could be verified with certainty (29 %). 30 problems (24%) were probable and the remaining 58 (47 %) were possible. Discontinuities and start-up delays were easiest to verify based on other information (start up delays: 10 certain, 18 probable, 6 possible; discontinuities 19 certain, 6 probable, 11 possible). The production rate problems (7 certain, 6 probable, 41 possible) were most often inferred from the project data and had no mention in the project memos.

In 34 cases (27 %), an alarm was generated before the problem happened. On average, the alarm was generated 17.5 workdays before the problem. In the worst case, the alarm was generated on the same day, and in the best case, the alarm was generated 45 workdays before the problem.

17 alarms (50 %) resulted in a control action. On average, the control action was effective 5.6 workdays after the alarm was generated. In the best case, the control action happened immediately and in the worst case, 15 days after the alarm. The production rate was increased in 3 cases, the plan was changed 16 times. In all of

these cases, the control actions were inadequate because the problem actually happened.

Control actions were effective in those cases where an alarm was generated, but the problem did not happen because of a successful control action. There were 29 alarms which did not result in a problem. Of these, 13 were false alarms. Control actions were implemented to remove 14 of the alarms. The remaining two problems did not actualize, because the succeeding tasks were actually delayed by something else. Control actions involved increasing the production rate of the predecessor (5 times), changing the plan (7 times) and suspending a task (2 times).

These data reveal five interesting classes of cases: 1) problem – no alarm 2) problem - alarm – no control action 3) problem - alarm – failed control action 4) problem - alarm – successful control action 5) false alarm. These cases are explored in more detail in the following section.

A.8.1 No alarm

89 cases which resulted in a problem but where no alarm was generated were analyzed more closely. Five groups of cases were found.

Case 1: Missing dependency

25 cases out of 90 cases (28%) had a missing dependency link in the system, i.e., the system did not know that the tasks would cause problems for each other. Usually these cases happened for tasks which were delayed a lot from the original baseline and the planner had not added the link, because it would not have been necessary if the original plan had been followed. Another common reason was that the tasks could be done in either sequence but not at the same time.

Examples:

- The elastomer floor of the mechanical room did not have a link to the waterproofing of the roof above. The roof should have been finished a lot earlier
- The masonry walls did not have a dependency to the mechanical ducts, because they could be done in either sequence, however not at the same time. Delays in both tasks forced them to start at the same time resulting in problems.
- The floor drains resulted in problems to both the masonry walls and the mechanical ducts, because they could not be done at the same time

Case 2: Many tasks in the same location

In 37 cases (42%), there were many tasks going on in the same location and they were slowing each other down. There was no dependency link in the system. In these cases there was no actual technical dependency, but multiple trades working in the same location did not have enough space to work productively. In these cases, one or two trades might be able to work with a normal production rate and the others had to slow down.

Examples:

- The electrical, sprinkler, mechanical ducts, and roof water drains going on at the same time in a small location
- The fire hydrant lines, mosaic floor tiling, shop ceiling painting, sprinkler, and lighting fixtures going on at the same time in one section of the shop floor (area of 1,000 m2).

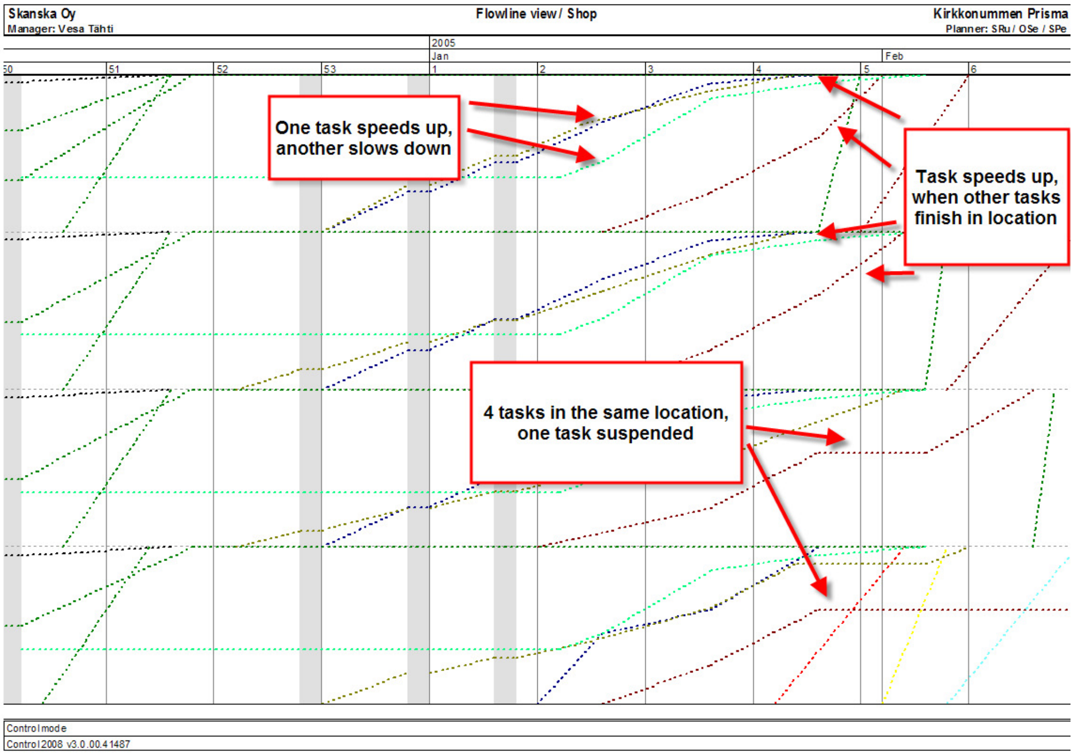


Figure A-6: Tasks tended to slow down or get suspended when many tasks happened at the same time in the same location

Figure A-6 above illustrates this problem type. The shop hall locations were large (1,000 m^2 each) but at any given moment, there were up to four tasks working in the same location. All the tasks had lower production rates than planned when they happened together. In the figure, there are three problem types illustrated. If one task speeds up in the location, the other tasks tended to slow down. If new tasks entered the location, a previous task often slowed down or was suspended. The productivity effects of the tasks in the same location are best seen from the third example in figure A-6, where a task speeds up considerably after the other tasks finish in the location. It should be noted that in the original plan all the tasks were planned to happen alone in their location, but a decision was made to start the tasks early, because there was seemingly room to commence work. From the example above, it seems that this decision had a cost in terms of productivity.

Case 3: wrong dependency in the system

In 1 case out of 90, the link was there but it was incorrect. The air raid shelter was planned to overlap with the structure with a negative lag in the logic link. The structure started according to the planned logic, but air raid shelter still caused a productivity problem to the structure.

Case 4: Not at the same time in the same location

17 times (19 %), tasks were suspended or had start-up delays because they could not enter the same location at the same time as another task. In this case there was no technical dependency – the tasks could be done in any order. However, the work space was too small for both to continue at the same time. This type is similar to the productivity loss described in case 2. In some cases, the tasks sometimes prevented each other from working in the same location, and sometimes slowed each other down. It may be that this is actually the same problem type, but the subcontractor made a decision to suspend work instead of working with lower productivity and hence higher cost.

- The mosaic floor tiling was suspended when the plasterwork started in the location (two times in two different locations)
- The suspended ceiling frames were suspended when painting started in the location

Case 5: Problem within the same baseline task

In 4 cases (4 %), the problems were caused between the detail tasks of the same baseline task. Location-based planning assumes that the same task contains only the work done by the same subcontractor, and thus alarms are generated only if another subcontractor is going to have problems. However, in this project, the detail tasks of the different subcontractors were sometimes planned within the same baseline task and could interfere with each other without causing alarms in the system.

Examples:

- The waterproofing subcontractor caused problems to the contractor pouring the surface slab on the roof for many weeks. There was no alarm, because both were part of the "Roofing" baseline task

Case 6: Start-up delay caused by plan change

In 3 cases (3%), the start date of a task which was supposed to start the next week was suddenly changed. This change often resulted from the fact that other work was going on in the area.

Examples:

- The sprinkler and storm drains were delayed in section 1. The painting of the shop hall ceiling was planned to start during the following week. The plan was changed so that the painting of the shop hall would be done after the mosaic floor tiling. This problem was classified as being caused by the sprinkler and storm drains, which initiated the plan change.

Case 8: Other

Two alarms were not given because of some other reason which was not possible to categorize.

A.8.2 Alarm → no control action

There were 20 cases when an alarm was generated before the problem, but no control action was implemented. Table A-9 shows how many days before the problem the alarm happened, and whether a control action took place. The table includes all the cases where the problem happened and all the cases where the problem did not happen but an alarm was correctly generated. False alarms have been removed from table.

Table A-9: Days before alarm and control actions

Days before alarm	No control action	Control action	Total
0-5	2		**2**
5	6	3	**9**
10	5	5	**10**
15	3	6	**9**
20	3	6	**9**
25	1	2	**3**
30		2	**2**

>30	0	8	**8**
Total	**20**	**32**	**52**

A chi2-test of the data shows that this kind of distribution could have happened by chance, assuming that the variables were independent with probability of 6.6 %. This is not a statistically significant result, but is still indicative. Alarms seemed to affect the project engineer's decision making in the weekly schedule control meetings. When the system indicated a new alarm, the project management usually did not believe in it right away, but started to gather more information. In cases where an alarm persisted for many weeks, the likelihood of the management believing in it increased and finally led to action.

Because the time of an alarm before the problem seems to have an effect in guiding control actions, the reasons for an alarm being generated ten days or less before the problem were examined by looking at 21 cases in detail. Each alarm was examined and the status of the previous week was observed to see why the alarm was not generated earlier.

Case 1: Start-up delay in the first location

In one case, the delayed alarm happened because the first location of the predecessor task started too late. Unexpectedly, the vinyl floor covering did not start on its planned control date. In the next schedule meeting, the start date was already delayed by four days and an alarm resulted. For tasks which should have been able to start because all the predecessors were completed, the forecast assumed they would start on the control date. This assumption was the reason for delayed alarms.

Case 2: Suspension of predecessor

In two cases, alarms were generated late because the predecessor was suspended and the forecast assumed that the suspended tasks would continue on the control date. This is closely related to case 1.

Example:

- The masonry walls were suspended because of the concrete pours. The system assumed that the work would continue right away, but actually the work continued a lot later and interfered with the cable tray task. An alarm was generated just five days earlier

Case 3: Detail plan updates

In four cases, detail plan changes caused immediate alarms. Typically, a dependency was added to the system

Example:

- The detail plan for the mechanical ducts was planned ten days before the ducts caused a problem to the cable trays. There was an immediate alarm.

Case 4: Progress information errors

In one case, there was error in the progress information which was corrected too late. The structure was marked complete in the first section, even though there was one broken slab which had to be replaced. This slab prevented the roofing work from starting. When the progress information was corrected, there was an immediate alarm, 5 days before the problem happened.

Case 5: Schedule forecast over-optimistic

Four cases happened because of an over-optimistic forecast. The schedule forecasting technique assumed that the forecast could not be calculated based on the first location, because the beginning of the task always has production problems. However, this project had large locations, and there were problems related to completing locations because the location breakdown structure had not been adequately designed to accommodate the mechanical, electrical and plumbing contractors. Therefore, the production rate forecast was calculated comparatively late. This caused the system to miss many alarms which could have been noticed earlier if the forecast was generated immediately when the data became available. Still more problematic were cases where a task existed only in one location but was of long duration. Example tasks were the air conditioning machine room tasks, which interfered with each other weekly.

Case 6: Sudden slowdown in the middle of a location

In two cases, the predecessor suddenly slowed down in the middle of a location. Because the forecast assumes that the work continues with the same production rate, this resulted in late alarms. It may be that the slowdowns were caused by the lack of prerequisites of continuing, for example errors in the design or a lack of materials.

Example:

- The mosaic floor tiling suddenly slowed down in the middle of a location, which caused an alarm just ten days before the problem. If the mosaic floor had continued with the same rate, an alarm would not have been needed.

Case 7: Starting successor early

In two cases, an alarm resulted from starting a successor out of sequence. For example, the lighting fixtures were planned to start after the mosaic floor tiling was completely finished, but they started while the mosaic floor tiling was still ongoing, resulting in an immediate alarm.

Case 8: Miscellaneous reasons

The remaining five cases were caused by other reasons which were difficult to classify.

A.8.3 Alarm → Control action → problem

In 16 cases, a control action took place, but the problem still happened. These cases can be divided into seven groups.

Case 1: Dependency was changed or removed

In 8 cases, an alarm was removed by changing or removing the dependency causing the alarm. These changes were often over-optimistic, and even though the succeeding task could be successfully started in the location, there were slowdowns or discontinuities during production. Many of these problems happened in the main mechanical room. Originally, the plumbing work in the main mechanical room was supposed to start after the mechanical contractor was completely finished in the location. The electrical contractor was supposed to come in after the plumber was completely finished. However, the mechanical contractor was delayed and plans were changed so that the tasks were overlapping. These changes removed the immediate alarm, but caused a total of 17 production problems inside the mechanical room. Figure A-7 illustrates these problems.

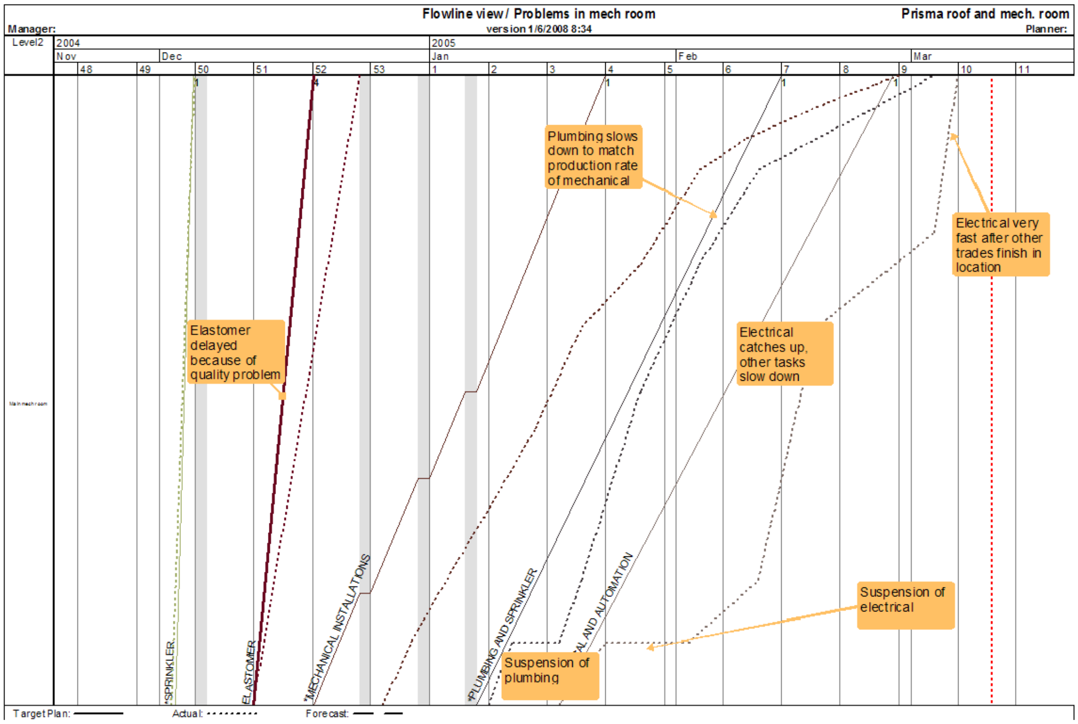


Figure A-7: Problems in the Prisma main mechanical room caused changing the plan, so that the mechanical, plumbing and electrical contractors work in the main mechanical room happened simultaneously

Case 2: Successor start date delayed as a control action

In three cases, an alarm was removed because a successor was shifted to start later and the planned start date of the successor was the next week. Because the commitments were not recorded in the system, it was assumed that a change in the start date communicated in previous week would in itself cause a problem to the subcontractor. Therefore, this control action was considered valid only if the plan change was done more than one week before the planned start date.

Case 3: Error in progress information

In one case, the production rate of the structure was increased to prevent problems to the succeeding task. However, there were errors in the progress data and a location which had been considered complete was still in progress. An alarm was removed, but the problem still happened.

Case 4: The plan was changed to remove an alarm, but the changed plan was not followed

In two cases, a plan change was done to remove an alarm. However, the changed plan was not followed and the problem happened. For example, it was known that the mechanical room steel frame would be delayed because of production rate issues. The roofing plan was changed to start in other locations first, and to go to the main mechanical room area later after the completion of the steel structure. This plan change removed the alarm, but the production rate problems happened when the roofing contractor started in the mechanical room section earlier than planned.

Case 5: Predecessor production rate was successfully increased but the successor was too fast

In one case, the control action would have been successful, but the successor task suddenly increased the production rate, which caused a problem. The production rate of the structure was increased to prevent a clash with the ventilation work in the crawl space. However, the ventilation work increased production rate also which caused a new clash with the structure.

Case 6: A control action was implemented but was too small to prevent the problem

In one case, the production rate was increased by over 20 %, but it was not enough to prevent the problem or remove the alarm.

Case 7: Miscellaneous causes

One case was not easy to classify and involved complex circumstances.

A.8.4 Alarm → Control action → no problem

There were 14 alarms which did not actualize because the problems were prevented by successful control actions. The production rate was changed 5 times, 7 alarms were removed because of a change of plan, and 2 alarms were removed by suspending a task in a location.

Control action type 1: change of production rate

A production rate increase removed an alarm and prevented the problem 5 times in the project. In one case, there was supporting evidence that resources had been added. Other times, the production rate increase was unexplained. In these other cases it is possible that the resources worked overtime to catch up, or there was a factor affecting productivity negatively which was removed.

Control action type 2: plan change

The plan was changed so that it removed the problem in 8 cases. Dependencies were changed in three cases. For example, the dependency of the roofing work to the concrete floor topping inside was removed, and it was decided that temporary weather protection would be used if necessary. In another example, the painting of the shop hall ceiling was planned to happen before the mosaic floor tiling. The dependency was changed so that the mosaic floor tiling would happen first in two sections and the painting would happen first in two sections.

In three cases, successor start dates were shifted forwards to remove alarms. This was not classified as a start-up delay if the change happened two weeks or more before the task should have been started in the previous schedule.

In two cases, the plan was changed to change the sequence of the successor task. For example, the suspended ceiling frames task was changed to happen last in the location where the wall tiling was delayed.

Control action type 3: suspending a task

In two cases, an alarm was removed by suspending the predecessor to allow the successor to start according to the plan. Both the masonry walls and the mechanical ducts were suspended to allow floor pours to take place in section 5. This control action caused a problem to the masonry wall contractor because he did not have another location to work in. However, the mechanical contractor had other tasks going on at the same time and could work in the other locations with no loss of productivity. Figure A-8 shows both of these examples.

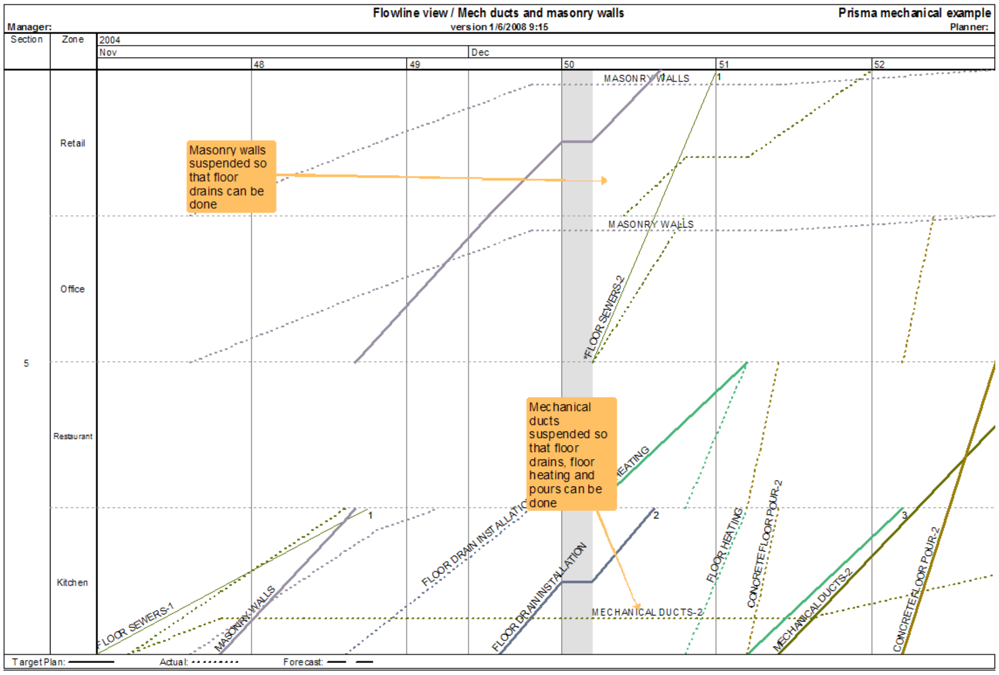


Figure A-8: Examples of suspending a task as a control action so that other tasks can continue

A.8.5 False alarms

There were 13 false alarms during the project. These are damaging to the perceived reliability of the alarm system and may lead to delayed reaction or no reaction to valid alarms.

Case 1: wrong dependency

In seven cases the reason was a wrong dependency. Examples:

- The plasterboard walls had been defined as a predecessor to the suspended ceiling frames. In fact these tasks could happen together
- The main mechanical room concrete pour was a predecessor to the elastomer floor finishing, with a 10-day lag. In reality, the 10-day lag was an overly conservative estimate of the concrete drying time and the elastomer could start earlier.

Case 2: Same subcontractor and resources

In two cases, an alarm was generated when a task of the same subcontractor and the same resource type was going to cause problems to another task of the same subcontractor. Because in this case, there is no break of commitment or problems in hand-over between subcontractors, these cases can be classified as false alarms. For example, the wall tiling was delayed and this affected the start time of the floor tiling. Because the same people were doing both tasks, there was no problem.

Case 3: Same location at the same time but no problem happened

In one case, the dependency was valid, the tasks happened in the same location but no problem happened according to the progress data. The mosaic floor tiling was a predecessor to the lighting fixtures. The lighting fixtures started while the mosaic floor tiling was still in progress. However, there was no immediate effect on the production rate of the lighting fixtures.

Case 4: Tasks should not be in the same location but could be done in any sequence

In one case, the dependency had been chosen, but in reality the tasks could happen in any sequence – just not at the same time. For example, the heating pipes had a dependency to the suspended ceilings. When the tasks were going on in the same location, the suspended ceilings caused a problem to the heating pipes but could finish before the heating pipes did.

Case 5: Wrong progress information

In two cases, a false alarm was generated because the forecast was operating on the basis of false progress information. There was a task in the shop hall related to “other electrical cable trays”. Actually, all the electrical cable trays had been finished as part of the scope of the Strong power cable trays task. This fact caused two false alarms – one because the preceding tasks were not finished, and one because of the forecast delay of this task. This error was found and the task removed only after several weeks.

A.9 Analysis of construction phases

Based on the data gathering process and discussions with the project engineer in the weekly progress meetings, it became clear that different construction phases work in very different ways. There was a feeling that everything in the Foundations and Structural phases were very well controlled, but things started to get out of control during the interior construction; especially related to the mechanical, electrical and plumbing activities. Those tasks did not seem to follow the decisions of the project management, but instead seemed to operate on an entirely different logic.

To evaluate the hypothesis that there was a fundamental difference between the interior work and the other work stages, the main numerical variables were calculated for each construction phase: Foundations, Structure, Roofing, Façade, Interior construction work, Interior MEP work, and Commissioning. The results were calculated for production rate deviation, start date deviation, finish date deviation, PPC, each production problem type, and each downstream effect type. The analysis was done only for the detail tasks.

A.9.1 Production rate deviation by construction phase

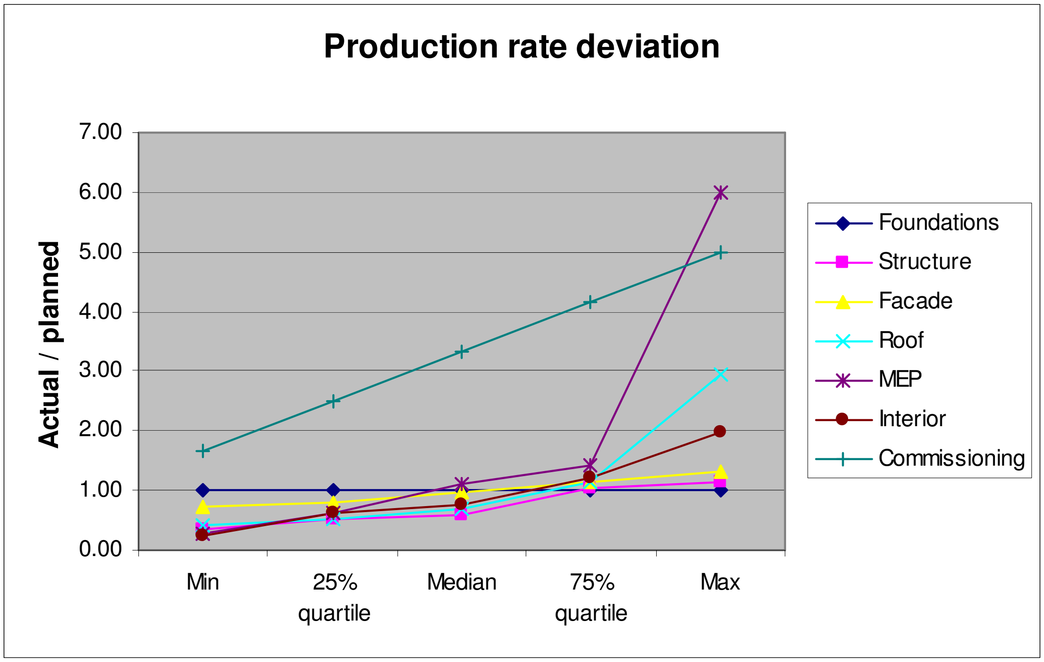


Figure A-9: Production rate deviation by construction phase

Figure A-9 above shows the range, quartiles and median of the construction phases for production rate deviation. MEP has both the smallest minimum and the largest maximum. All the commissioning related activities were done much faster than planned. Based on direct observation, the commissioning related tasks had to be accelerated because the end-of-project buffer had been exhausted. However, it can not be concluded based on these data that the production rate deviations compared to the plans were notably different between the other construction phases.

A.9.2 Start date deviation by construction phase

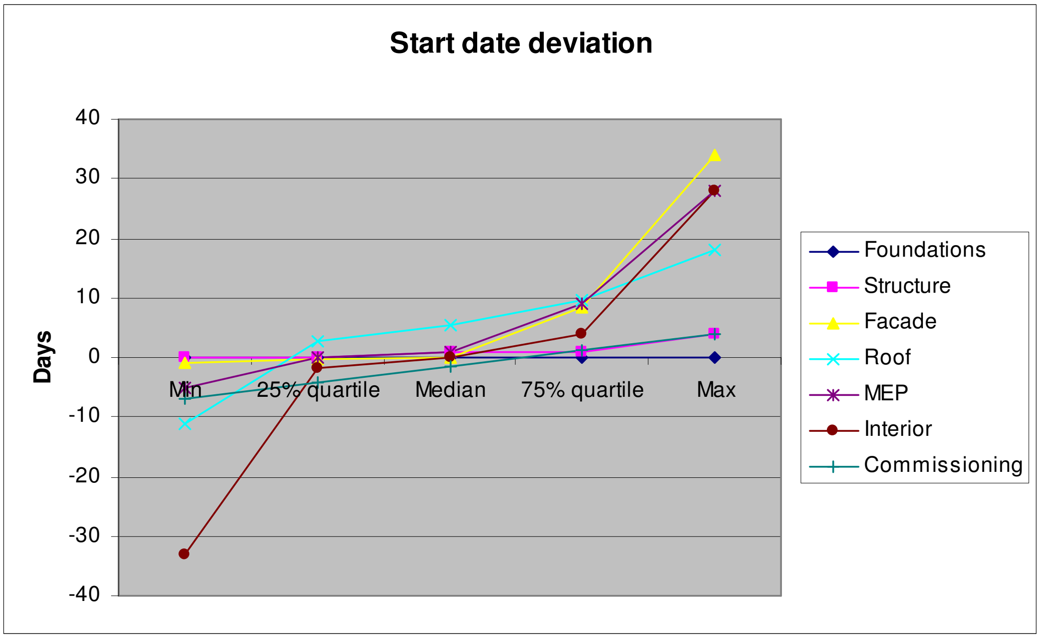


Figure A-10: Start date deviations by construction phase

In the start date deviations (Figure A-10), some differences start to emerge. The roofing, interior work, façade and MEP work clearly have higher start date deviations for tasks in 75 % quartile and maximum. However, the differences are small. This can be explained by the fact that the start dates were well controlled in this project.

A.9.3 Finish date deviation by construction phase

The finish date deviation follows the same pattern (figure A-11). Commissioning has all the values below the line, which is understandable because if any commissioning-related activity is delayed, the whole project would be delayed. Roofing had big resource and weather problems in this project, which explains its poor performance. The façade, MEP and interior work follow the same pattern, with MEP having the largest spread of values.

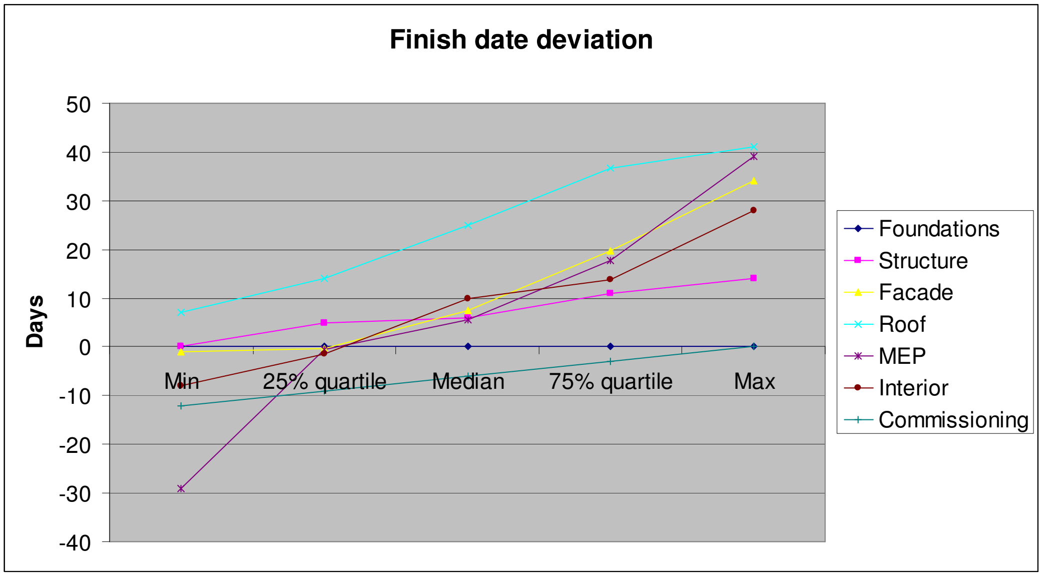


Figure A-11: Finish date deviation by construction phase

A.9.4 PPC by construction phase

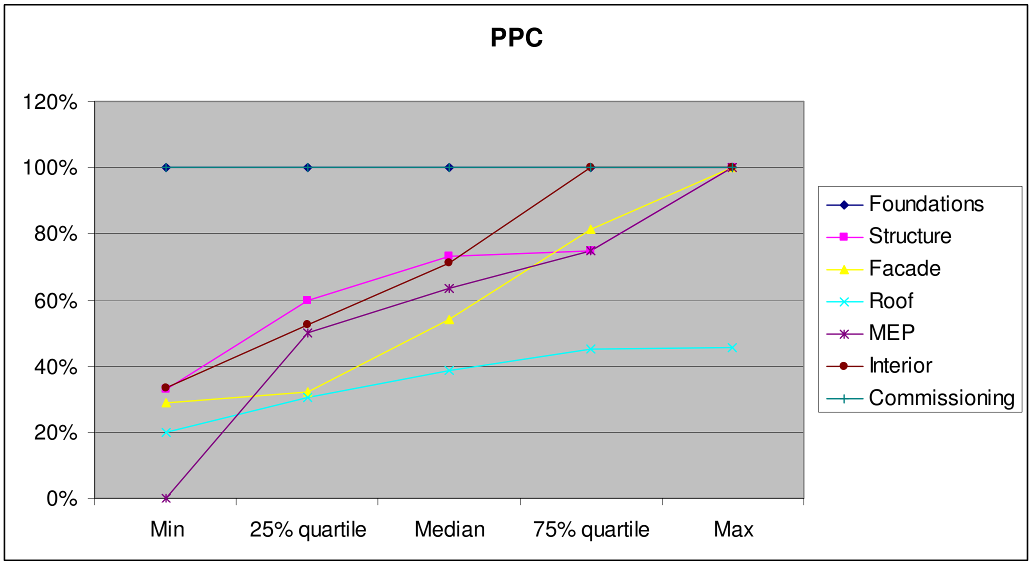


Figure A-12: PPC by construction phase

In terms of weekly plan reliability (figure A-12), tasks related to roofing underperformed in this project. The MEP and façade had worse medians than the structure or interior finishes.

A.9.5 Start-up delays by construction phase

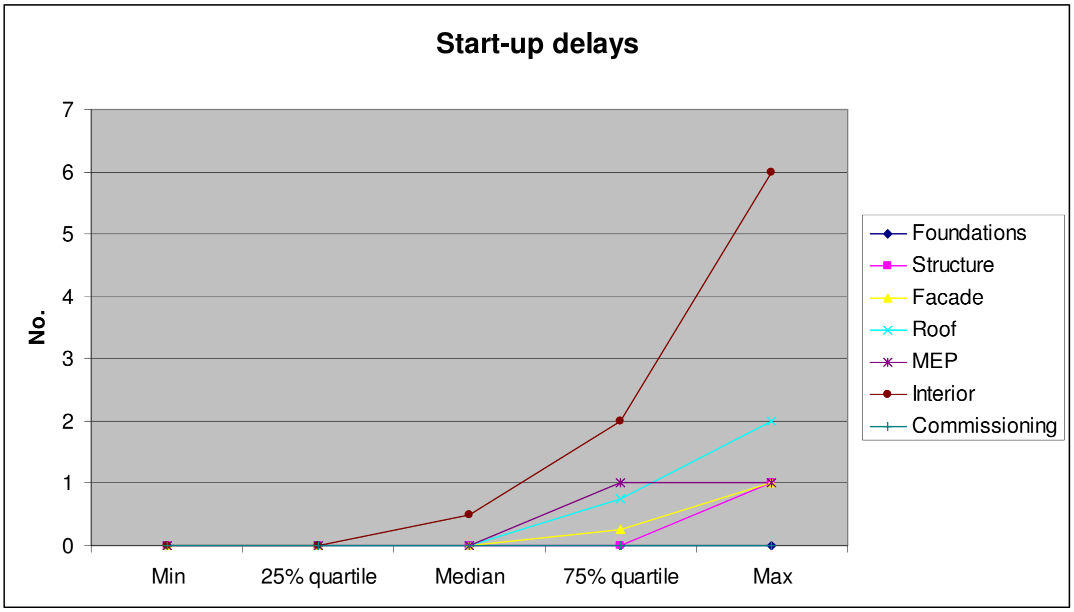


Figure A-13: Start-up delays by construction phase

Figure A-13 shows how many times tasks could not start on the week they were planned to start because of delays to other tasks. Here, interior construction has a clearly different profile to the other construction phases.

A.9.6 Discontinuities by construction phase

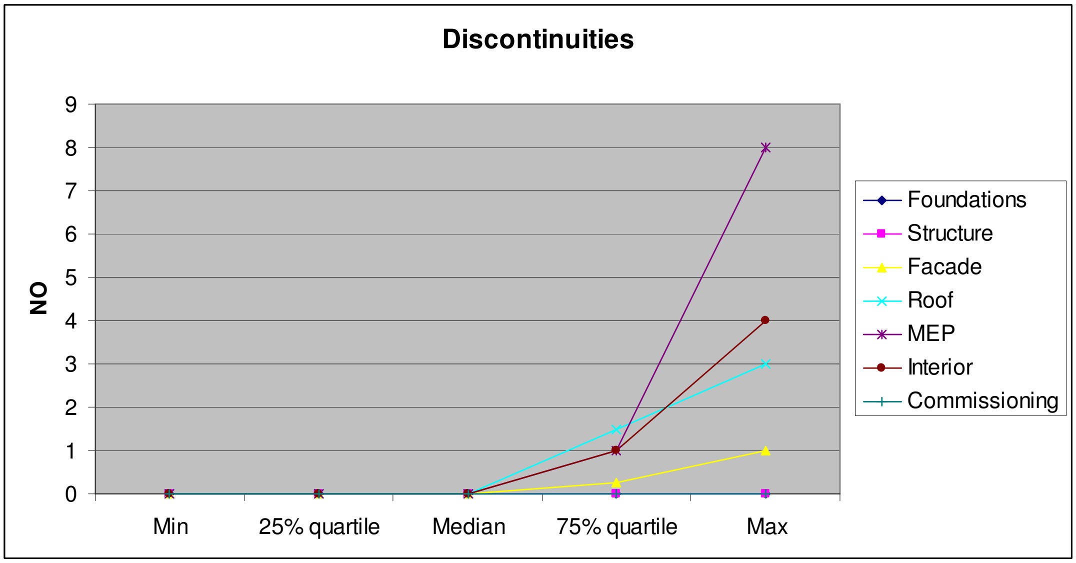


Figure A-14: Discontinuities by construction phase

In terms of discontinuities (figure A-14) MEP, Interior finishes and Roofing clearly rise above other the construction phases.

A.9.7 Slowdowns by construction phase

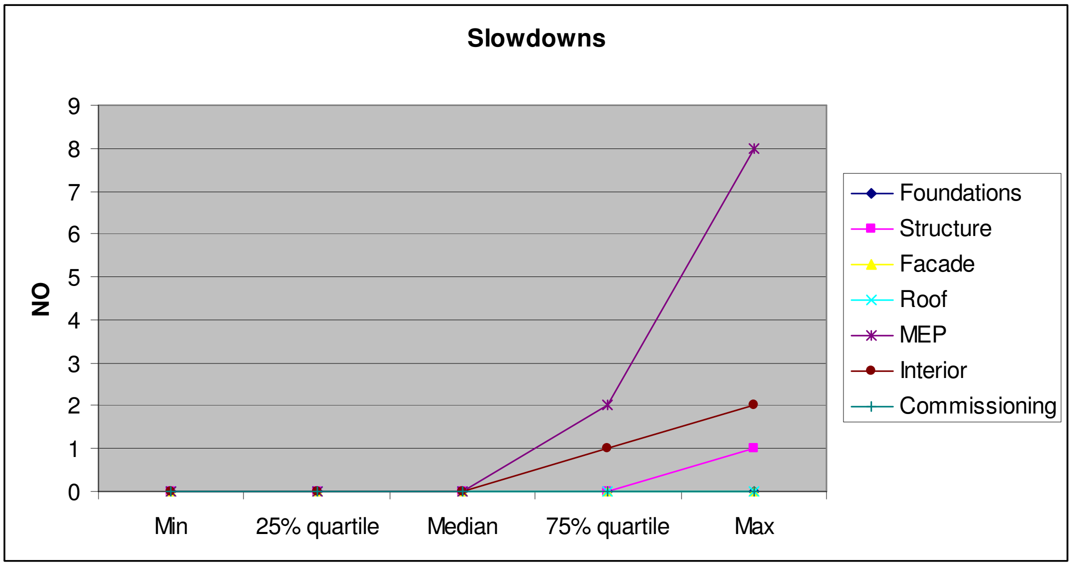


Figure A-15: Slowdowns by construction phase

Slowdowns also show differences between the interior / MEP and the other trades. In particular, the MEP trades often had many slowdowns during production caused by the other tasks.

A.9.8 Downstream start-up delays by construction phase

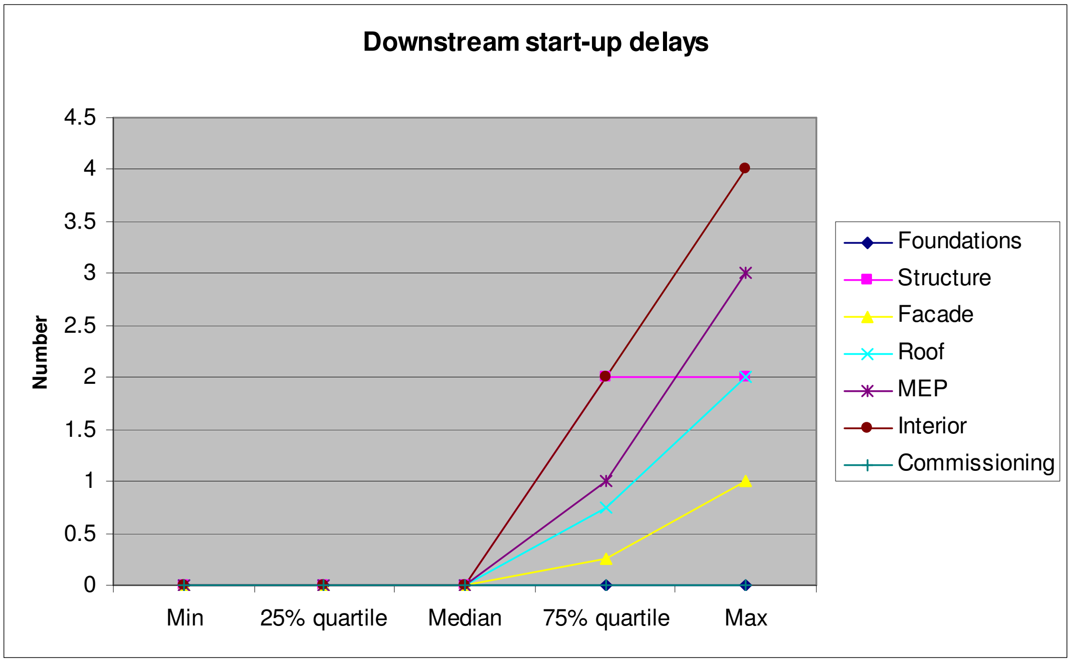


Figure A-16: Downstream start-up delays by construction phase

Most of the construction phases have a similar profile in the downstream start-up delays. The worst 25 % of tasks were causing more start-up delays in the finishes and MEP, but all construction phases except the foundations and commissioning had some tasks which caused downstream start-up delays and the median for all the construction phases was zero (meaning that 50% of tasks of all the construction phases did not cause start-up delays to the other tasks)

A.9.9 Downstream discontinuities by construction phase

In terms of downstream discontinuities, most of the construction phases share the same profile (Figure A-17). Notable exceptions are the foundations (with only one task in this project) and the façade and commissioning which did not cause any discontinuities.

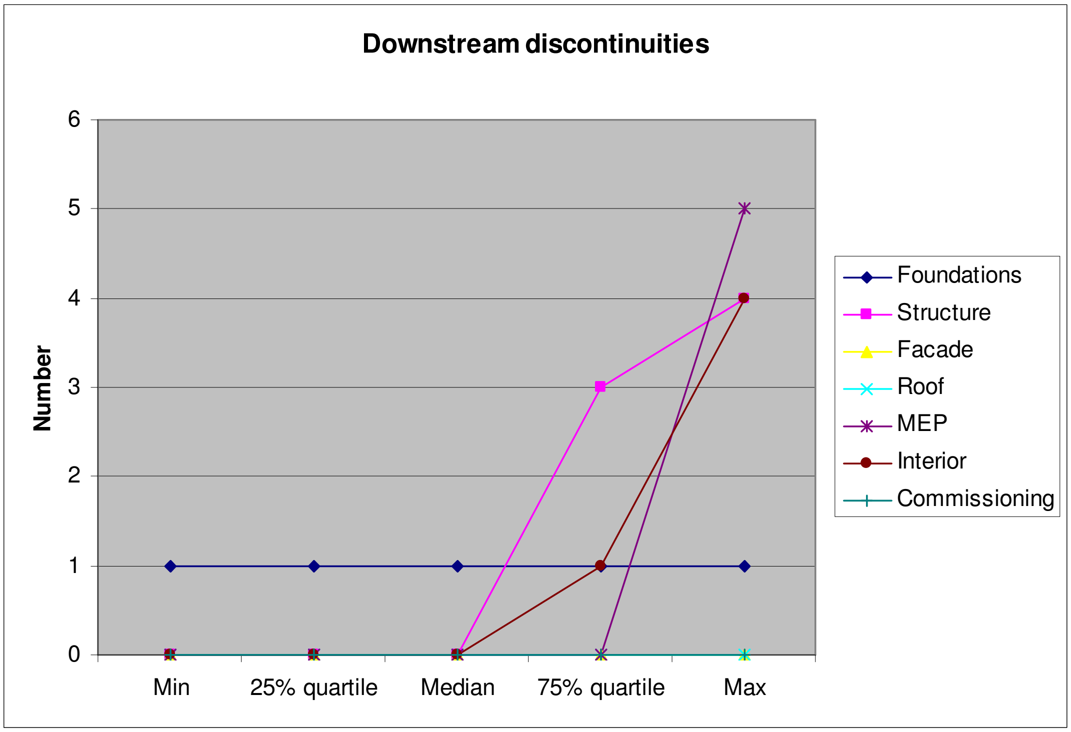


Figure A-17: Downstream discontinuities by construction phase

A.9.10 Downstream slowdowns by construction phase

The MEP and interior finishes clearly caused the most downstream slowdowns (Figure A-18). Even though the median for all phases was zero (50 % of tasks did not cause any slowdowns), the 75 % quartile for MEP is 4 downstream slowdowns. This means that 25 % of the MEP tasks slowed down the production of some other task at least 4 times.

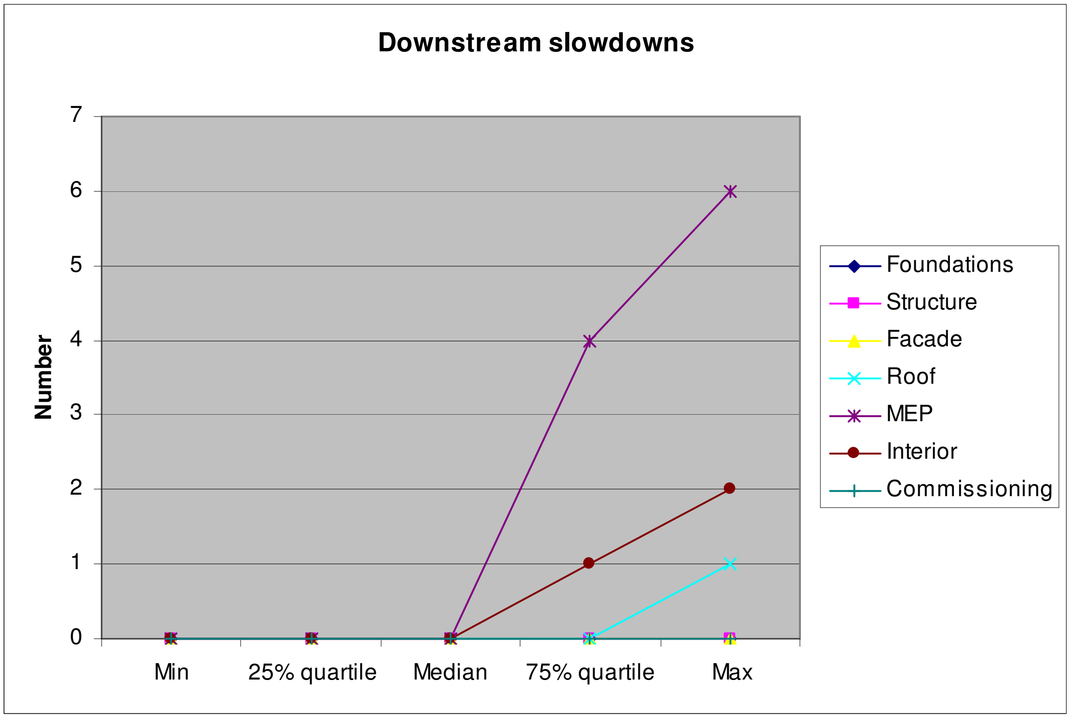


Figure A-18: Downstream slowdowns by construction phase

A.9.11 Differences of construction phases

From the results presented in this section, it can be concluded that the MEP and interior phases differ from the other construction phases mainly in slowdowns caused by the other tasks and the production rate problems caused to the other tasks. All the other deviation types, start date deviations, production rate deviations, PPC and finish rate deviations have similar trends to the other construction phases. In this project, Roofing performed badly on the start date deviation, finish date deviation and PPC, but did not cause more production problems to the other tasks than the other construction phases. The MEP and interior phases have more interlinked tasks which cause cascading slowdown effects. These effects will be researched in more detail in the week-by-week analysis.

A.10 Differences of small locations and large locations

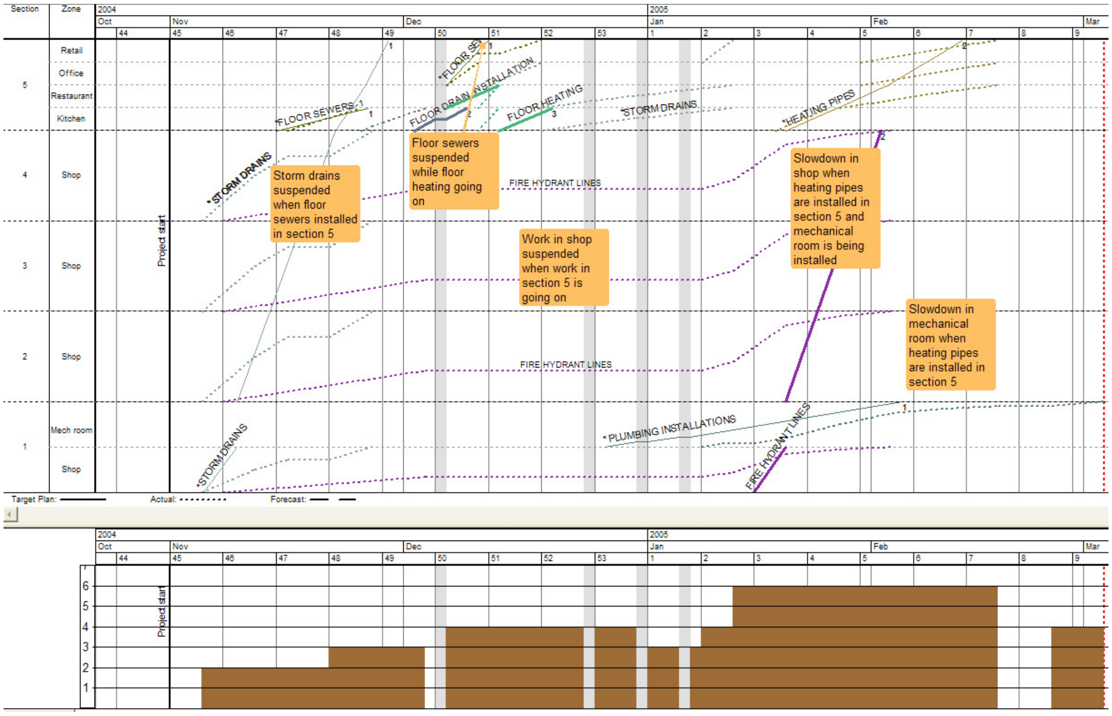
The project Location Breakdown Structure had 4 large sections (shop hall) and 6 smaller areas including the kitchen, restaurant, office, retail spaces, main mechanical room, and a smaller mechanical room. Most of the production problems seemed to concentrate in the small areas. The differences were researched by looking at the percentage of deviations in the small locations and large locations and comparing that to the approximate total man hours of work in the small locations and large locations.

The small locations had approximately 30 % of total man hours, and the large locations had 70 % of man hours. Out of 34 start-up delays, 21 (62%) happened in the small locations and 13 (38%) in the large locations. Out of 36 discontinuities, 27 (75%) happened in the small locations and 9 (25 %) in the large locations. Out of 54 slowdowns, 41 (76%) happened in the small locations and 13 (24 %) happened in the large locations.

From these results it can be concluded that most of the production problems happen in the small locations, even though the quantity of work may be considerably lower in these locations.

A.11 Analysis of resource use

During the analysis of the project data, an observation was made that the Mechanical, Electrical and Plumbing contractors seemed to have slowdowns in one part of the project, but fast production in another part of the project. This was caused by the fact that the resource profiles stayed remarkably level during the project and were not increased or decreased based on available locations or schedule status. Because resource use was not explicitly discussed during meetings, it seems that the subcontractors prioritized the tasks according to their own criteria. When the General Contractor required more resources for a task, they were shifted from another part of the project and the slowdown shifted to another task.



Storm drains suspended when floor sewers installed in section 5

Floor sewers suspended while floor heating going on

Work in shop suspended when work in section 5 is going on

Slowdown in shop when heating pipes are installed in section 5 and mechanical room is being installed

Slowdown in mechanical room when heating pipes are installed in section 5

Figure A-19: Plumbing work in Prisma

Figure A-19 above shows the actual resources the plumbing contractor had on site (weekly report from subcontractor meeting memos) and their actual progress in each task and area of the project. The most important results from the figure are:

- A subcontractor does not always increase resources when new tasks start.
- Existing multi-skilled resources are reallocated instead
- This reallocation process causes ongoing tasks to be slowed down or suspended

The original schedule for the plumbing did not include quantity or resource information. To compare the original resource graph assumed by the General Contractor's schedule to the actual resource graph, the original schedule was resource loaded by using approximate total actual man hours of each task. The results are shown in figure A-20.

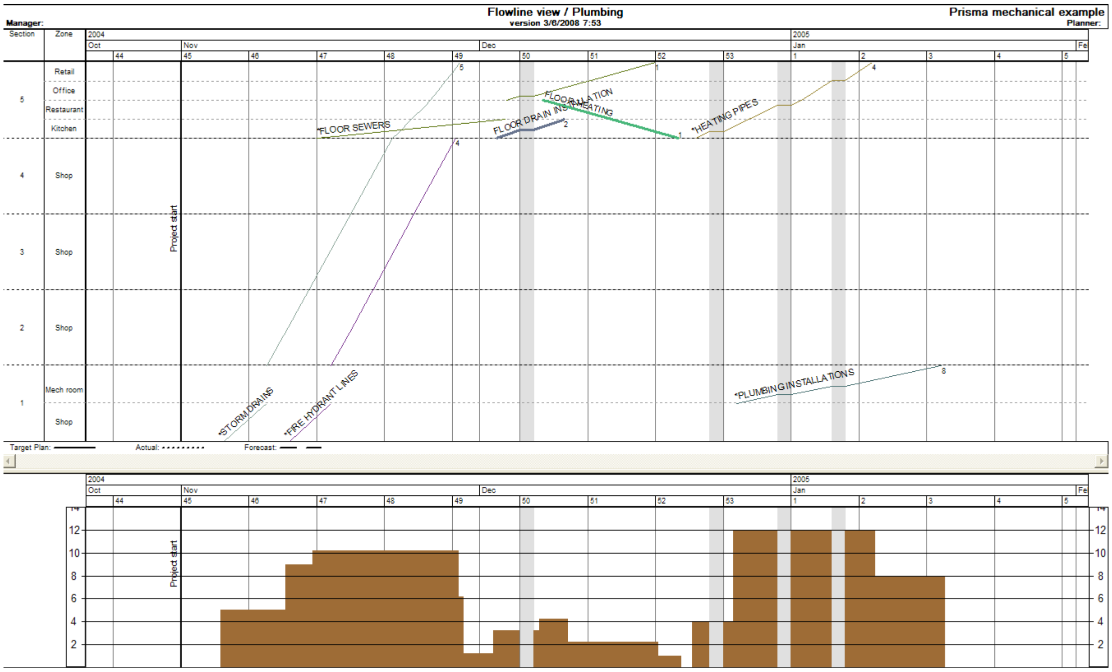


Figure A-20: Planned resource loading based on actual man hours spent on each task

The small numbers on the top of each line mean the average number of people working on the task, assuming that work has to be finished in the planned time period and the actual man hours needed is known. The planned resource profile assumes ten plumbers in the beginning, then a break of five weeks, and then a peak of 12 plumbers. Compare this to the actual resource use in figure A-19, where the actual resource use is 2 people in the beginning, slowly increasing to three and four, and finally six people at the end. As the end result, the plumbing subcontractor is able to achieve an even resource flow. By doing so, the subcontractor is causing slowdowns to all the other trades. However, because the interior work and MEP is so tightly interrelated, these cascading slowdowns eventually affect the plumbing contractor himself, who then has a valid reason for not increasing resources.

A.12 Summary of results in Case Prisma

The project finished on time. However, the 1.5-month buffer at the end of the project was completely eaten. Additionally, there was a lot of waste in the process, which was manifested as start-up delays, discontinuities, and slowdowns. The reliability of the baseline schedule, detail schedules and weekly plans was poor. Although the start dates were very close to those planned, the finish dates of the tasks were delayed for all construction phases and the tasks caused cascading production problems to each other.

An analysis of the data revealed a tendency to start tasks as early as possible, instead of delaying them to allow better continuity and productivity. The controlling was focused on starting activities on time, instead of focusing on the production process. Although the start-up delays and discontinuities were documented very well, the production slowdowns went largely unnoticed. The production rates were not discussed in the meeting memos. Instead, production was managed by looking at the current status of each task and location compared to the baseline schedule. The production control process focused on the past behavior, instead of focusing on preventing future problems. However, the subcontractor meetings show evidence of strong production control when deviations were noticed.

The detail schedules were updated almost weekly, which led to more problems than benefits. Commitment was not recorded in the schedules. Instead, schedules were living documents which changed weekly. The schedules did not show whether a start date was promised to the subcontractor, or whether the production rate had been agreed with the subcontractor. Therefore, some of the analysis may have been based on detail schedules which were still works in progress or lacked commitment.

The success of the weekly schedules was found to be correlated both with the successful implementation of the baseline schedule and the detailed schedule. More research needs to be done about cause-and-effect.

There was strong evidence of cascading production problems. If a task experienced slowdowns, it was highly likely that it also caused slowdowns to other tasks. In this project, the cascading effects may be even more pronounced, because there were little or no buffers between the tasks in the interior finishes and MEP phases. Analysis by construction phase showed that the MEP and interior tasks caused most of these cascading slowdown problems. These problems happened mostly in the small locations, even though more work happened in the large locations. Therefore, the location size needs to be taken into consideration when deciding buffer sizes and control actions.

An analysis of the resource use of the MEP contractors revealed that an important reason for the poor performance of the MEP trades and cascading slowdowns was the lack of knowledge of the MEP contractor resource requirements. The General Contractor did not have quantity or resource information for the MEP trades, but they were included in the schedule based on the total duration. Deviations happened because the subcontractors did not mobilize enough resources to meet the implicitly assumed resource requirements of the General Contractor's schedule. This was a sensible decision from the subcontractors' point of view, because the General Contractor's schedule implicitly assumed high resource peaks, probably exceeding resource availability, and then months of downtime followed by high resource peaks.

As a conclusion, for multi-skilled MEP contractors it is not enough to show a continuous Flowline to ensure efficient production. Instead the overall resource use needs to be considered.

Another important problem in this project was that the location break-down structure of the project was defined by the General Contractor based on the structural requirements. The MEP contractors were not consulted, and in the shop hall area, the chosen breakdown did not correspond with the direction of the main ducts, pipes and cable trays through the hall. This caused immediate deviations in the shop hall area, because the tasks needed to happen in all the locations at the same time, instead of completely finishing in the location as assumed by the schedule.

Many problems were identified in the production control system itself. Alarms were often not generated at all or were generated too late for them to be useful. The main problems were found to relate to missing or wrong dependencies, over-optimistic forecasts, having many tasks in the same location, and starting work in wrong sequence. To correct these problems, both the production control process and the production control system need to change.

Appendix B: Case study II: Glomson retail park

B.1 Project description

The Glomson Retail Park was a 2-floor retail center with 4 large retail spaces. The total size of the project was 10,638 gross m^2. The structure was pre-cast concrete. One side of the façade had a curtain wall, the other sides were metal veneer. The building was divided to four sections, according to the sequence of erecting the structure. Section 1 had the main mechanical room on the roof. Section 3 had an air raid shelter which needed to be built before the structural work could begin on that section.

The finishes and MEP were planned using the retail space breakdown. The retail spaces were allocated to sections. Section 1 included mostly administrative functions, such as offices and storage areas. Section 3 had unrented tenant space on the first floor, and a large furniture shop on the second floor. Section 4 had the main lobby and an electronics store on the lower floor and a furniture shop on the second floor. Section 2 only had a second floor, and because functionally the shop on section 3 extended to section 2, only section 3 was used for the planning of the interior finishes, instead of artificially splitting the area according to the structure. Each tenant had very different specifications for their interior finishes. Consequently, almost all of the locations had different floor finishes, different types of suspended ceiling, and also changing sequences related to the ceiling installations.

The General Contractor of the project was Hartela. The project contract duration was from September 2004 to August 2005. A one-year duration was considered standard for this project size. Structurally, the building was considered easy because of its regular box-shape (figure B-1). However, there were major uncertainties related to the earthworks and foundations because of inadequate soil studies. Also, there was some uncertainty about the tenant fit-out. One retail space had not been rented when the baseline planning started.

Figure B-1: Glomson retail park was structurally simple box-shape building

B.2 Available starting data

Many things were unknown when scheduling started. When the baseline schedule was planned, the design information of the MEP systems was unavailable. Initial location-based schedules had been drafted before the project was made available to the author. The task lists and their approximate sequence were well established. The site manager was familiar with location-based planning and had used the planning software in his previous project. The project engineer was a recent graduate from a polytechnic and did not have prior experience of location-based techniques. He got the main responsibility for planning. The site manager participated in evaluating the schedule.

A cost estimate of the project did not have the quantities by location. Many of the quantities were taken off again by the project engineer corresponding to the selected location break-down structure. The productivity rates were taken from Finnish productivity database (Mäki & Koskenvesa 2002) and adjusted based on the site manager's expertise. In the initial versions of the schedule, the MEP durations were roughly estimated based on previous, similar projects.

Many of the quantities were rough approximations at this stage because all the tenant decisions were not available and the design was incomplete. One of the large retail areas did not have a tenant at this stage, so all the quantities for finishes in that area were uncertain.

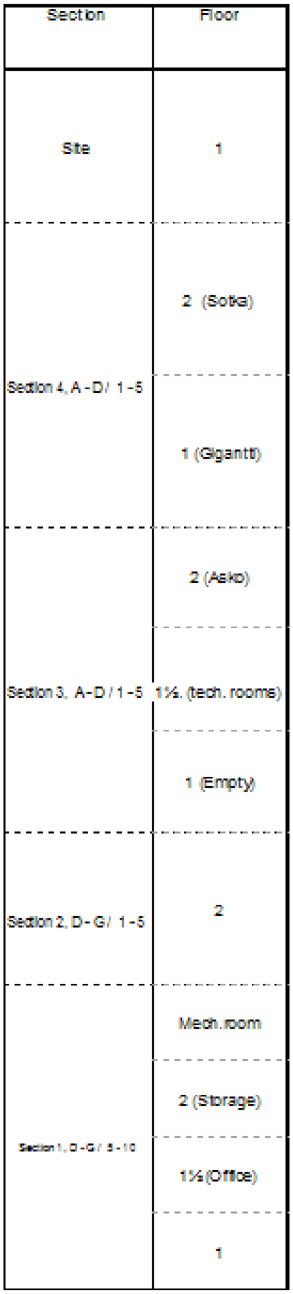
B.3 Schedule planning process

The site manager was familiar with location-based scheduling from earlier projects and wanted to implement it in this project. The project engineer was charged to develop the schedule under the site manager's supervision. He did not have previous experience, but was trained by the author. Because only the foundations had been procured when the baseline scheduling started, the scheduling process was free from constraints. Only the end date was fixed by contract with the Owner.

The Bill of Quantities of the project was used to define the schedule tasks. The most important tasks were defined by the site manager, and the project engineer did a location-based take-off to get the quantities by location for those tasks. The productivity rates and crews from the Finnish generic productivity database were used to calculate the durations. All the durations and production rates were double checked by the site manager. Finally the tasks were aligned so that they had similar slopes but were able to be performed as continuously as possible. The MEP trades did not have quantity information, but enough empty space was reserved in between the construction trades and the MEP tasks were planned to have the same slope. The durations were checked by the site manager.

B.3.1 Location Breakdown Structure

The Location Breakdown Structure was defined on two hierarchy levels. There were four sections corresponding to the erection sequence of the structure and earthworks. The sections were divided into floors. Each section and floor corresponded well with one functional area (i.e. technical space, storage area, retail space, or office area) of building except section 2. Section 2 was on a higher elevation and had just the second floor. The furniture shop of Section 3 on the second floor extended also to section 2. Therefore section 2 was not used at all during the interior construction. All the interior quantities physically belonging to section 2 were allocated to section 3. The idea was to have all the quantities of a retail space in one location. Figure B-2 shows the Location Breakdown Structure of the project.



Section	Floor
Site	1
Section 4, A - D / 1 - 5	2 (Sotka)
	1 (Gigantti)
Section 3, A - D / 1 - 5	2 (Asko)
	1½. (tech. rooms)
	1 (Empty)
Section 2, D - G / 1 - 5	2
Section 1, D - G / 5 - 10	Mech. room
	2 (Storage)
	1½ (Office)
	1

Figure B-2: Location Breakdown Structure of Glomson

B.3.2 Task list

The level of detail for the master schedule was low. Some examples of the level of detail are shown in table B-1 below:

Table B-1: Level of detail for baseline tasks

SYSTEM	TASKS
Earthworks / **Foundations**	Excavation, Piling, Foundations, Drainage, Fills
Structure, Roofing, Facade	Structure, Roofing, Curtain wall
Finishes	Concrete floor topping, Interior walls, Elastomer floor and painting, Restroom tiling, Plasterwork, Painting, Vinyl floor covering, Laminate floor covering, Floor tiling, Final painting, Final cleaning
Mechanical	Main mechanical room mechanical, Overhead mechanical and plumbing, Mechanical and plumbing trim
Electrical	Main mechanical room electrical, Electrical conduits, cable trays and cabling, Lighting and electrical equipment
Plumbing	Main mechanical room plumbing, Overhead mechanical and plumbing, Mechanical and plumbing trim

B.3.3 Resources / productivity rates

The number of required crews was optimized to align the schedule. The structure was identified to be the bottleneck task and all the interior tasks were planned to have the same slope. The earthworks schedule was defined by the contract, which was already in place when the schedule planning started. Resource use was continuous except for the MEP tasks which had multiple locations going on at the same time.

B.3.4 Dependencies, lags and buffers

On the baseline level. all the tasks had dependencies and the dependency network was complete. Risk analysis or simulation was not used to optimize buffers. Nevertheless, some buffers were planned between the construction phases. The last interior tasks were planned to be completed one month before end of the the project and the final month was reserved for handover activities and final cleaning. In practice, this final month operated as a project buffer. The master schedule in the Flowline format is presented in figure B-3.

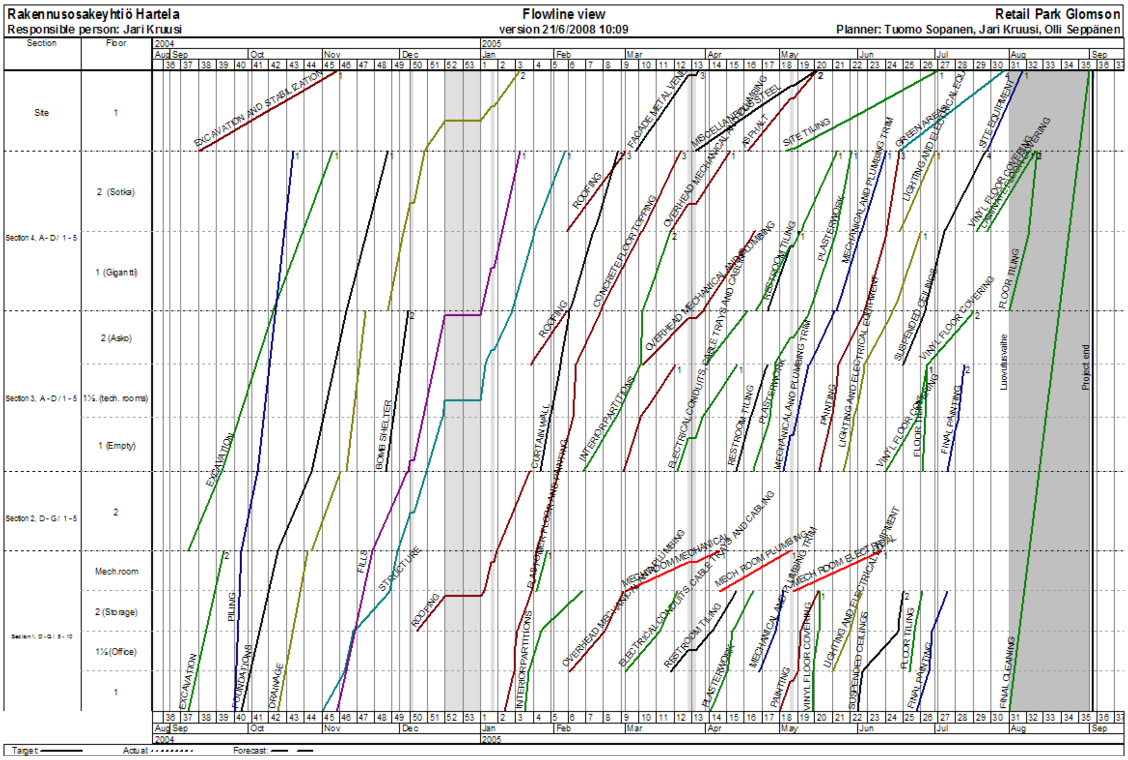
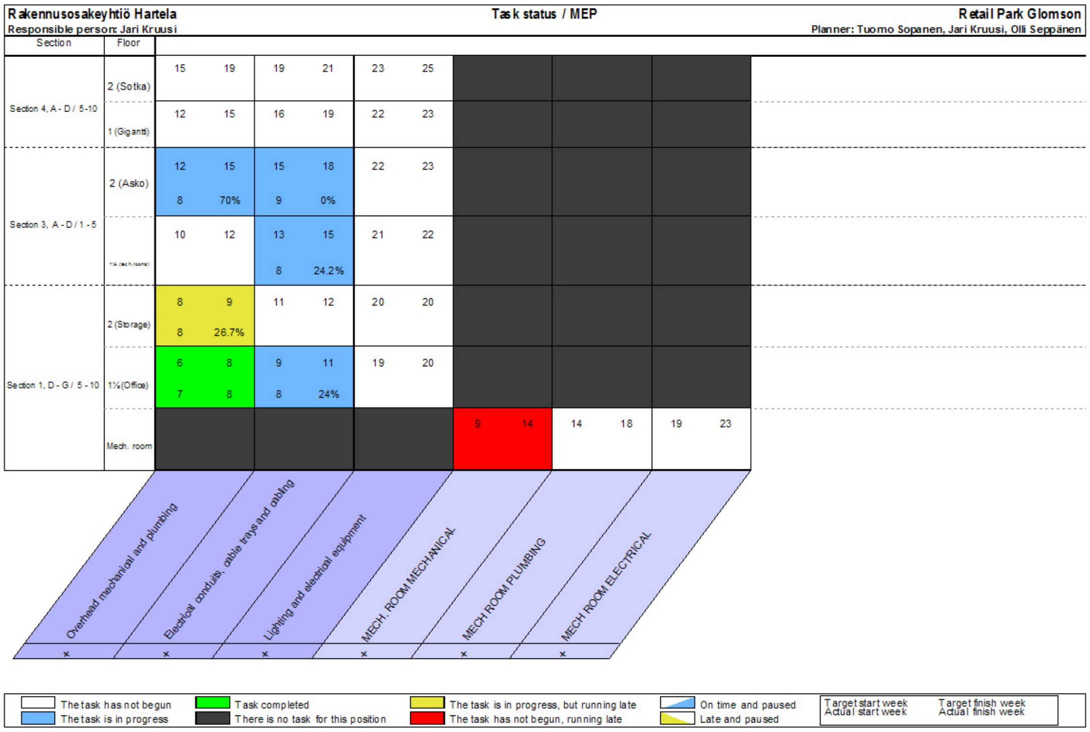


Figure B-3: Master schedule of Glomson retail park

B.4 Schedule controlling process

B.4.1 Monitoring process

Project status was monitored weekly by the project engineer. He printed out the control chart and went to all the locations of the project to see the status of activities. The results were entered into the planning software weekly and were sent to the author. In the event of deviations (red or yellow squares), a comment about the reason for the deviation was sometimes, but unsystematically entered into the system. An example control chart is shown in figure B-4 of the MEP work on week 9/2005 compared to the baseline schedule.



Rakennusosakeyhtiö Hartela **Task status / MEP** **Retail Park Glomson**

Responsible person: Jari Kruusi

Planner: Tuomo Sopanen, Jari Kruusi, Olli Seppänen

Section	Floor	Overhead mechanical and plumbing	Electrical conduits, cable trays and cabling	Lighting and electrical equipment	MECH. ROOM MECHANICAL	MECH ROOM PLUMBING	MECH ROOM ELECTRICAL
Section 4, A - D / 5-10	2 (Sotka)	□ 15 19	□ 19 21	□ 23 25	■	■	■
	1 (Gigantti)	□ 12 15	□ 16 19	□ 22 23	■	■	■
Section 3, A - D / 1 - 5	2 (Asko)	🟦 12 15 8 70%	🟦 15 18 9 0%	□ 22 23	■	■	■
	1½ (tech. rooms)	□ 10 12	🟦 13 15 8 24.2%	□ 21 22	■	■	■
Section 1, D - G / 5 - 10	2 (Storage)	🟨 8 9 8 26.7%	□ 11 12	□ 20 20	■	■	■
	1½ (Office)	🟩 6 8 7 8	🟦 9 11 8 24%	□ 19 20	■	■	■
	Mech. room	■	■	■	🟥 9 14	□ 14 18	□ 19 23
		×	×	×	×	×	×

- □ The task has not begun
- 🟦 The task is in progress
- 🟩 Task completed
- ■ There is no task for this position
- 🟨 The task is in progress, but running late
- 🟥 The task has not begun, running late
- ◢ On time and paused
- ◣ Late and paused

Target start week	Target finish week
Actual start week	Actual finish week

Figure B-4: Example control chart. MEP work on week 9/2005 compared to the baseline schedule. Many locations have started early (blue), the mechanical installation in the main mechanical room is delayed (red) and the overhead plumbing and mechanical work has started but is late on floor 2 of section 1 (yellow)

Each week, the start and end dates of the locations for the tasks were entered. If a location was ongoing for several weeks, the completion rate was sometimes used. The completion rates were estimated by visually comparing the actual status to the drawings, and in more complex tasks by asking the workers. Because the work was not actually measured, some completion rates may be inaccurate. For example, some tasks rapidly entered a 95% completion rate and then started gaining 1 % a week. In this case, the 95 % completion rate was most probably incorrect. Completion rates were often not reported for ongoing tasks, so it was often difficult to know whether a task was suspended or was progressing slowly.

Some errors were made during monitoring. For example, a task could be marked as completed on one week and opened again the following week, because some part of the scope was not completed. These inaccuracies have been taken into account in the analysis by assuming that the information from later weeks is correct in the case of conflicts.

Actual resources were not recorded for tasks but they were reported by the subcontractors in the site meeting memos.

B.4.2 Views used

The schedules were reported and monitored by using multiple Flowline views. In this project, the views were created for the structural phase, roofing and finishes. Additionally, the subcontractor views were created for the plumbing, electrical, concrete floor finishing, and concrete stairs subcontractors. The views appear not to have been consistently used for internal communication. Instead they seem to have served as a tool for only the project engineer and the site manager.

B.4.3 Production meetings

The subcontractor production meetings were held weekly. The General Contractor and the main subcontractors participated. The meetings were analyzed by the use of memos. In this project, the production meeting memos described for each subcontractor the ongoing tasks, the total number of resources on site, and sometimes information about future tasks (especially the start of new locations or tasks). The production meeting memos did not address deviations or delays. The major subcontractors' weekly report was attached to the production meeting memos. They described the completion rates of the tasks and activities and the schedule status of the subcontractor. It was interesting to note that every subcontractor reported every week that they were on schedule, regardless of the control chart colors or the actual status compared to the plans. The General Contractor did not dispute these status reports, even though the control charts and schedules showed delays.

The design status was reported by describing which new design was available and which design was ongoing. Additionally, the needs for the design specifications were documented. The effect on production of missing design was never documented in the memos. The need dates for design were not documented.

Safety was documented by describing the results of safety measurement and detailing work-related accidents and near accidents.

Additionally, subcontractor and general contractor issues were addressed. Often these related to the starting meetings, quality issues and change orders. Sometimes schedule-related issues were documented here by a subcontractor or the General Contractor requesting them to expedite some activity. In these cases, the downstream effect of the delay in that activity was never mentioned.

B.4.4 Owner meetings

The owner meetings were monthly. According to the memos they concentrated mainly on the design issues, tenant requirements and change orders. Schedule-related issues were reported in the appendixes. The main memo only included one sentence describing the schedule status. In some memos, a delay of a maximum of one week was reported, but it was qualified by saying that it would not affect the final completion date. Normally, the project was reported to be following the schedule on average.

The monthly client schedule report attached to the client meetings had the following information:

- The number of workers of GC, mechanical/plumbing contractor, electrical contractor and other contractors
- New subcontractors / material suppliers
- Ongoing tasks and their status
    - Status was described verbally, not by using completion rates
- Schedule status
    - Gantt charts and occasionally Flowline figures were attached and verbally described
    - The conclusion was always "on average on schedule" or at most delayed by one week which - according to report - "would not affect the deadline".

B.4.5 Detailed task planning process

In the structural and the beginning of the finishes phases, the detail tasks were planned and updated weekly. In many cases, more detail was added to the baseline tasks. Table B-2 shows all the baseline tasks which were exploded to more than 1 detail task.

In two cases, the work of multiple subcontractors was planned under the same baseline task. For example the mechanical and plumbing ducts and pipes included the work of the plumbing, mechanical, and sprinkler contractor. The interior walls included the masonry walls and plasterboard walls. This resulted in missing alarms, because the alarm system assumed that alarms were not needed within the same baseline task.

Table B-2: Level of detail of detail tasks in Glomson

Baseline task	**Detail tasks**
Structure	Columns, beams and walls; Slabs
Concrete stairs	Steps and mosaic floor tiling; Stair railings
Roofing	Vapor closure and waterproofing; Eaves
Interior walls	Masonry walls; Plasterboard walls
Curtain wall	Curtain wall frame; Closed parts and inside connections; Glazing
Mechanical and plumbing ducts and pipes	Plumbing; Mechanical ducts + insulation + diffusers; Sprinkler
Concrete floor finishing	Each pour had a separate activity
Electrical Conduits, Cable trays and cabling	Cable trays; Strong power cabling; Telecabling

The detail tasks were most often planned by phase. For example, the structure was planned as one entity, the curtain wall and roofing as one entity, the concrete floor finishing and interior walls as one entity, electrical as one entity, the plumbing and mechanical as one entity, and then all the finishes as one entity. In some cases, such as the sprinkler and painting, the detail tasks were planned for individual tasks. After the MEP and finishes had been planned to their final level of detail, the detail schedules were basically locked with very few changes. The last 15 weeks of the project had no changes to the schedule and the schedule was only monitored.

Subcontractor input was asked for the planning of each major planning entity. The quantities, resources and production rates were updated before the start of the task. However, the quantity information was not received from the other MEP contractors other than the electrical contractor. Consequently, most of the MEP tasks were scheduled without quantities or resources. This lack of resource information created problems because the subcontractors had level resources on site, even though the schedule assumed fluctuations in resource needs.

The detail task planning used dependencies well until the MEP and finishes stage. The MEP and finishes schedules were mostly planned without dependencies. Flowlines were visually placed so that interferences did not happen and work was going on in the correct sequence, but the actual logic was rarely added in this stage. Additionally, the existing dependencies were often updated many times to correct the forecast or to remove alarms. Sometimes dependencies were removed even though they were actually valid. The lack of dependencies made the production control information look better than the reality and the project had almost no alarms in the final stages of the project.

The sequence of the locations was changed many times according to starting data availability. For example, the space where tenant was unknown, was changed to be last in the sequence and some other locations were changed to be implemented in a different sequence during the fit-out phase.

The start dates of tasks were often updated based on the situation in the field. For example, the delay in the structure prompted the moving of the start date of the curtain wall three weeks ahead. The concrete floor finishing task pour schedule was kept up-to-date and there were changes weekly. The production rates were sometimes rescheduled based on the actual. For example, the masonry subcontractor had more resources on site than originally planned and achieved a better production rate. This was eventually updated also to the detail schedule.

B.4.7 Control actions

Control actions were rarely modeled in the schedule. In one rare example, the delays to the structure prompted the addition of one mobile crane to help in the installation. Normally, the control actions were not modeled in the schedule and few control actions could be inferred from data. Even when there were delays, production problems were not mentioned in the production meetings. The normal way seemed to be to accept delays and the downstream effects and trust that the buffers between the tasks and the end-of-project buffer would absorb the time impact. Alarms were often removed by removing the dependency. This was done without analyzing the effect of changing the logic.

B.4.8 Weekly plan process

The weekly plans were created by the project engineer based on what he thought possible. The schedule was used in seeing what should be done but the project engineer decided if it could be done, in his opinion. Sometimes he asked the opinion of the workers. The site manager approved all the weekly plans. The status of the weekly plans was calculated every week and PPC was reported back to the project. There was only limited interest in the weekly planning or getting better PPC results.

B.5 Reliability of baseline schedule

The numerical variables described in chapter 3 show that the baseline schedule was not implemented very well in this project. Table B-3 shows the results for the numerical variables of the 28 baseline tasks in the project. The results are presented using the minimum, 25% quartile, median, 75% quartile, and maximum, in addition to the mean and standard deviation because the distributions are skewed.

Table B-3: minimum, average, maximum and standard deviation of a selected numerical variables (chapter 3).

VARIABLE	MIN	25%	Median	75%	MAX	Mean	STD
Planned discontinuities	0.00	0.00	0.00	0.00	4.00	0.36	0.95
Actual discontinuities	0.00	0.00	0.00	1.00	7.00	0.68	1.44
Quantity deviation	0.47	0.93	1.00	1.00	1.38	0.95	0.21
Production rate deviation	0.28	0.54	0.89	1.39	5.42	1.22	1.13
Start date deviation	-30.00	-2.50	4.50	13.25	32.00	3.54	16.00
Finish date deviation	-60.00	-1.50	10.00	24.25	59.00	12.21	25.29
PPC	20%	40%	57%	73%	100%	58%	26%

The results show that discontinuities were not a major problem in this project. Although the maximum and 75 % quartile had more than the planned discontinuities, the median task was both planned and produced continuously without work breaks.

Quantity variations were small in this project and in many cases the actual quantities were below the planned quantities. This was caused by conservative estimates of the planning phase before the final tenant requirements were known. For example, the schedule included more interior walls, painting and suspended ceilings, because the worst case scenario of tenant choice was assumed.

The production rates reveal the same pattern as Prisma; there are both very slow and very fast outlier tasks. The median task was 10% slower than planned. Half of the tasks had production rates of between 54 % and 139 % compared to the plan. Very slow tasks included painting (28 % of planned), suspended ceilings (40 % of planned), the main mechanical room plumbing (36 % of planned), and interior walls (40 % of planned). Very fast tasks included smoke removing hatches on roof (540 % of planned), excavation (211 % of planned) and concrete floor topping (230 % of planned). Because over 50 % of the tasks were slower than planned, the production rates were not very well controlled in the project.

Consistent with the other case studies and earlier research by author (Seppänen & Kankainen 2004), the start dates were much better controlled than the finish dates – the average delay of the start of an activity was 3.54 days (median 4.5 days) and the average finish date delay was 12.21 days (median 10 days). Both the start dates and finish dates have outliers, but 50 % of the range was -2.5…13.25 days for the start dates and -1.5…24.25 days for the finish dates, indicating problems of finishing tasks on time. The high standard deviations and the range of the start date and finish date deviations indicate that there was high variability depending on the task. Examples of tasks which were significantly delayed were the restroom tiling (59 days), the main mechanical room plumbing installation (52 days), the main mechanical room HVAC installation (50 days), and the interior walls (46 days). Examples of tasks which finished early included the floor tiling (-60 days) and the vinyl floor covering (-22 days). Most of the long delays (the restroom tiling, interior walls) occurred because one of the retail spaces was rented relatively late and had to be constructed out of sequence. The early finish examples were caused by a change of floor covering materials in some of the retail spaces to have different kind of tiles done by a different contractor, and thus smaller scope to finish.

PPC varied from 20 % to 100 %, with the average task having 58 % PPC. Very high PPC tasks were those with few dependencies to other tasks, such as the excavation and soil stabilization (only happened outside of the building footprint, PPC 100%), Piling (PPC 100%), Restroom tiling (PPC 100%), Asphalt (PPC 100%) and Site equipment (PPC 100%). Very low PPCs were found in the mechanical room (HVAC 25 %, Plumbing 38%, Electrical 20%), painting (33%), suspended ceilings (31%), Backfills (25%) and the Green areas (25%).

Overall, the results show that the baseline schedule was not well implemented. The start dates were well controlled, but production was typically slower than planned, and each task tended to finish later than planned in the baseline. The results show that the start dates were controlled with push principles without prerequisites to productively finish the tasks on time.

Table B-4 shows the percentage of tasks with interesting properties from the standpoint of location-based scheduling. The majority of trades were able to have a continuous workflow and to work in the planned sequence. This result is better than in the other case studies and means that many subcontractors were able to have a continuous flow of work for their crews. The production rate problems were common, but discontinuities of production happened to fewer tasks than in the other case studies.

Table B-4: Baseline results

Variable	**%**
Planned Continuity	79%
Actual continuity	64%
Actual Location sequence	61%
Deviation: Start-up delay	46%
Deviation: Discontinuity	29%
Deviation: Slowdown	49%
Downstream:Start-up delay	21%
Downstream. Discontinuity	36%
Downstream: Production rate	61%

A correlation analysis was run for the baseline schedule data. The significant correlations are shown in table B-5.

Table B-5: Significant correlations on the baseline level in Glomson

Variables	**Correlation**
Quantity-based vs. Finish date deviation	__-0.493**__
Quantity-based vs Slowdown	__-0.666**__
Quantity-based vs. DS Slowdown	__-0.658**__
Actual Continuity vs. Finish-date deviation	_0.407*_
Total float vs. Start date deviation	___0.532**___
Total float vs. Finish date deviation	_0.375*_
Production rate - PPC	__0.545**__
Start date deviation - finish date deviation	__0.479**__
Slowdown - finish date deviation	_0.475*_
Discontinuity - finish date deviation	_0.429*_
Finish date deviation - DS Slowdown	_0.461*_
Discontinuity - working in planned sequence	__-0.477**__
Slowdown - working in planned sequence	__-0.486**__
Working in planned sequence - DS production rate	_-0.436*_
Working in planned sequence - DS Discontinuity	_-0.439*_
Discontinuity - DS discontinuity	_0.377*_
Slowdown - DS Discontinuity	_0.434*_
Slowdown - DS Slowdown	__0.888**__

Many of the correlations are shared with the Prisma case study. However, there are some new interesting correlations. The quantities are seemingly important. Tasks with quantity information rarely suffered from slowdowns or caused slowdowns and had less finish date delays. The correlations are very strong. This may be explained by another underlying factor: all the other tasks except the tasks related to the MEP were quantity-based in this project. Therefore, the result is actually saying that the MEP tasks suffered from slowdowns and caused slowdowns more than the other tasks, a result shared with the Prisma case study.

The total float and start date delay correlated significantly. Similarly, the total float and finish date deviation correlated. This result shows that the criticality and float had some importance for production control, even though they were not explicitly used for controlling. Higher PPC correlated with a higher production rate, a result which was shared with the first case study. A late start correlated with a late finish. A delay in the finish date was partly explained by the number of discontinuities. The number of production rate problems caused by the other tasks also correlated with finishing late. A delay in the finish date contributed to causing downstream slowdowns. Importantly, working in the planned sequence correlated negatively both with suffering production problems (discontinuities and slowdowns) and causing them to other trades. Experiencing discontinuities and slowdowns were strongly correlated with causing discontinuities and slowdowns. An especially strong correlation was suffering from slowdowns and causing slowdowns to other tasks – a result shared with Prisma.

The results give additional evidence that preventing cascading problems are important in improving production control results. This case study also shows very strong correlations that imply that the MEP tasks are the main problem areas related to cascading slowdowns. The total float has at least implicitly been considered by the management in deciding whether a task can be delayed.

B.6 Reliability of the detailed schedules

The reliability of the detail task planning process was evaluated by comparing the progress data to the detail task schedule of the week before the detail task started in any location. The method of selecting the comparison date has been described in detail in the Methods section (Chapter 3). Any updates after the start of production were ignored in this comparison. The variables used in the analysis were the same as with the baseline tasks. Table B-6 shows the results of the numerical variables.

Table B-6: Results of detail task reliability variables

VARIABLE	MIN	25%	Median	75%	MAX	Mean	STD
Planned discontinuities	0.00	0.00	0.00	1.75	7.00	0.97	1.72
Actual discontinuities	0.00	0.00	0.00	1.00	7.00	0.84	1.39
Quantity deviation	0.77	1.00	1.00	1.00	1.87	1.03	0.17
Production rate deviation	0.30	0.59	0.83	1.13	5.20	1.10	0.92
Start date deviation	-43.00	-1.00	1.00	3.75	29.00	0.58	11.24
Finish date deviation	-45.00	-4.00	5.20	15.75	48.00	6.38	17.58
PPC	20%	40%	57%	75%	100%	59%	25%

On the detailed level, the standard deviations and ranges between 25% and 75% quartiles of all actual variables are lower than on the baseline level, which indicates that the detail task planning process worked better in this project than the baseline planning. Although there are some very high start and finish date deviations, the averages are much better than with the baseline plans, and the standard deviations show that there is less variability in them. As should be expected, because the comparison date was one week before the start, the start date variability of most of the tasks was under a week. Also, the finish dates were more reliable, with the median finish date being delayed one week from the planned finish date (2 weeks in the baseline). Even though the performance was better than with the baseline plan, the result of finishing on average 5 days behind a schedule that was planned together with the subcontractor one week before the start of work is not a good result.

Table B-7: Results of detail tasks

Variable	%
Planned Continuity	61%
Actual continuity	55%
Actual Location sequence	68%
Deviation: Start-up delay	16%
Deviation: Discontinuity	26%
Deviation: Slowdown	39%
Downstream:Start-up delay	16%
Downstream. Discontinuity	29%
Downstream: Production rate	55%

On the detail task level, the start-up delays were rare compared to the baseline results. Also the production rates were more often within 80 % of the planned production rate. The downstream effects were rarer than on the baseline level. This gives support to the detail schedule process working better in this project.

Table B-8: Significant correlation in Glomson

Variables	Correlation
Planned continuity - quantity-based	-0.35*
Planned continuity - actual discontinuities	-0.408*
Planned continuity - actual continuity	0.464**
Planned continuity - working in planned sequence	0.378*
Planned continuity - DS discontinuity	-0.385*
Quantity based - slowdown	-0.497**
Quantity based - DS slowdown	-0.582**

Quantity deviation - start date deviation	-0.351*
Slowdown - working in planned sequence	-0.371*
Working in planned sequence - DS start-up delay	-0.377*
Working in planned sequence - DS discontinuity	-0.495**
Working in planned sequence - DS slowdown	-0.355*
Start date deviation - finish date deviation	0.56**
Production rate - PPC	0.565**
Production rate - finish date deviation	-0.379*
Discontinuity - finish date deviation	0.394*
Slowdown - DS slowdown	0.78**
Actual continuity - DS discontinuity	-0.323*
Finish date deviation - DS discontinuity	0.353*
Slowdown - PPC	-0.396*

Table B-8 shows all the significant correlations of the detail task numerical variables. Suffering from slowdowns correlated with working out of sequence. Working out of sequence correlated with all downstream production problem types. A plausible explanation could be that suffering from slowdown causes a subcontractor to move to another location out of sequence to improve productivity. However, this decision results in causing further problems downstream. This was also shown by the direct observation of the pattern of how the detail tasks were changed. The sequences were changed almost weekly to adapt to circumstances. Because the schedule did not have information about the commitment, it is impossible to know if the subcontractors were relying on a planned sequence, or if the schedule was being updated based on the actual sequence that "emerged" in the field. However, the data show that these adjustments caused problems.

The start date delay correlated strongly with finish date delay (correlation 0.56**), which indicates that the start dates were delayed often so much that they could not be recovered by control actions. Typically, the detail tasks have shorter durations than the baseline tasks, which explains this correlation: any deviation in the start date is more likely to result in deviation to the end date. A higher production rate correlated strongly with higher PPC and lower finish date deviation. The finish date deviations were also explained by the discontinuities caused by other tasks and the overall production rate. In this project, the problems suffered by the task and caused to downstream tasks were not as highly correlated as in the other case studies. However, a strong correlation was found between suffering production rate problems and causing downstream production rate problems. Downstream discontinuities were explained by finish date deviation. Suffering from slowdowns decreased PPC.

Example of detail task adjustment – sprinkler and painting

The sprinkler and painting detail task adjustments are good examples of how much the production plans changed week-to-week, and what actually happened on site.

Figure B-5 shows the status of the detail tasks just before the start of the sprinkler work. The work was planned to be continuous with one crew, except for the mechanical room, which would require the mobilization of another crew. The painting is planned to be continuous, with one crew flowing through sections 2 and 3, and an additional crew working in section 4. Although there are no planned dependencies, the tasks were not planned to happen at the same time in the same locations (except for the sprinkler center and the painting on floor 1½ in section 3).

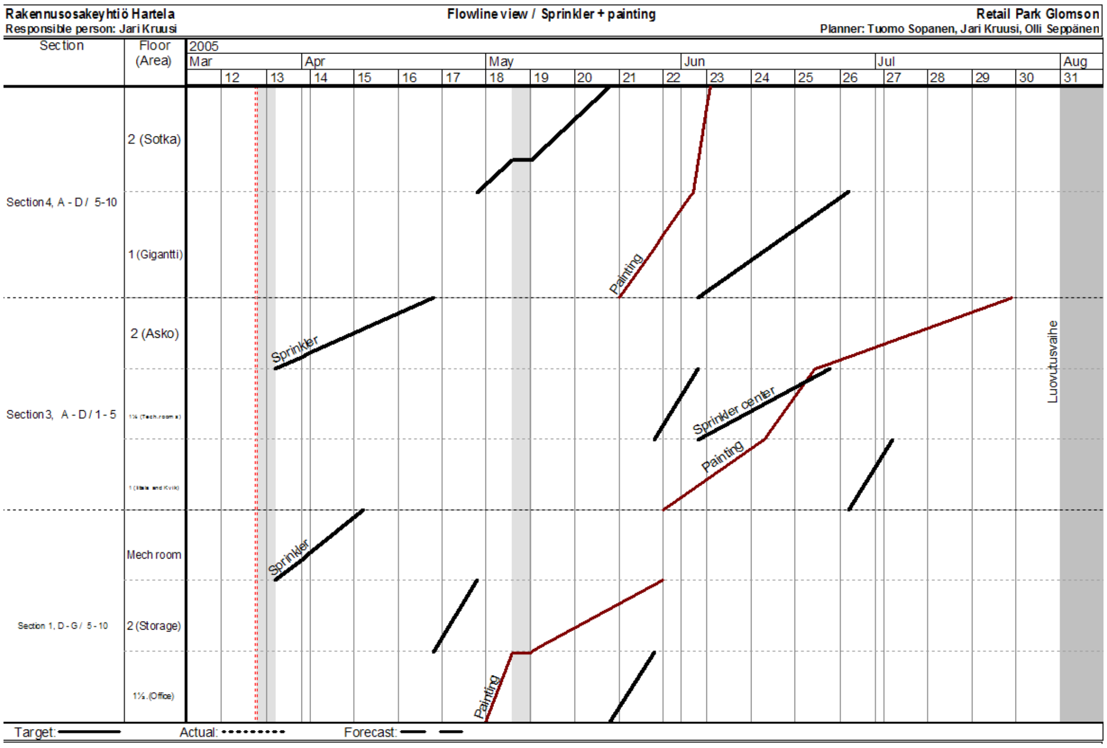


Figure B-5: Painting and Sprinkler one week before start of sprinkler work

One week later, the painting detail schedule was planned (figure B-6). The start date was moved back to the current week (apparently because of free locations) and the work was re-planned with one crew. In the resulting detail schedule, work was continuous and did not interfere with the sprinkler work. There were some overlaps in the locations, but the locations were large. Even though there were still no dependencies, it is apparent that the schedule was planned so that interference was minimized. The sprinkler schedule stayed unchanged, except for a delay in the mechanical room.

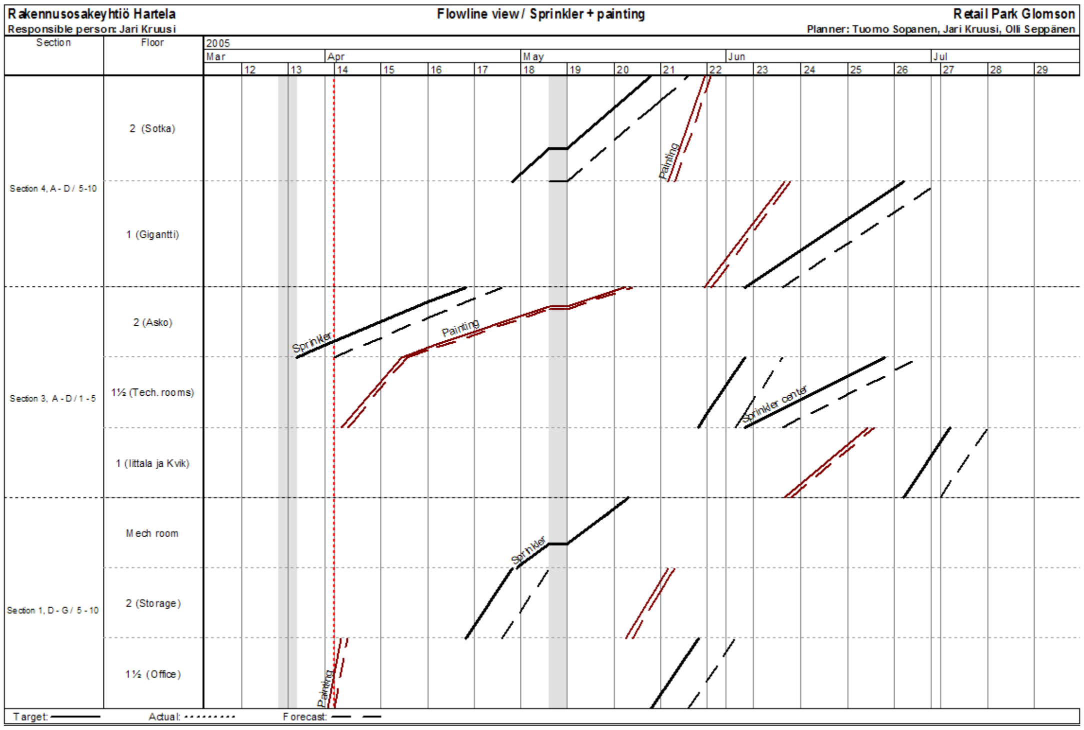


Figure B-6: The sprinkler and painting schedule one week before the start of painting

Figure B-7 below shows the final detail schedules with the progress information and also the problems caused by the sprinkler to the painting. The painting started with planned logic. However, the sequence of the sprinkler and painting in section 1 was changed in such a way that they happened at the same time, causing problems. Similarly, section 4 was done in the wrong sequence (the sprinkler started there before the technical rooms and the painting started there before the 2nd floor, as planned) which caused the painting and sprinkler to happen together with a bad production rate on the 1st floor. Finally, the sprinkler entered before the painting to section 3 on the 1st floor, which caused a problem to the painting. Although some of these problems may have their root causes somewhere other than the change of sequence, these kinds of examples were common and are reflected in the correlation analysis.

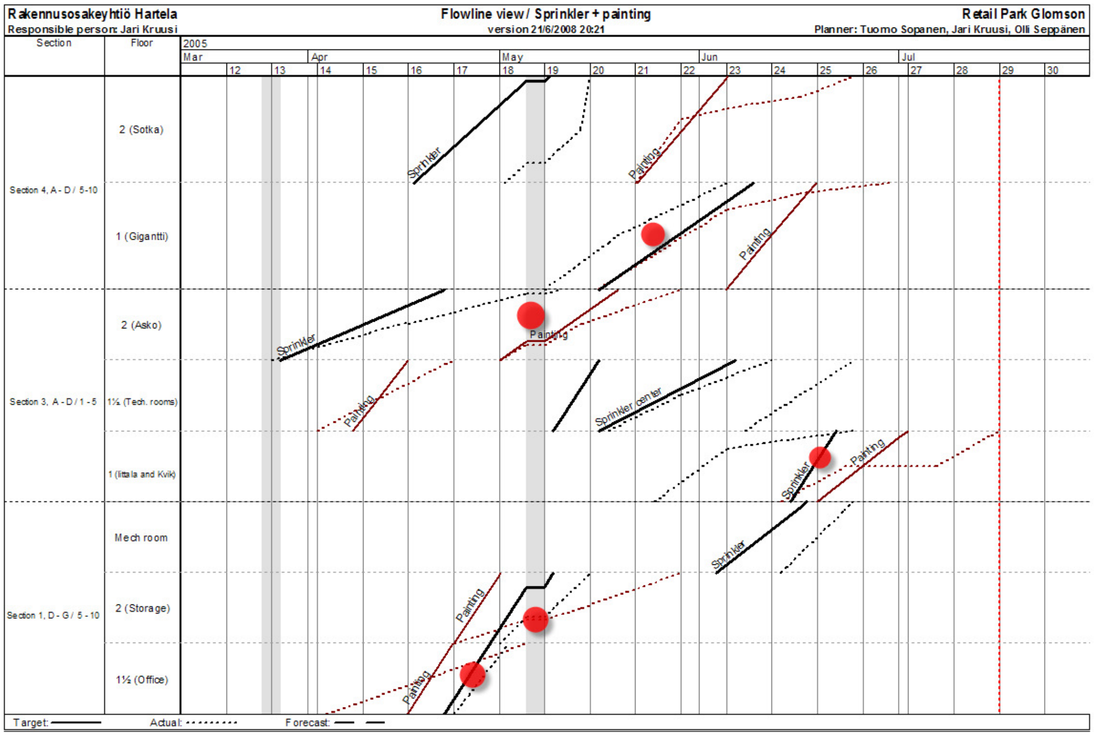


Figure B-7: Actual production and final plan of sprinkler and painting

B.7 Analysis of weekly planning reliability

Weekly plan reliability was analyzed by use of PPC. The previous sections have described the PPC averages for both the baseline and detail tasks to find correlations to the other variables. Figure B-8 shows PPC as a function of time.

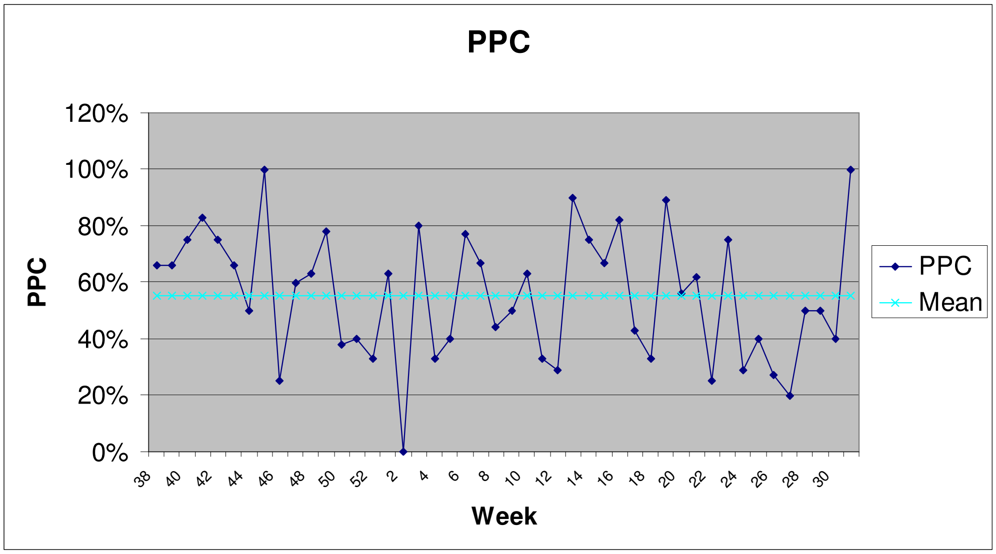


Figure B-8: PPC as function of time

The average PPC was 58%. The trend is random and has a series of above average PPC, and then a series of low PPCs alternating. This means that there is no consistent improvement over time. A PPC value of 58% is not a good result, because Last Planner studies often reach PPCs of 80 % or higher (for example Ballard 2000). It is something to be expected when active efforts are not taken to improve PPC. In this case study, there was no noticeable effort by the project team to achieve a better PPC. The main objective of the project team was to finish the building on time instead of increasing productivity or minimizing waste using lean principles.

B.8 Analysis of problem tasks

In the previous sections the baseline schedules, and to lesser extent the detailed schedules, were found to be unreliable. In this project the baseline plan was of quite good quality with most of the tasks having quantities. However, there was high uncertainty related to the quantities and the logic of tasks which could have explained some of the problems. Based on the observations on site, controlling production was not analytic and because of errors in the progress data, the information from the production control system was often incorrect. This project also had a tendency to schedule the detail tasks without any logic relationships to the other tasks, which reduced the quality of the available information.

A total of 122 production problems were identified from the project data. Because there were 38 detail tasks, the average task caused 3.2 problems to the other tasks during implementation. However, the distribution is skewed. The worst task caused 17 problems (painting) and many tasks did not cause any problems at all. Of these 122 problems, 5 could be verified with certainty (4 %). 46 problems (38%) were probable and the remaining 71 (58 %) were possible. Start-up delays were easiest to verify based on other information (start up delays: 1 certain, 5 probable, 2 possible). Both discontinuities and slowdowns had a large percentage of possible issues (discontinuities 0 certain, 8 probable, 12 possible, slowdowns 4 certain, 33 probable, 57 possible). Compared to the other case studies, the uncertainty of issues in this project is higher. This result is most probably caused by two issues: the schedule was lacking many critical dependencies (which led to less probable issues) and the contractor meeting memos very rarely had any mention of the production problems (explaining fewer certain issues).

In 16 cases (13 %), an alarm was generated before a problem happened. On average, an alarm was generated 22 workdays before the problem. In the worst case, an alarm was generated five days earlier, and in the best case the alarm was generated 45 workdays before the problem.

12 alarms (75%) resulted in a control action but the problem still happened. On average, the control action was effective 18.75 workdays after the alarm was generated. In the best case, the control action happened 5 workdays later, and in the worst case 45 days after the alarm. The production rate was increased in ten cases, the plan was changed twice. In all of these cases, the control actions were inadequate or too late because the problem actually happened.

Control actions were effective in those cases where an alarm was generated but did not actualize because of a successful control action. There were 17 alarms which did not result in a problem. Of these, 10 were false alarms. Control actions were implemented to remove 6 of the alarms, and 1 problem did not actualize because there was another reason for delaying the successor (the structure also suffered from design problems). Control actions included increasing the production rate (4 times) and changing the plan (2 times).

These data reveal five interesting classes of cases: 1) problem – no alarm 2) problem – alarm – no control action 3) problem – alarm – failed control action 4) problem – alarm – successful control action 5) false alarm. These cases are explored in more detail in the following section.

B.7.1 No alarm

The 106 cases which resulted in a problem but no alarm was generated were analyzed more closely. Five groups of case were found.

Case 1: Missing dependency

36 out of the 106 cases (34 %) had a missing dependency link in the system, i.e. the system did not know that the tasks would cause problems for each other. In this project, the most common reason for these cases was that the project team did not enter any dependencies into the system but instead scheduled by using dates.

Examples:

- The main mechanical room mechanical work, plumbing work and electrical work did not have any dependencies to each other, even though they had to be performed in a small area in a constrained sequence
- The painting did not have links to the suspended ceiling and caused repeated problems

- The sprinkler work did not have any dependencies (all were removed during the course of the project to remove the alarms)

Case 2: Many tasks in the same location

In 54 cases (51 %), there were many tasks going on in the same location and they were slowing each other down. There were no dependency links in the system. In these cases, there was no actual technical dependency, but multiple trades working in the same location did not have enough space to work productively. In these cases, one or two trades might be able to work with a normal production rate and the others had to slow down.

Examples:

- The sprinkler and painting work slowing each other down when happening in the same location (see figure B-6 above)
- The vinyl floor covering and electrical work at the same time in the same location

Case 3: wrong dependency in the system

In 3 cases out of 106 (3%), the logic link was there but it was incorrect. In one case the relationship itself was incorrect: the painting was planned to happen before the sprinkler, even though it had been agreed that the sprinkler pipes would be painted. In two cases, a problem happened because the lighting was supposed to happen before the suspended ceilings. However, some of the lights had to be installed before the suspended ceilings and some of the lights in the same location after the suspended ceilings.

Case 4: Not at the same time in the same location

On 12 occasions (11 %), tasks were suspended or had start-up delays because they could not enter the same location at the same time as another task. In this case there was no technical dependency – the tasks could be done in any order. However, the work space was too small for both to continue at the same time. 10 of these issues affected either the office or the smallest retail space, which were both small locations. 1 was related to the concrete pouring which requires a lot of empty space without other contractors. The final one was related to the eaves and curtain wall happening at the same time on the same elevation.

Examples:

- The interior walls had started before the interior concrete pours. It was not possible to pour before the workspace was free

- It was not possible to commence the restroom tiling at the smallest retail space because of the electrical and painting contractors working in the same space.

Case 5: Problems within the same baseline task

There were no cases where the main reason for not generating an alarm was that two detail tasks were in the same baseline task. However, the masonry walls and plasterboard walls would have entered this category if a dependency had been planned between them. Because they did not have a dependency link at all, they were allocated to group 1, no dependency.

Case 6: Only finish-to-finish dependency in system

In one case, only the finish of the task was constrained by a dependency. In this case the system could not generate an alarm. The Backfills had a Finish-to-Finish dependency to the drainage but a delay in the drainage delayed the start of the backfills.

B.7.2 Alarm → no control action

There were 5 cases when an alarm was generated before a problem but no control action was implemented. Table B-8 shows how many days before the problem the alarm happened, and whether a control action took place. The table includes all the cases where the problem happened and all the cases where the problem did not happen but an alarm was correctly generated. False alarms have been removed from the table. Because the number of cases was small, the groups have been combined so that the Chi2-test gives valid results.

Table B-8: Effect of timing of alarm on control actions

Days before alarm	No control action	Control action	Total
5-10	3	3	**6**
15-20	2	4	**6**
25+	0	11	**11**
Total	**5**	**18**	**23**

The Chi2-test of the data shows that this kind of distribution could have happened by chance, assuming that the variables were independent, with a probability of 4.2 %. This result is statistically significant. Alarms were more likely to result in a control action if they were generated earlier.

Because the time of alarm before the problem seems to have an effect on the guiding control actions, the reasons for generating alarms ten days or less before the problems were examined by looking at the six cases in more detail. Each alarm was examined and the status of the previous week was observed to see why the alarm was not generated earlier.

Case 1: Start-up delay in the first location

In one case, the alarm was delayed because the first location of the predecessor task started too late. Unexpectedly, the painting did not start according to the detail plan in the technical room. The alarm was given only after the start date of the painting had already been delayed by one week because the forecast assumed a start on the control date.

Case 2: Schedule forecast over-optimistic

Two cases happened because of over-optimistic forecasts. The schedule forecasting technique assumed that the forecast could not be calculated based on the first location, because the beginning of the task always had production problems. The structure had been split so that each location was a separate task. Therefore, the task could not have two finished locations, which was a prerequisite of the production rate forecasting. The structure was always forecast to happen on the planned production rate. Because of this reason, one alarm was given too late. One alarm was given too late for a similar reason, because the curtain wall locations were not completely finished. Therefore, the production rate could not be forecast and the alarm was given too late.

Case 3: Successor started early

In one case, an alarm happened late because the successor started too early. The structure started earlier than planned in the location where the air raid shelter was being installed. This caused an immediate alarm

Case 4: Out of sequence work

One case resulted from starting a successor out of sequence. The roof carpentry started unexpectedly before the curtain wall, resulting in an immediate alarm. The problem happened the next week.

Case 5: Miscellaneous reason

The final case happened because the project engineer had activated a setting in the controlling software which only showed the alarms which would happen in the next two weeks and two locations.

B.7.3 Alarm → Control action → problem

In two cases, a control action took place and the alarm was removed, but the problem still happened later. These cases can be divided to 2 groups.

Case 1: Dependency was changed or removed

The link between the curtain wall and the roofing was removed. In effect, the management did not think that there would be a problem, so they altered the logic to remove the alarm. However, the problem still happened.

Case 2: Successor start date delayed as a control action

The curtain wall start date was changed after it was recognized that the structure would not be finished on time in the location where the curtain wall was supposed to start. However, the change was done one week before the start of the task so it was classified as a problem.

B.7.4 Alarm → Control action → no problem

There were six alarms which did not actualize because the problems were prevented with successful control actions. The production rate was changed four times and two alarms were removed because of the change of plan.

Control action type 1: change of production rate

None of the four cases where the production rate increase happened after an alarm had supporting documentation about the reason. There was an unexplained production rate increase in the foundations task (3 times) and the interior walls task (once) but the subcontractor had the same resources on site. It is possible that the resources worked overtime to catch up, or there was a factor affecting productivity negatively which was removed. Figure B-9 shows an example of the increased production rate in the foundations.

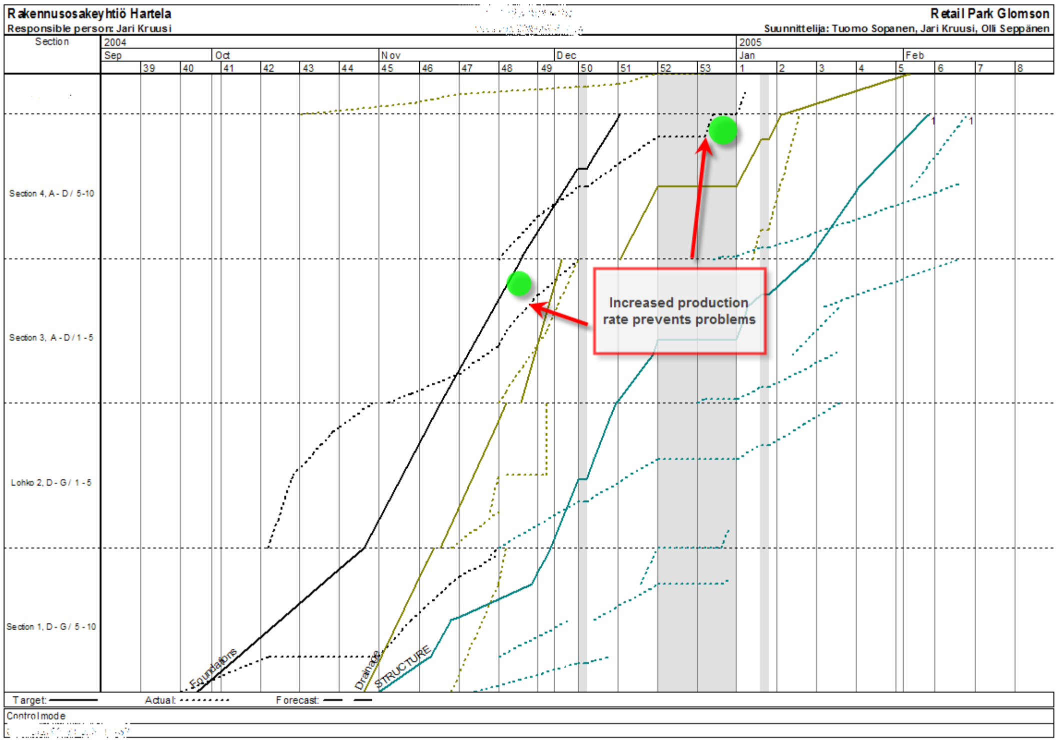


Figure B-9: Example of an increased production rate preventing a production problem

Control action type 2: plan change

The plan was changed so that it removed the problem in two cases. The first case was to plan to take another crane to catch up the delays in the structure. The other plan change was to change the roofing plan so that the vapor closure and waterproofing would be done by the same crew. This slowed down the work sufficiently that the problem did not occur in the second location.

B.7.5 False alarms

There were 11 false alarms during the project. These are damaging to the perceived reliability of the alarm system, and may lead to a delayed reaction or no reaction to valid alarms.

Case 1: wrong dependency

In 2 cases, the reason for the false alarm was a wrong dependency. There was a Finish-to-Start dependency from the smoke removing hatches to the roofing. However, the roofing could go on without problems even though the hatches had not been installed. In this case, the real dependency would have been Finish-to-Finish.

Another example was a dependency from the restroom tiling to the floor tiling. However, the floor tiling referred to the lobby floor tiling which did not have an actual dependency to the restrooms.

Case 2: Same subcontractor and resources

In one case, there was an alarm when the vinyl floor covering task had a dependency to the vinyl floor covering in another location. The two locations had been split to separate the tasks and the resource flow was modeled by adding a dependency. This caused an alarm every time the first part was delayed.

Case 3: Same location at the same time but no problem happened

In two cases, the dependency was apparently valid, but the tasks could happen together without causing any visible problems to each other.

- The mechanical ducts and electrical cable trays happened without problems in the same area
- The drainage and backfills happened without problems in the same area

Case 4: Tasks should not be in the same location but could be done in any sequence

In two cases, the dependency had been chosen, but in reality the tasks could happen in any sequence – just not at the same time. The suspended ceilings had a dependency to the vinyl floor covering and caused an alarm. The vinyl floor covering could be done before the suspended ceilings without problems. Similarly, the floor tiling was done before the suspended ceilings, even though the dependency was the other way around.

Case 5: Wrong progress data

In one case, a false alarm was given because the forecast was operating on the basis of false progress information. The driven piling was replaced by the drilled piling on the 1st section, because the soil was more rocky than expected. The drilled piling was included in the foundations task scope. However, the piling task was not changed to be completed in the area when the change was done, and a false alarm of out-of-sequence work remained.

Case 6: Small part of scope left unfinished

On two occasions, only small part of the predecessor was unfinished, and the successor could start work without problems. For example, the structure was missing a few roof slabs, but the roofing could start without problems from the other end of the section. Another example was the curtain wall and interior concrete topping pours. The pours could be done inside the large location as long as the façade strip was not poured. Because the areas were large, the complete section could not have been done with one pour anyway.

B.9 Analysis of the construction phases

In the correlation analysis, it was shown that the MEP tasks behaved differently from the other tasks. Because this finding was shared in the Prisma case study based on direct observation in the weekly progress meetings, and confirmed in this case study by discussions with the project engineer, further analysis on the construction phase differences was done also in this project.

To evaluate the hypothesis that there was a fundamental difference between the interior / MEP work and the other work stages, the main numerical variables were calculated for each construction phase: Foundations, Structure, Roofing, Façade, Interior construction work, Interior MEP work, and Commissioning. Results were calculated for the production rate deviation, the start date deviation, finish date deviation, PPC, each production problem type, and each downstream effect type. The analysis was done only for the detail tasks.

B.9.1 Production rate deviation by construction phase

Figure B-10 below shows the range, quartiles, and median of construction phases for the production rate deviation (actual production rate / planned production rate). The structural tasks are below all the others in this comparison. This is caused by the fact that the same resources were split over multiple detail tasks, installing both on the same day. The foundations and roof are the only construction phases where the median production rate is almost at the planned level. The roof, foundations and façade all have outlier tasks with very high production rates compared to the plans. The structure, MEP and interior under-performed in the production rate analysis.

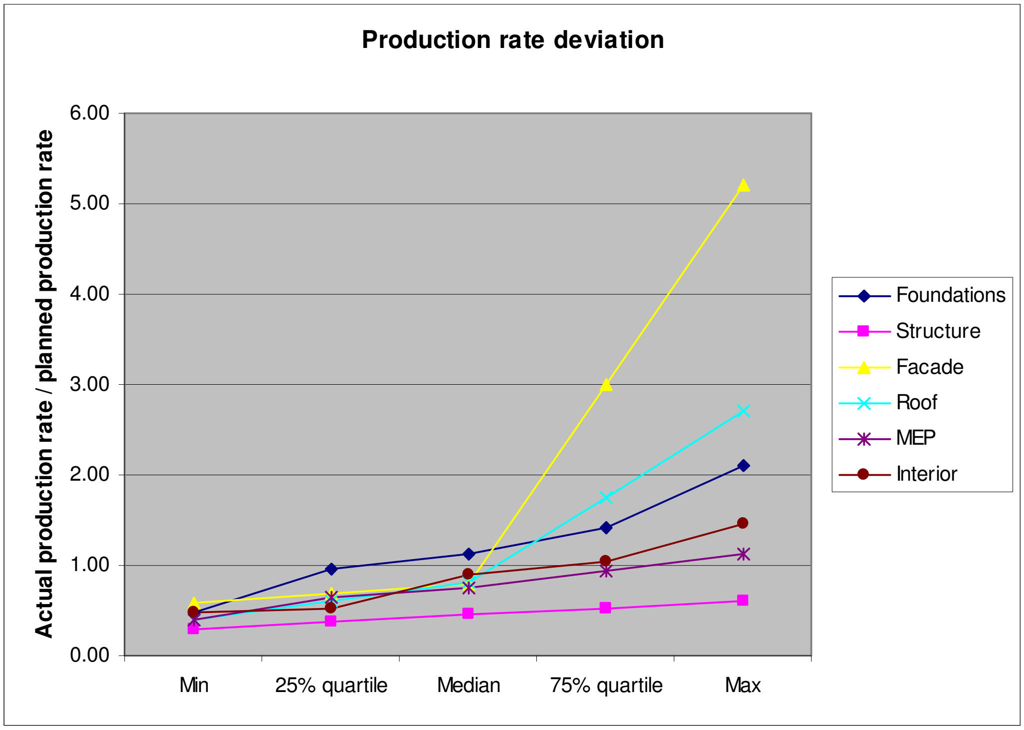


Figure B-10: Actual production rate / planned production rate distribution for tasks in each construction phase

B.9.2 Start date deviation by construction phase

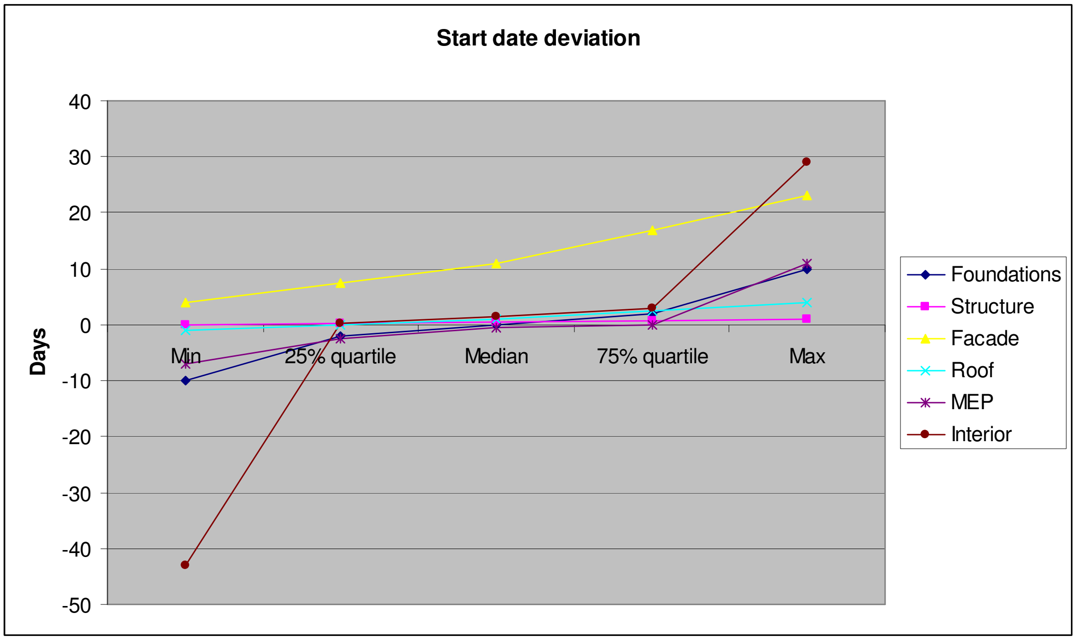


Figure B-11: Actual start date – planned start date distribution for the tasks in each construction phase

In the start date deviations (figure B-11), it can be seen that the interior finishes task has very high extreme deviations in both directions. The façade tasks had high delays in all of the tasks. Most of the construction phases have 50 % of the range very close to zero – i.e. most of the tasks started according to their detail plan.

B.9.3 Finish date deviation by construction phase

The finish date deviation (Figure B-12) follows the same pattern. The structure and foundations had major problems in this project (the death of a crane operator, design issues, a major quantity increase in the foundation work) which explains their delays and also the delay of the roofing and part of the delay of the façade. The MEP and interior tasks were, on average, delayed and especially the top 25 % of tasks had long delays.

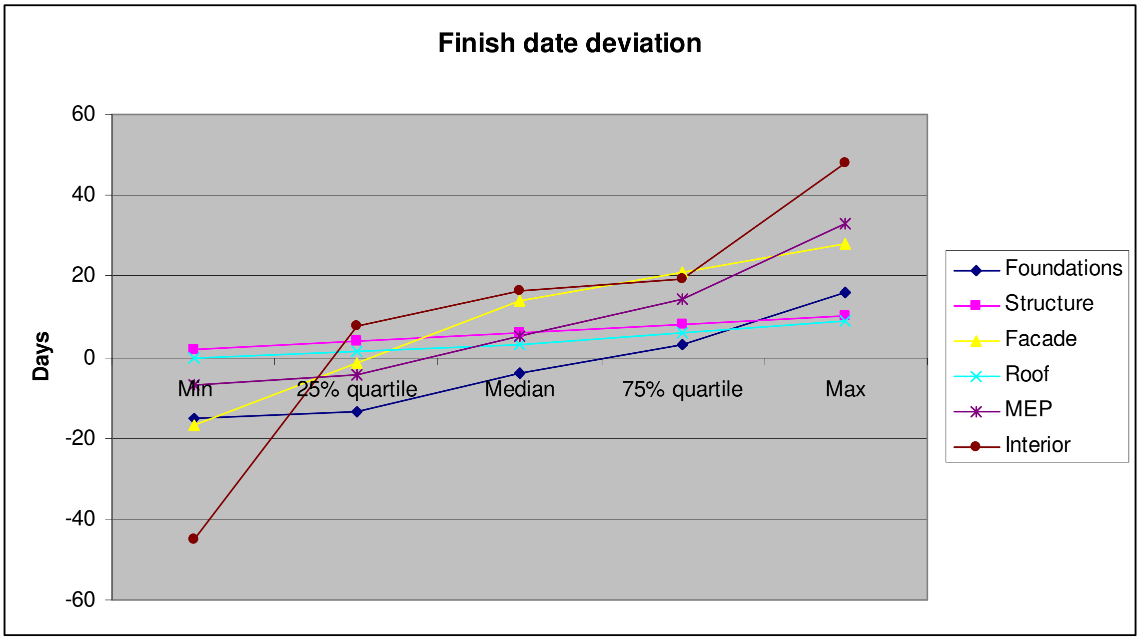


Figure B-12: Actual finish date – the planned finish date distribution for the tasks in each construction phase

B.9.4 PPC by construction phase

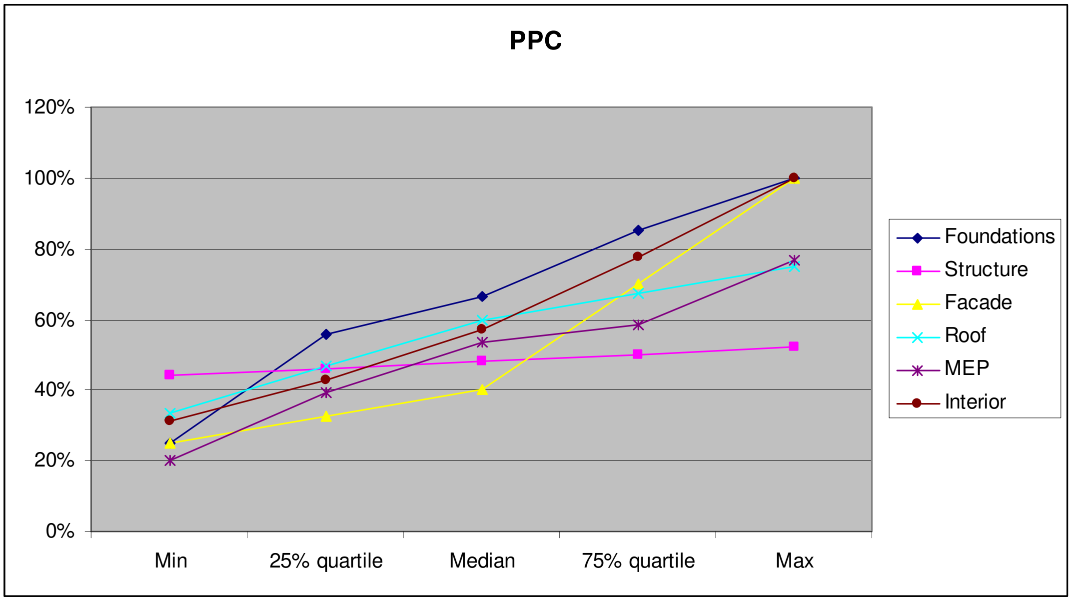


Figure B-13: PPC distribution for the tasks in each construction phase

In terms of the weekly plan reliability, the foundations, roofing, and interior work had the best results in this project. The MEP, façade and structure had lowest PPCs as the median. However, the foundations also had very bad tasks, and the MEP had some tasks approaching 80 % PPC. The curtain wall had high PPC tasks, but most of the tasks performed badly.

B.9.5 Start-up delays by construction phase

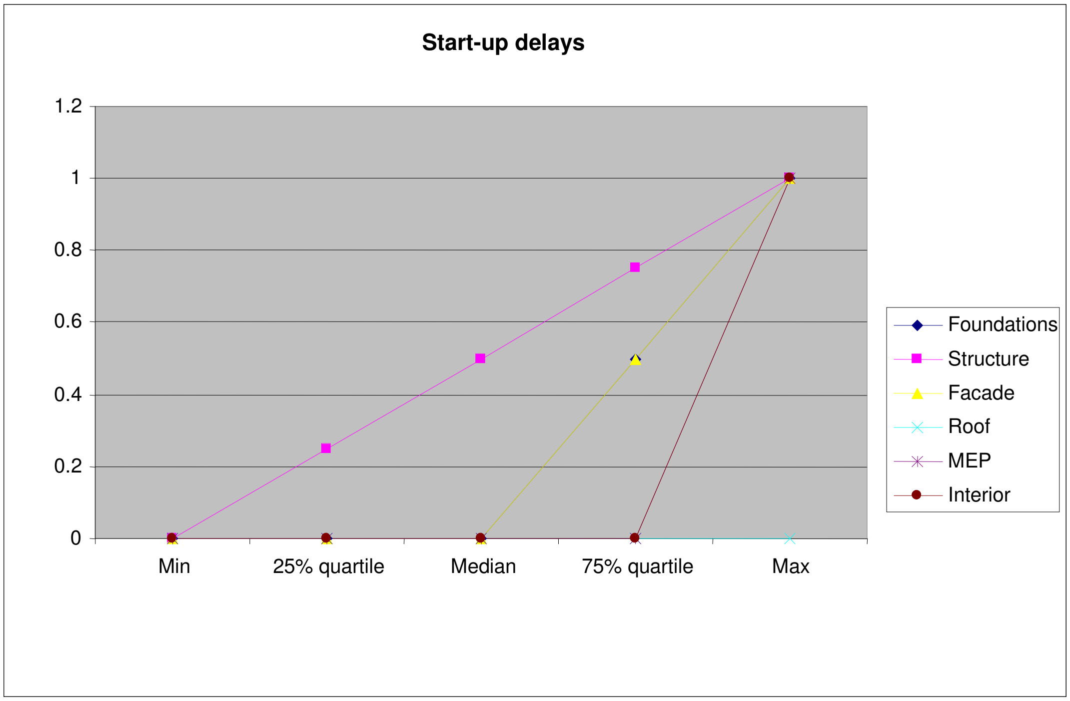


Figure B-14: Number of start-up delays distribution for the tasks in each construction phase

Figure B-14 shows how many times the tasks could not start on the week they were planned to start because of the delays of the other tasks. In this project, the start-up delays were not a problem and no task was delayed repeatedly.

B.9.6 Discontinuities by construction phase

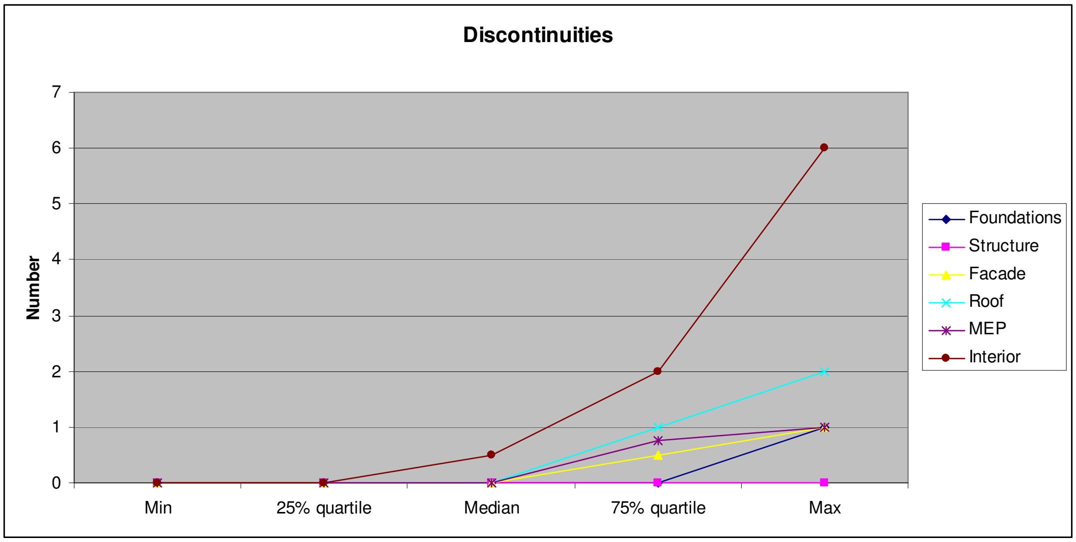


Figure B-15: Number of discontinuities distribution for the tasks in each construction phase

In terms of the discontinuities (figure B-15), the interior construction clearly rises above the other construction phases. Many of the interior construction tasks experienced discontinuities, although they were not a problem in this case study in general.

B.9.6 Slowdowns by construction phase

The slowdowns have large differences between the interior/MEP and the other trades (figure B-16). Almost all the MEP tasks had some slowdowns. The median task was slowed down by the other tasks six times during the project. The interior finishes task has a similar graph, but while the extreme maximum number is higher, most of the range is below the MEP slowdowns. It seems that the interior finishes subcontractors reacted more often by stopping work and leaving the site.

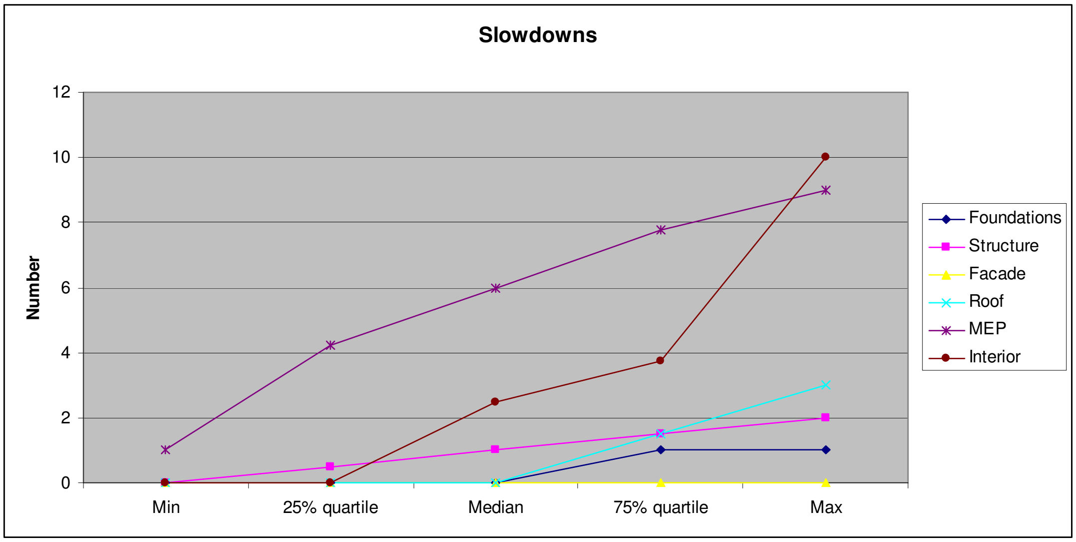


Figure B-16: Number of discontinuities distribution for the tasks in each construction phase

B.9.7 Downstream start-up delays by construction phase

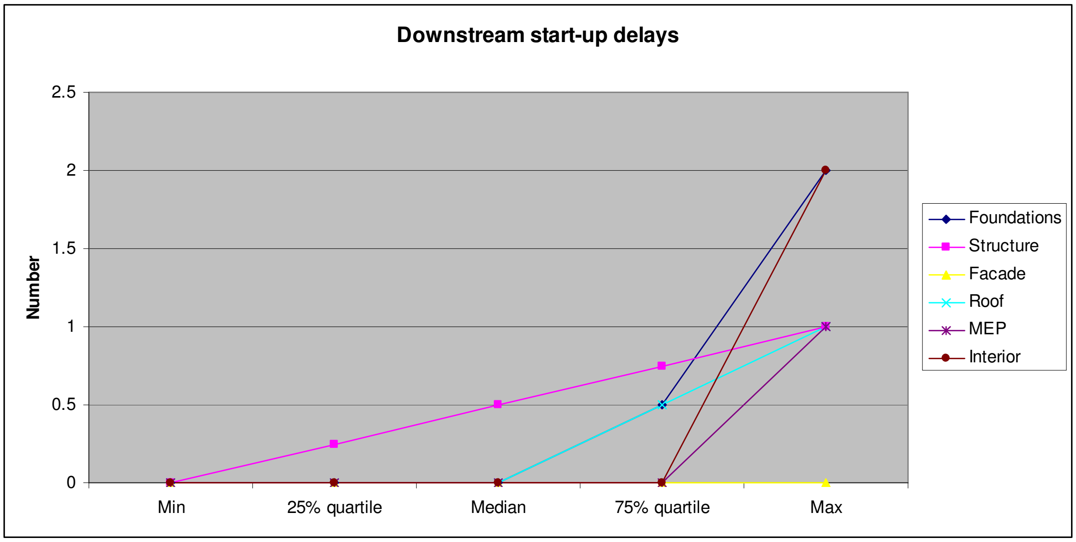


Figure B-17: Number of downstream start-up delays distribution for the tasks in each construction phase

Most of the construction phases have a similar profile in the downstream start-up delays (Figure B-17). The façade did not cause any downstream start-up delays.

B.9.8 Downstream discontinuities by construction phase

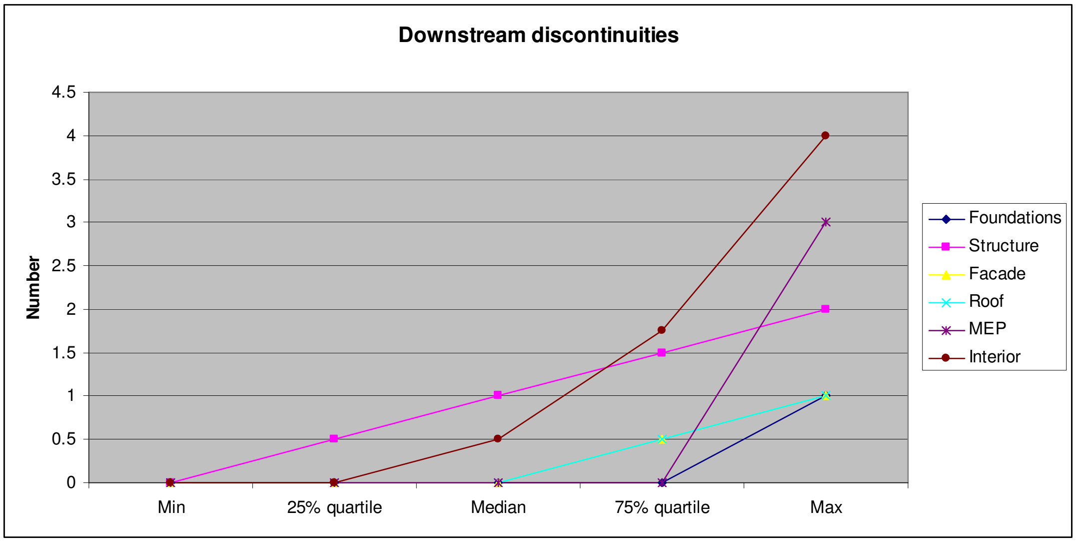


Figure B-18: Number of downstream discontinuities distribution for the tasks in each construction phase

In terms of downstream discontinuities, most of the construction phases share the same profile (Figure B-18). The interior construction and structure tended to cause the most discontinuities in the median and 75 % quartile.

B.9.9 Downstream slowdowns by construction phase

The MEP and interior finishes clearly caused the most downstream slowdowns (Figure B-19). Also, the median task caused problems in both phases. In the MEP phase, all the tasks caused at least one slowdown, and the worst tasks caused 10 slowdowns. 25 % of the MEP tasks caused slowdowns at least 8 times! With the interior finishes, the extreme case is higher (12 times) but the median task slowed down the other tasks just once, and 25 % of the tasks 4 times or more.

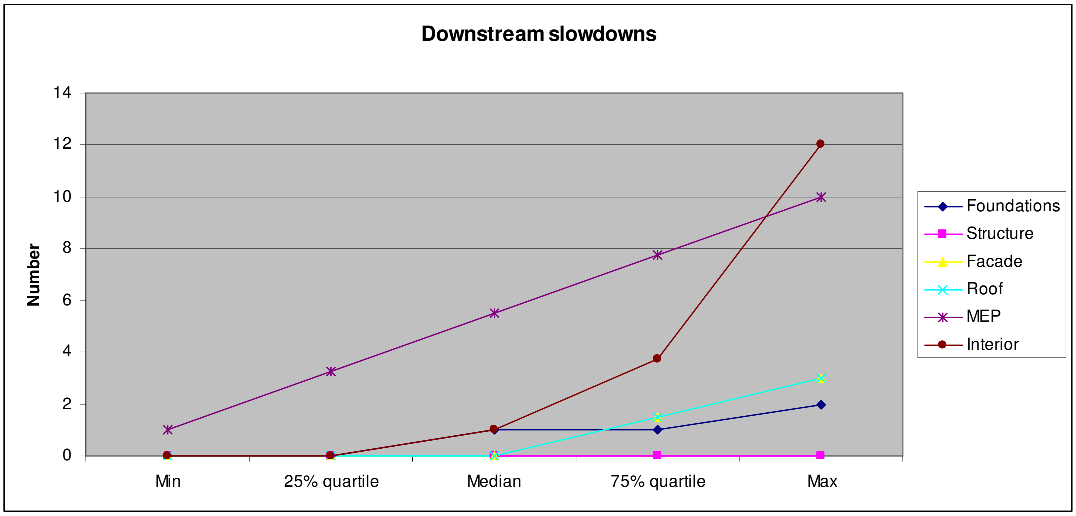


Figure B-19: Number of downstream slowdowns distribution for the tasks in each construction phase

B.9.10 Differences in the construction phases

From the results presented in this section, it can be concluded that the MEP and interior phases differed from the other construction phases mainly in terms of the slowdowns caused by the other tasks and the production rate problems caused to the other tasks. The interior construction also caused more discontinuities to other tasks than the other phases. All the other deviation types, start date deviations, production rate deviations, PPC, and finish rate deviations have similar trends with the other construction phases. In this project the structure performed badly on PPC, but did not cause more production problems to the other tasks than the other construction phases. The MEP and interior phases have more interlinked tasks which cause cascading slowdown effects. These effects will be researched in more detail in the week-by-week analysis.

B.10 Differences of small locations and large locations

The project Location Breakdown Structure had 4 large areas (Section 2, Asko, Gigantti, Sotka) of more than 1,000 m^2 and 6 smaller areas, including the offices, storage areas, main mechanical room, technical rooms, and the smallest retail space. Most of the production problems seemed to be concentrated in the small areas. The differences were researched by looking at the percentage of deviations in the small locations and large locations and comparing that to the approximate total man hours in the small locations and large locations.

The small locations had approximately 27 % of man hours and the large locations had 73 % of man hours. Out of the 7 start-up delays, 2 (29%) happened in the small locations and 5 (71%) in the large locations. Out of the 20 discontinuities, 13 (65%) happened in the small locations and 7 (35 %) in the large locations. Out of the 95 slowdowns, 54 (57%) happened in the small locations and 41 (43 %) happened the in large locations.

From these results it can be concluded that related to total quantity of work, the small locations get a disproportionate amount of production problems.

B.11 Analysis of resource use

In this project, the electrical subcontractor was the only subcontractor with many different tasks. The mechanical and plumbing subcontractor had just two tasks each, because they could finish their overhead installations completely in one round. The other task was for the mechanical room. Therefore, the resource use was analyzed for the electrical to find out if resource use exhibited the same patterns as in Prisma.

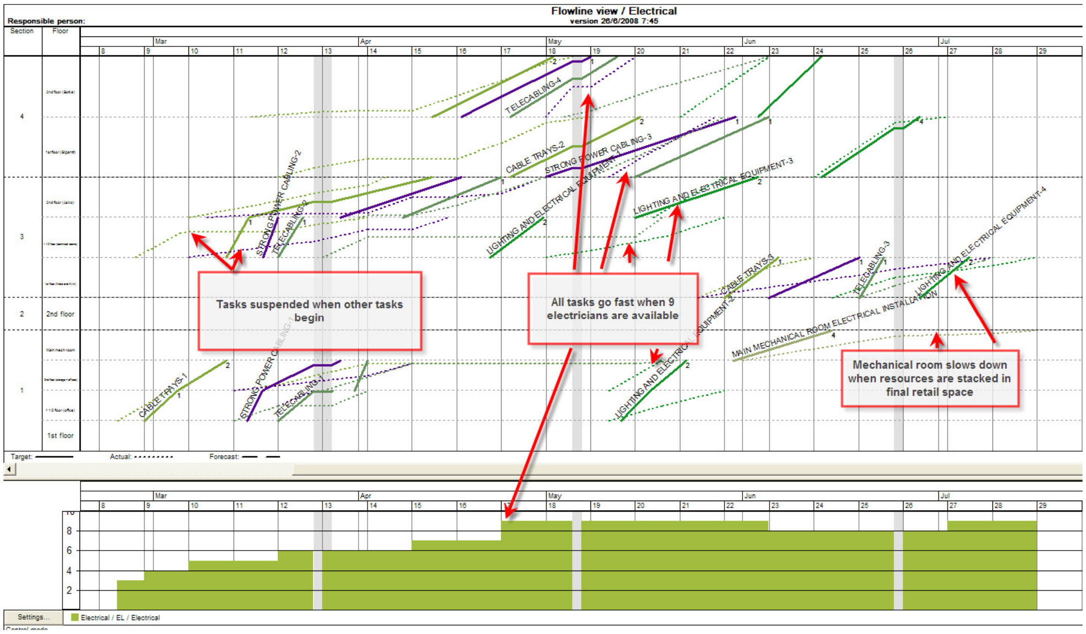


Figure B-20: Actual production and actual resources of the electrical subcontractor in Glomson

The actual progress and actual resource use for the electrical contractor is shown in figure B-20. The figure shows that in the beginning, many simultaneously ongoing tasks show suspensions and slowdowns. When the number of electricians is increased to 9, all the tasks continue with their expected production rate or faster. However, the delays continue at the end of the project when the mechanical room is stacked with finishing the last retail space with the same 9 electricians.

The original schedule for the electricians had been resource-loaded with the quantities and consumptions from the electrical contractor. Therefore, the resource profile in figure B-21 was known by the General Contractor. However, there has been seemingly no effort to balance the resource loading. The electrical contractor is planned to start with one electrician, slowly increase to 6 electricians in April, then to reduce to 2 electricians until finally in July (the summer holiday month in Finland) there should be 12 electricians. In reality, the resource graph was much more level with more resources earlier and with lower peaks. However, the actual man hours used were 180 % of those planned. Part of the increase was because of the change orders in Gigantti and Iittala and Kvik and the higher than expected amount of work in the main mechanical room.

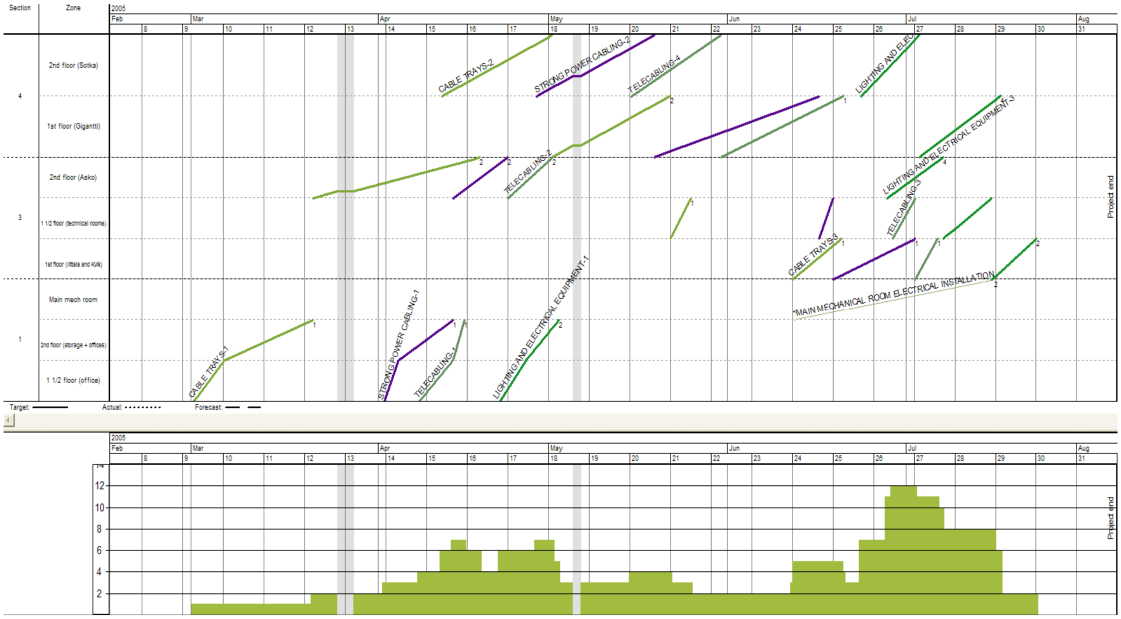


Figure B-21: Planned resource use and the schedule for the electrical contractor

B.12 Summary of results in Glomson

The project finished on time. However, half of the 1-month buffer at the end of the project was used up. There was a lot of waste in production, which in this project was manifested mainly as discontinuities and especially slowdowns. The reliability of the baseline schedule and weekly plans was poor. The detail schedules were better controlled, in terms of both the start and finish dates. Most of the tasks caused at least some production problems to other tasks. In this project, the slowdowns were the most common downstream effect type.

The production control in this project was characterized by a denial of the problems. Although many production problems can be inferred from the data, most of them were not noticed in any way by the project team, and were not discussed in the production meetings with the subcontractors or with the clients. Only 4% of the problems were mentioned in the meeting memos.

The detail schedule updating caused problems, because the schedules were changed weekly and problems were caused by changing sequences without checking whether multiple trades would be working in the same location at the same time. Because there were large changes in the schedules every week, it is difficult to know which schedule was agreed with the subcontractor. Therefore, some of the analysis may have been based on the detail schedules, which were works in progress, instead of finalized plans. Because the detail tasks were constantly changing, it may be that the production control problems were caused by comparing the actual data to the most current detail plan which in turn was updated based on the actual production. This may have given the false impression of always following the planned schedule.

The success of the weekly schedules was found to be correlated both with the successful implementation of the baseline schedule and the detailed schedule. In this project, there was no improvement over time in PPC values, which, according to direct observation, resulted from a lack of interest by the project team to get better at this measurement.

There was strong evidence of cascading production problems. If a task experienced slowdowns, it was highly likely that it also caused slowdowns to other tasks. An analysis by construction phase showed that the MEP tasks caused most of these cascading slowdown problems. These problems happened mostly in the small locations, even though more work happened in the large locations. Therefore, the location size needs to be taken into consideration when deciding the buffer sizes and control actions.

The resource use analysis of the electrical contractor showed that even though the electrical schedule had been planned based on the quantities, production rates and resources, there had been no apparent effort to level the resources. Actually, the electrical contractor mobilized more resources at the beginning of project, and worked with a level workforce throughout the project. The resource peaks planned in the General Contractor’s schedule were not matched by the actual resource use. It seems that the resource needs were not discussed openly with the subcontractors, even though their data had been used to plan the resources.

The location breakdown structure worked well for production. The earthworks, foundations, structure, and roofing used the structural sections, while the finishes and MEP used the functional spaces. It was possible to plan all the trades according to this location breakdown structure. It seems that having a functional breakdown for the finishes and MEP, and a structural breakdown for the other trades gave good results even without input from the subcontractors. However, the sequence of the locations was not planned taking into account the available tenant information. For example, the empty retail space with no tenant was planned to happen in the early stages of the project. When the rental agreements were signed with two tenants instead one, large deviations happened, because the tasks had to jump over the empty retail space because of the lack of tenant information.

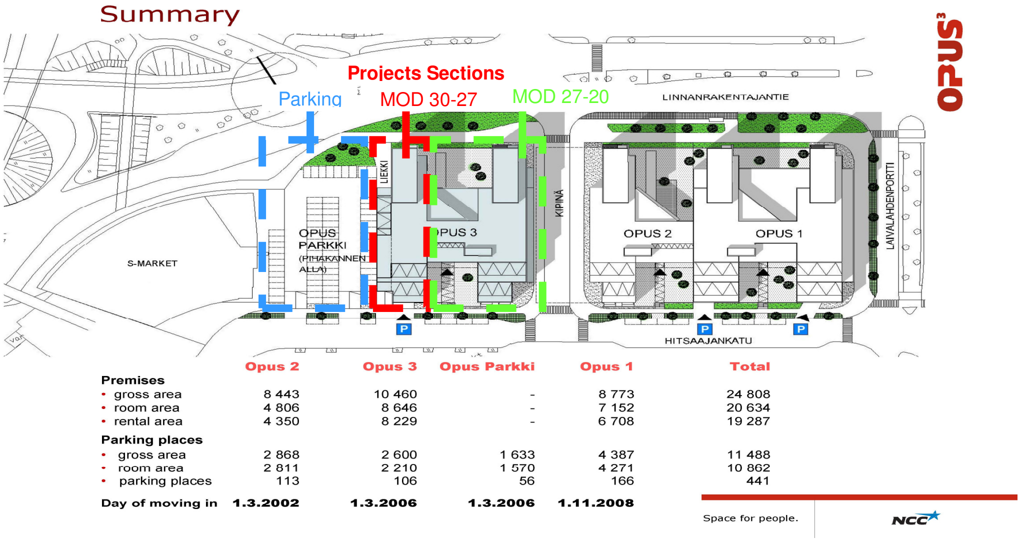
Many problems were identified in the production control system itself. Alarms were often not generated at all, or were generated too late for them to be useful. The main problems were found to relate to missing or wrong dependencies, over-optimistic forecasts, having many tasks in the same location, and starting work in the wrong sequence. In this project, there was a tendency to remove dependencies to solve alarms. As a consequence, alarms were not created for most of the production problems. To correct these problems both the production control process and the production control system need to change.

Appendix C: Case study III: Opus Business Park

C.1 Project description

The Opus Business Park was an office building with six floors and a parking hall below the main building. The total size of the project was 14,528 gross m^2. The building was divided into two sections, each of which was built as a structurally independent entity. The sections were basically identical, except for the connecting lobby portion, which was considered part of the second section (grid lines 27-20). Both of the sections had mechanical rooms on the roof. The first section had an air raid shelter. Additionally, there was a parking area below ground level. The parking hall had to be finished before the excavation of the second section could begin, because the second section was used as the parking area of the neighboring food market. The cars would be transferred on top of the parking deck when it was completed. The project was part of a multi-phase development. Phase 2 had already been completed previously, phase 1 was delayed, and this project was initially phase 3 (Opus 3). Figure C-1 shows a summary of the project.

The structure was pre-cast concrete with some minor cast-in-place areas. The connecting lobby area had a glass curtain wall, the other exterior walls were pre-cast elements with punched windows. Because the floor area decreased when going up the levels, there were small sections of roofing on the various floors, starting from floor 4.


Summary

	Opus 2	Opus 3	Opus Parkki	Opus 1	Total
Premises					
• gross area	8 443	10 460	-	8 773	24 808
• room area	4 806	8 646	-	7 152	20 634
• rental area	4 350	8 229	-	6 708	19 287
Parking places					
• gross area	2 868	2 600	1 633	4 387	11 488
• room area	2 811	2 210	1 570	4 271	10 862
• parking places	113	106	56	166	441
Day of moving in	**1.3.2002**	**1.3.2006**	**1.3.2006**	**1.11.2008**	

Figure C-1: Summary of Opus project

The finishes and MEP were planned for each section and each floor. The 1st floor included retail spaces and lobby functions and was different from the other floors. The other floors had identical office functions. The floor materials of floors 2 to 5 had a vinyl floor covering. The walls were movable system walls built on top of the floor covering to make it easier to accommodate user changes. Most of the MEP systems were placed in corridors inside the suspended ceiling bulkheads, and could be built before the end user information.

In this project, both the owner-developer and the General Contractor were part of the same construction group; NCC Construction Ltd. The project's original contract duration was from May 2004 to end of February 2006, based on the previous durations of similar projects. Because the client was internal, there was great pressure to cut the project duration and start receiving rental income earlier. One of the main goals of implementing location-based planning and controlling was to compress the duration by two months and hand over a good quality building faster than in previous projects.

This case study has been described previously in (Seppänen & Aalto 2005). At that time the project was still ongoing, and data had not been completely analyzed. Major new findings were made during the data analysis stage.

C.2 Available starting data

NCC Construction has devoted a lot of resources to implement location-based planning systems (Soini et al. 2004). This effort has made it possible to get location-based quantity take-off and standardized productivity rates for standard project types. The quality of the starting data makes it possible to plan the first drafts of the location-based schedule very quickly and to analyze multiple alternatives. The company databases include information about subcontracted work, which makes it possible to pre-plan the subcontracted work in great detail.

While the starting data were much better than in the other case studies, its apparent good quality caused problems in the production phase. The original quantities were used throughout the process, and were not updated during production, except in a few special cases (such as the number of elements in the structure which are easy to measure). There were a lot of changes because tenant information was not updated to the quantities. Also, it turned out that the MEP quantities were based on assumptions based on similar quantities in other projects. These quantities and consumption rates were often wrong, which was revealed in the large deviations in the MEP trades during production. A major difficulty was caused by the fact that there was no way to tell which of the quantities were accurate and which were assumptions. In most cases, the schedule planners simply trusted that the quantities were correct.

In this case study, all the quantities were available based on the sections and floors and thus could directly be used in the location-based planning. The project engineer had already finished the first draft of the location-based schedule before start of this research project. The NCC database of productivity rates had been used by the project engineer to develop a fully resource-loaded, location-based schedule.

C.3 Schedule planning process

The project engineer was responsible for the scheduling. He had some experience of location-based scheduling, because he had learned it at school and had used it to develop the initial schedule. The site manager and the other project team members had not been exposed to location-based planning or control before. They were trained by the project engineer to read the Flowline diagrams and control charts. The project engineer refused to print out the traditional Gantt Charts, so even the subcontractors and the Owner had to use the Flowline diagrams and control charts for schedule communication purposes.

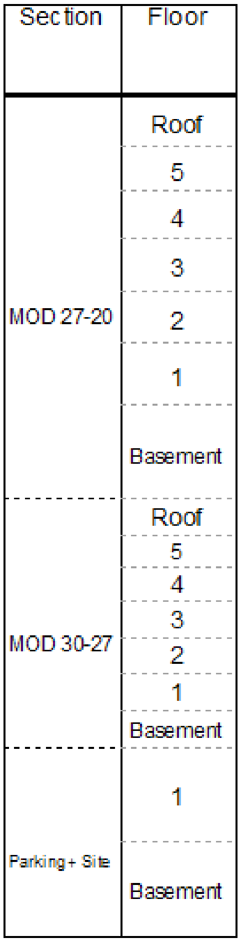
Because the starting data was already location-based and all the quantity items had a resource consumption estimate from the NCC database, it was possible to evaluate multiple different alternative schedules in a short period of time. Two main alternatives were examined: 1) a completely continuous schedule and 2) work continuous within each section, but with a break of workflow in between the two sections.

A completely continuous schedule would have had the same end date as the partially continuous schedule, but both of the sections would have been finished at approximately the same time. In this option all of the tasks would have been continuous. Because the finishes tasks were much faster than the structure, this would have delayed the start dates in the first section. A partially continuous schedule had one work break for all the finishes and the MEP tasks between the sections. This schedule achieved much of the same benefits as the completely continuous schedule, but enabled the first section to be finished earlier, thus reducing the risk of exceeding the total duration. The project team decided to implement the partially continuous alternative and take the break between the sections into account in the contracts with the subcontractors.

In the final baseline schedule, the production rates were synchronized and buffers were planned between the most important activities. All of the task durations were based on the quantities, resources, and productivity data from earlier projects or from the Finnish productivity database (Mäki & Koskenvesa 2002).

C.3.1 Location Breakdown Structure

The Location Breakdown Structure of the project was defined on two hierarchy levels. There were three sections – the parking, grid lines 30-27 and grid lines 27-20. The sections were subdivided into the basement, 5 floors, and the roof. The parking area was divided into the parking and the deck, which also had green areas and site tiling. Figure C-2 shows the location breakdown structure of the project.



Section	Floor
MOD 27-20	Roof
	5
	4
	3
	2
	1
	Basement
MOD 30-27	Roof
	5
	4
	3
	2
	1
	Basement
Parking + Site	1
	Basement

Figure C-2: Location Breakdown Structure of Opus

C.3.2 Task list

The level of detail for the master schedule was more detailed than in the other case studies, especially concerning the MEP work. This was the result of having the quantity information for all the anticipated work in the project. Some examples of the level of detail are shown in table C-1 below:

Table C-1: Level of detail of baseline tasks in Opus

SYSTEM	TASKS
Earthworks / Foundations	Excavation and rock blasting, Foundations, Air raid Shelter, Fills, Bottom sewers, Slab-on-Grade, Cast-in-place stairs and support walls
Structure, Roofing, Facade	Pre-cast concrete structure and facade, Wooden windows, Roof carpentry (eaves), Roofing, Metal windows and curtain wall, Façade louvers and metal veneer, Mechanical room steel structure, Mechanical room Paroc elements, Roof steelwork
Finishes	Concrete floor topping, Masonry walls, Suspended ceiling bulkheads, Plasterboard walls, Plasterwork, Painting, Restroom tiling, Vinyl floor covering, Movable system walls, Wood-frame glass walls, Wooden doors, Metal doors, Fire-rated doors, Suspended ceiling frames, Closing suspended ceilings, Door ironmongery, Furniture installation, Molding and equipment, Wood paneling of auditorium and sauna, Finishing and final cleaning
Plumbing	Plumbing vertical risers, Heat distribution room plumbing, Plumbing distribution, Radiators, Cooling pipes, Main mechanical room plumbing work, Water and Sewer fittings
Mechanical	Mechanical ducts, Mechanical distribution, Main mechanical room machines, Cooling beams, Cooling equipment, Mechanical duct insulation, Tuning of air flows
Electrical	Cable trays, Transformer, Main switchboard, Primary cabling, Secondary cabling, Group switchboards and risers, Electrical pipes in interior walls, Light installation, Electrical work in main mechanical room
Automation	Automation work, Automation work in main mechanical rooms
Site work	Parking deck concreting, Parking deck thermal insulation and waterproofing, Asphalt, Site tiling and rockwork, Support wall natural stone covering, Green areas, Exterior equipment

C.3.3 Resources and productivity rates

The productivity rates and crews were taken mainly from the NCC internal database of productivities. These rates were compared to the Finnish generic productivity database. The number of required crews was optimized to align the schedule. In this project, the structure was the bottleneck task, and all interior tasks were planned to have a similar slope. As in the other case studies, the earthworks schedule was already defined by the contract which was already in place when the schedule planning started.

C.3.4 Dependencies, lags and buffers

On the baseline level, all of the tasks had dependencies and the dependency network was complete. A Monte Carlo simulation (Kankainen & Seppänen 2003) was used to find any risky areas and to optimize the buffers. The earthworks and foundations were considered to have an opportunity for acceleration, instead of risks of delay. The structure was risky because a production rate of 18 elements / day was planned and there was no allowance for weather delays, even though the structure was built in the middle of the Finnish winter. Therefore, the actual production rate had to be higher if weather delays actualized to stay inside the schedule. Historical production rates in good conditions have averaged 16 to 20 elements / day in similar buildings. In the finishes phase, the biggest uncertainty was associated with the suspended ceilings and the system walls because of varying tenant requirements. The risks related to the first floor were recognized by having greater duration risks there. The suspended ceiling bulkheads were thought to have an opportunity for acceleration rather than risk, so no buffers were added there. The MEP tasks were not taken into consideration during the risk analysis.

Buffers were added based on the risk analysis results. The delay of the structure potentially causes cascading effects in the interior work, so buffers were planned between the structure and the first inside task: the concrete floor topping. Some buffers were also added between the finishes tasks which had the greatest uncertainty. However, the second section had few or no buffers. The resulting master schedule in Flowline format is presented in figure C-3.

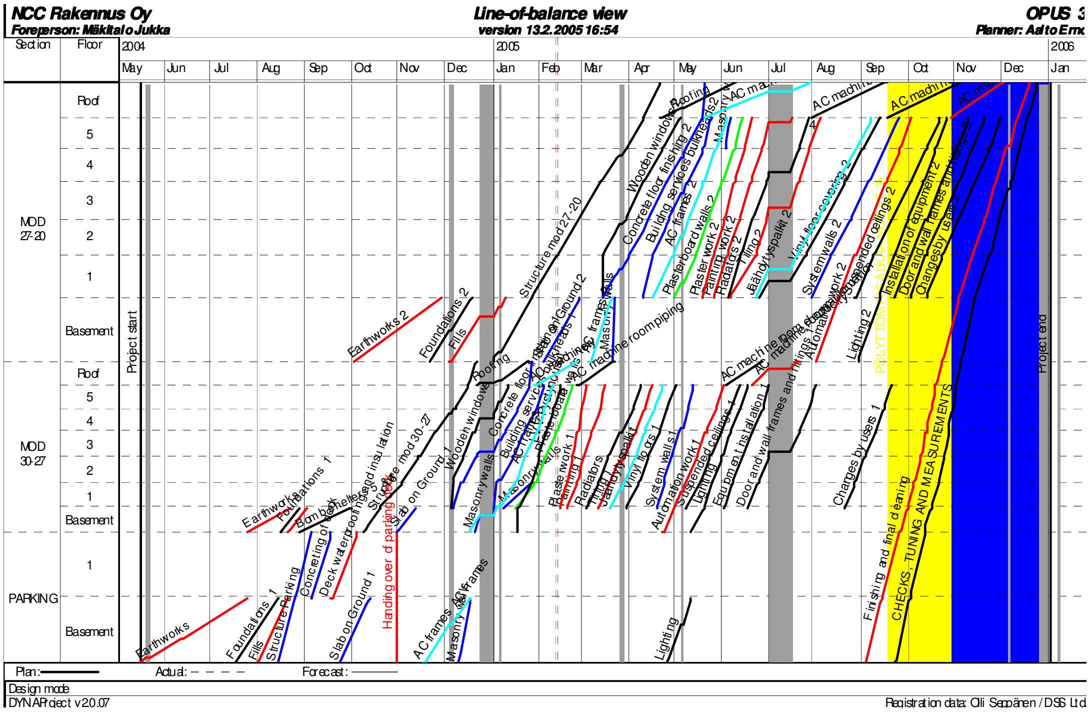
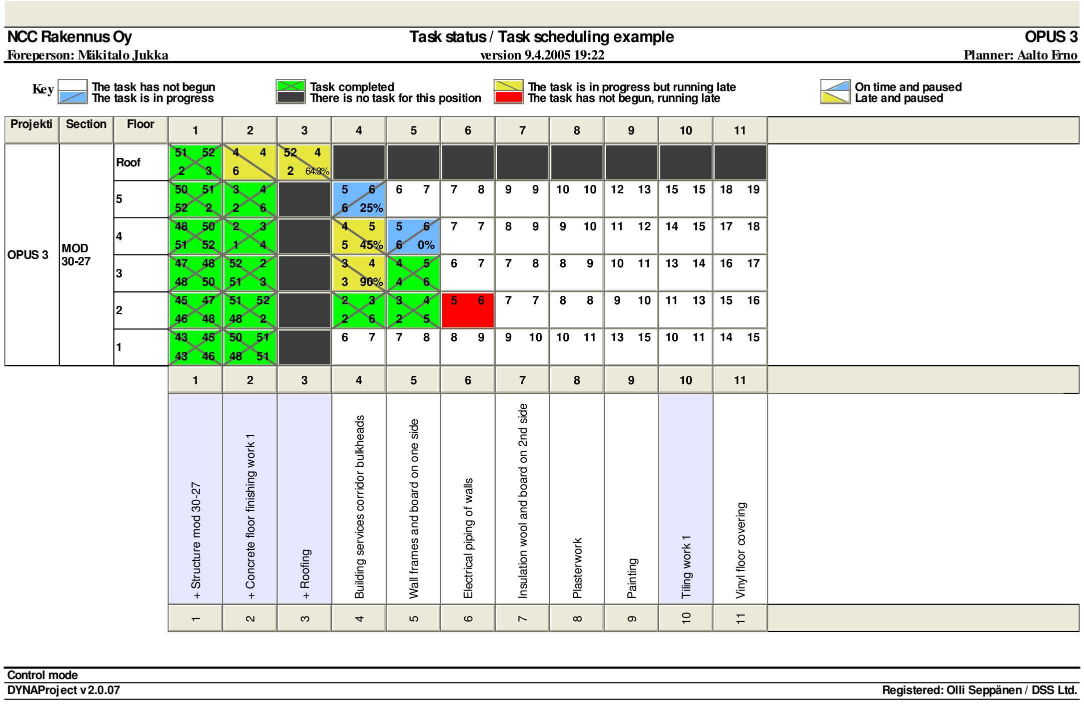


Figure C-3: Master schedule of the Opus project – For clarity, only the construction and MEP tasks which reserve the entire location are shown (Seppänen & Aalto 2005)

C.4 Schedule controlling process

C.4.1 Monitoring process

The status was monitored weekly by the project engineer. He printed out the control chart and went to all of the locations of the project to see the status of the activities. The results were entered into software weekly and were sent to the author. In the event of deviations (red or yellow squares), a comment about the reason for the deviation was sometimes, but unsystematically entered into the system. An example control chart is shown in figure C-4.



NCC Rakennus Oy **Task status / Task scheduling example** **OPUS 3**
Foreperson: Mäkitalo Jukka version 9.4.2005 19:22 Planner: Aalto Erno

Key
☐ The task has not begun
▨ The task is in progress
🟩 Task completed
■ There is no task for this position
▨ The task is in progress but running late
🟥 The task has not begun, running late
▨ On time and paused
▨ Late and paused

Projekti	Section	Floor	1	2	3	4	5	6	7	8	9	10	11
OPUS 3	MOD 30-27	Roof	51 52 2 3	4 4 6	52 4 2 64.3%	■	■	■	■	■	■	■	■
		5	50 51 52 2	3 4 2 6	■	5 6 6 25%	6 7	7 8	9 9	10 10	12 13	15 15	18 19
		4	48 50 51 52	2 3 1 4	■	4 5 5 45%	5 6 6 0%	7 7	8 9	9 10	11 12	14 15	17 18
		3	47 48 48 50	52 2 51 3	■	3 4 3 90%	4 5 4 6	6 7	7 8	8 9	10 11	13 14	16 17
		2	45 47 46 48	51 52 48 2	■	2 3 2 6	3 4 2 5	5 6	7 7	8 8	9 10	11 13	15 16
		1	43 45 43 46	50 51 48 51	■	6 7	7 8	8 9	9 10	10 11	13 15	10 11	14 15
			1	2	3	4	5	6	7	8	9	10	11
			+ Structure mod 30-27	+ Concrete floor finishing work 1	+ Roofing	Building services corridor bulkheads	Wall frames and board on one side	Electrical piping of walls	Insulation wool and board on 2nd side	Plasterwork	Painting	Tiling work 1	Vinyl floor covering
			1	2	3	4	5	6	7	8	9	10	11

Control mode
DYNAProject v2.0.07 Registered: Olli Seppänen / DSS Ltd.

Figure C-4: Control chart shows graphically the schedule status of each task and location (Seppänen & Aalto 2005)

Each week, the actual start and end dates of tasks in the locations were entered. If a location was ongoing for several weeks, the completion rate was used. The completion rates were estimated by visually comparing the actual status to the drawings, and in more complex tasks by asking the workers. Because the work was not actually measured, some of the completion rates may have been inaccurate. Complete work stoppages were not always entered into the system. For example, some tasks stayed at the same completion rate for ten or more weeks. This was interpreted by the author as a suspension of the task, instead of very slow progress. These problems with data affected only a few tasks and locations.

Some errors were made during monitoring. For example, a task could be marked as completed one week and opened again the following week, because some part of the scope was not completed. In this project, this happened for the system walls which were marked as started in a location very early in the process, but then the actual start date was moved later many times and finally removed. It looks like a model installation was done early, but the work did not start with a good production rate until three months later. These inaccuracies have been taken into account in the analysis by assuming that the information from the later weeks is correct in the case of conflicts.

The project engineer was critical to the monitoring process. When he was on holiday, sick, or busy with other tasks, the project data did not get properly updated. In these cases, the data was corrected by the project engineer after he got back, based on the subcontractor memos and discussions with the subcontractors. The production data of 17 weeks in the project were entered afterwards. Even though this data were less reliable than when data that were collected real-time, the project engineer spent a lot of effort to get the actual data afterwards.

The handover phase had poor data quality. This was caused by the fact that the commissioning activities were done by floor, not by section. The commissioning had to be done by floor because the mechanical room effect areas were different than the original sections. Therefore entire floors needed to be dust-free before equipment could be tested, and it did not make sense to follow the original sequence where the work would completely finish in one section before moving to next section. This issue had not been taken to consideration during the pre-planning of the project. Instead of adjusting the location breakdown structure, the project team switched to traditional Gantt charts for managing this phase, and only the remaining production tasks were tracked using the Flowline. Although most of the data could be reconstructed by using a combination of the monitored Gantt charts and weekly plans, it is very difficult to accurately identify any deviations and production problems at this stage. The handover related tasks may look better than the actual production in the analysis. Because only 4 out of the 66 baseline tasks and 15 out of the 179 detail tasks belonged to this phase, this had minor effects on the reliability of the analysis as whole.

The actual resources were not recorded for the tasks, but they were reported by the subcontractors in the site meeting memos.

C.4.2 Views used

The schedules were reported and monitored by using filtered Flowline and control chart views. In this project, views were created for the structure, roofing, slab on grade and concrete floor topping, vertical shaft MEP installations, corridor work and finishes, and MEP work in the office rooms. The 1st floor was reported and planned as its own view, because it contained special purpose, non-repetitive spaces such as the auditorium, lobby and retail spaces. Subcontractor views were created for the electrical, vinyl floor covering, suspended ceiling, plasterboard wall, and wooden glass wall subcontractors. Additionally, progress views were created for production meeting purposes and for reporting to the Owner.

C.4.3 Production meetings

The production meetings were held weekly. They were analyzed by the use of memos. In this project, the production meeting memos described for each subcontractor the ongoing tasks, the total number of resources on site, the need for design specifications and sometimes information about future tasks (especially the start dates of new locations or tasks).

The production meeting memos very rarely had any mentions of deviations or delays. A notable exception was the electrical contractor who delivered the switchboards late. This deviation was noted in many memos. Only very rarely was interference between the subcontractors noted, and usually only when it applied to the start dates of tasks.

The design status was reported by sometimes describing which new design was available, and which design was ongoing. In this project, the memos tended to report missing design specifications, instead of looking forward to describe which design specifications would be needed in the future. The need dates for design information were not documented.

Safety was documented by describing the results of safety measurement and detailing work-related accidents and near accidents.

The memos also had a summary of the schedule of ongoing tasks in the end. This seemed to be a combination of the schedule forecast and a verbal description of the planned schedule. Some tasks were mentioned in the present tense (e.g. work ongoing on the 4th floor), some tasks had a mention of an expected completion date (e.g. it will likely finish at the latest on week 18) and some tasks had some form of look-ahead planning information (e.g. the concrete floor topping is being poured on 5th floor and will be poured on the 6th floor in week 5). There was little consistency in this part of the memo, except that the same task tended to be reported in the same way from week to week (probably as a result of cutting and pasting information from the previous memo to the next one).

Additionally, general contractor issues were addressed. These normally related to the availability of crane lifting capacity, mobile crane use, protecting ready surfaces, cleaning of ready spaces, and self-commissioning activities. Sometimes schedule-related issues were documented here by the General Contractor requesting to expedite an activity. In this project, downstream activity was also mentioned. An example note in the memo was: “the mechanical room will be poured on week 5, the floor drains must be installed before the pour". Mentioning the dependencies between activities was not done at all in the other case projects.

This project was the only one of the case projects where the Flowline figures and control charts were regularly appended to the production meeting memos. This shows that the location-based management system was actually used to control production instead of just gathering data for this research.

C.4.4 Owner meetings

The owner meetings were held monthly but started late in the process. The project started in May 2004, but the first owner meeting was in May 2005, i.e. one year after the start of the project. This project was a pilot project for the new NCC Owner reporting system. NCC's goal was to get a competitive advantage by improving the Owner reporting system and being honest about delays and describing what control actions will be taken to recover. The internal project where the Owner was part of the same group was selected to be the case study, because it is easier to practice honesty with people in the same company.

The Owner report had a high level description of schedule status, costs, change orders, procurement, resources, quality management, safety, and environmental issues. The high level report functioned with traffic lights: a green light said OK, a yellow light indicated minor problems, and red light meant that something was wrong. In addition to the lights, each variable had a verbal description. The schedule status report described the actual degree of completion and compared it to the planned degree of completion on the status date. It also had a verbal comparison of the actual schedule to the master schedule. The following completion rates and schedule status were reported:

- May 2005: 41 % actual / 44% planned, on time
- June 2005: 51 % actual / 55% planned, on time
- August 2005: 62 % actual / 68 % planned, one week late from the baseline
- September 2005: 68 % actual / 71 % planned, one week late from the baseline
- October 2005: 80 % actual / 83 % planned, one week late from the baseline
- November 2005: 89 % actual / 92 % planned, one week late from the baseline

The design schedule was also reported and it gave deadlines to the Owner regarding the final tenant changes. The resources indicated the total resources on site and their change to the previous report.

The schedule status was reported in more detail later in the report. Each report included a list of tasks which were delayed and the reason for the delay. For example, the vinyl floor covering work was delayed by one week in September; the reason was that the subcontractor had run out of material. Normally, only a few tasks were reported to be delayed. The control chart at the summary level was also appended to every Owner report.

Even though the idea of honest reporting was good, the reports did not seem to match the real production data well. If comparisons had been made against the originally approved baseline, many more tasks would have been late. Although the progress data was objective, the baseline schedule was updated between the reports. For example, the cooling beams were delivered late to the site. The baseline was changed to take into account this change. The Owner report said that the cooling beams were two weeks late, even though they were actually ten weeks late compared to the original schedule. The majority of the production problems or delays were not reported in the Owner reports. However, compared to the other case projects, the Owner reporting was based on much better data. As in the other case projects, the schedule forecast information was not reported and control actions to catch up with delays were not described.

C.4.5 Detailed task planning process

The detail task planning started in the structural phase in October 2004. The detail tasks were planned and updated weekly. In many cases, more detail was added to the baseline tasks. Because the two sections had a break in between for most of the trades, the detail tasks were analyzed separately for both sections for all of the tasks which were not actually implemented in parallel floor by floor. In many cases, the detail tasks had different levels of detail between the sections. For example, the Slab-on-Grade was divided into four subtasks in the first section, but only the pours were planned in the second section. This was caused by two reasons: the team learned in the first section that they did not get enough benefit from detailed planning compared to the effort of getting the actual data. On the other hand, the team was much busier when the second section was planned in detail.

Table C-2 shows all the baseline tasks which were exploded to more than 1 detail task. Because almost all of the tasks were divided into detail tasks based on the sections, the table only shows the tasks in sections if the level of detail is different.

Table C-2: Level of detail of detail tasks

Baseline task	Detail tasks
Slab-on-grade	Thermal insulation – parking + MOD 30-27; reinforcement – parking + MOD 30-27; Concreting – parking + MOD 30-27; Stoppers – parking + MOD 30-27; Concreting MOD 27-20
Pre-cast concrete structure	Columns, beams and walls; Slabs; Joint pours and reinforcement; Cast-in-place parts; Façade elements
Roofing	Initial pour on roof MOD 30-27; Vapor closure MOD 30-27; Waterproofing MOD 30-27; Roof drains MOD 30-27; Gravel insulation MOD 30-27; Block masonry Main mechanical room MOD 30-27; Surface slab MOD 30-27; Wool insulation on roof MOD 30-27; Initial pour on roof MOD 27-20;Vapor closure MOD 27-20; Waterproofing MOD 27-20; Gravel insulation + surface slab MOD 20-27
Metal windows and curtain wall	Metal windows and curtain wall MOD 30-27; Metal windows and curtain wall MOD 27-20; Metal glass interior walls MOD 27-20
Concrete floor topping	Concrete surface afterwork MOD 30-27; Building temporary wall MOD 30-27; Siporex shafts MOD 30-27; Beans MOD 30-27; Heating equipment MOD 30-27; Concrete pour and leveling MOD 30-27; Preparation for pour MOD 27-20; Concrete pour and leveling MOD 27-20
MEP corridor bulkheads	MEP corridor bulkheads MOD 30-27; Plasterboard walls board and 1st side MOD 30-27; MEP corridor bulkheads MOD 27-20
Plasterboard walls	Electrical piping MOD 30-27; Insulation and 2nd board MOD 30-27; Framing and 1st board MOD 27-20; Electrical piping MOD 27-20; Insulation and 2nd board MOD 27-20
Plasterwork	Plasterwork MOD 30-27; Plasterwork of exterior walls MOD 27-20
Painting	Painting MOD 30-27; Plasterwork of plasterboard walls and painting MOD 27-20; Black painting of walls, Black painting of ceilings
Tiling	Restroom tiling MOD 30-27; Restroom tiling MOD 27-20; Lobby tiling MOD 27-20
Vinyl floor covering	Vinyl floor covering MOD 30-27; Vinyl floor covering MOD 27-20; Quartz vinyl tiling MOD 30-27
Restroom wooden doors	Restroom wooden doors; Retail space wooden doors
Wood paneling of sauna and auditorium	Auditorium wood paneling; Lobby wood paneling; Sauna wood paneling
Suspended ceiling frames	Suspended ceiling frames and MEP boards MOD 30-27; Wool area frames MOD 30-27; Suspended ceiling frames, MEP boards and corridor cassettes MOD 27-20; Wool areas and suspended ceiling frames MOD 27-20; Wire net and corridor ceilings; Suspended ceiling frames and MEP boards Auditorium
Equipment / Furniture	Equipment / furniture; Auditorium AV-equipment and furniture; Information desk; Restroom fittings
Finishing and final cleaning	Final painting round; Dust-free cleaning; Final cleaning
Mechanical ducts	Mechanical corridor ducts; Mechanical vertical ducts

Electrical installations in rooms	Fire alarm; Electrical columns and their connections; Electrical installations in rooms
Room lighting	Corridor lighting; Room lighting; Auditorium lighting; Meeting room lighting
Corridor cabling	Corridor cabling; Cable tray cabling
Checks, measurements, tuning	Self-commissioning checks; General checks
Parking deck structures (not in baseline)	Waterproofing on site; Gravel; Installing skin elements; Concrete sausage under element; Thermal insulation; Thermal insulation of basement wall; Steelwork of basement wall; Net reinforcement; Concrete slab pour; Beans and concrete in elevator area

In many cases, the detail tasks of multiple subcontractors were planned under the same baseline task. For example, the plasterboard walls task included also the electrical piping as a detail task. This left out many alarms, because the alarm system assumed that alarms are not needed within the same baseline task. This project also had some illogical task assignments. For example, the frames and the 1st board of plasterboard walls were planned under the baseline suspended ceiling bulkheads task in the first section. In the second section this was corrected. This created challenges for the analysis. Because these inconsistencies affected only four tasks, their effects on the overall reliability of results is small.

In this project, the detail schedule planning process was often in progress for many weeks, which means that the intermediate forecasts were often incorrect. Sometimes the detail schedules were updated every week according to the actual progress. For example, the roofing detail schedule had weekly updates. Changing plans weekly indicates that the schedule was not being used to issue directives for production. It may be that the subcontractor was not asked for input in the detail task planning phase and the subcontractor’s work sequence came as a surprise to the project engineer.

In this project, the detail tasks were planned one baseline task at a time. This resulted in frequent updates, because the logic of the complete schedule was not reviewed and changes in preceding tasks have a downstream effect on succeeding tasks because of the schedule logic. This was managed by the project engineer by removing dependencies to tasks which had not been properly planned. This behavior had the side effect of removing many alarms from the production control system.

The location break-down was updated during the production of the roof, the 1st floor and the sitework. The roofs were broken into seven zones in the first section (MOD 30-27), and to nine zones in the second section (MOD 27-20). This accurate breakdown was necessary because some zones were on the lower floors because the floor area decreased towards the top of the building. The 1st floor of both sections was divided into functional spaces – the corridor and lobby, auditorium, 1B, 1C, 1D, 1E-G, 1H and 1J (retail and office areas divided by the end-user). Work on site was divided into four sides of the building – street, main entrance, backyard and parking deck.

The quantities were rarely updated during implementation. This seems to point to a problem with having good starting data. The project team did not spend any time checking the quantities, but relied on the original quantities. However, the resources and production rates were updated many times the before start of the task.

The dependencies were often updated many times to correct the forecast or remove alarms. In this project, many detail tasks had no dependencies to other tasks, which resulted in no alarm being generated if a task was delayed. It seems that tasks were placed visually in the Flowline diagrams without considering the effects on the forecast and alarms by adding the correct logic. The sequence of completion was changed many times for the detail tasks. A typical example was that the first floor work was delayed to be last for most of the tasks. Often, the sequence was changed as a control action to prevent two trades from working in the same area.

The start dates of tasks were often updated based on the situation in the field. For example, the start date of the system walls was repeatedly moved forwards, because there was uncertainty about how they would be built. Similarly, the cooling beams were shifted forwards because their delivery was late. The roofing task experienced most changes and was updated almost weekly during production. In some cases, the production rates were rescheduled based on the actual. For example, the restroom tiling subcontractor had a much lower actual production rate than the detail task plan, because the contractor had one tiler instead of three, as assumed in the plan. The detail task was updated to have one tiler in the first two locations and three tilers in the last three locations.

In this project, detail task updating and planning continued to the end of project. However, new detail tasks were not planned in the last six weeks of the project. Updating in the last weeks was more related to changing the start dates of the delayed tasks.

C.4.6 Control actions

Control actions were sometimes modeled in the schedule. For example, start-up problems with the structure were corrected by removing the Christmas holiday and adding a mobile crane to help with the installations of the second section. It was more common that control actions were implemented but not documented in the schedule.

For example, many times resources were added and consequently problems were prevented, but the control action was not documented in the system.

C.4.7 Weekly plan process

The weekly plans were created by the project engineer based on what he thought was possible. The project engineer relied heavily on the master schedule to define the weekly assignments. Subcontractor input was rarely requested. The status of the weekly plans was calculated weekly, and PPC was reported back to the project. There was more interest in implementing the overall schedule than improving the PPC result.

C.5 Reliability of the baseline schedule

The numerical variables described in chapter 3 show that the baseline schedule was not implemented very well in this project. Table C-3 shows the results for the numerical variables of the 28 baseline tasks in the project. The results are presented using minimum, 25% quartile, median, 75% quartile and maximum, in addition to mean and standard deviation because the distributions are skewed.

Table C-3: minimum, average, maximum and standard deviation of selected numerical variables.

VARIABLE	MIN	25%	Median	75%	MAX	Mean	STD
Planned discontinuities	0.00	0.25	1.00	1.00	8.00	1.05	1.17
Actual discontinuities	0.00	1.00	2.00	4.00	9.00	2.29	2.06
Quantity deviation	0.50	1.00	1.00	1.00	1.69	0.99	0.14
Production rate deviation	0.40	0.65	0.95	1.56	4.77	1.21	0.81
Start date deviation	-9.00	5.00	14.50	63.75	110.00	32.20	34.34
Finish date deviation	-18.00	4.25	20.00	37.75	111.00	25.56	28.26
PPC	0%	41%	58%	83%	100%	60%	27%

The results presented in table C-3 show that there were, on average, more discontinuities in production than planned. There were some tasks which were planned to be discontinuous (8 planned discontinuities in maximum). The median task had one planned work break between the sections. However, in the actual production, the median task had two work breaks, and 25% of tasks had more than four breaks. It can be said that discontinuities of production were a problem in this project.

Quantity variations were minor. This was caused by the fact that most of the quantities were not re-estimated by project team, but the original quantities were trusted. Only rarely (minimum and maximum cases), were quantities estimated on site and corrected in the schedule. This reliance on the original, often assumed quantities led to many problems and incorrect resource assumptions, which will be described in detail later in this chapter.

The production rate results are similar to the other case studies. The median task is 5 % slower than planned, but mean is 21% faster, because of very fast outlier tasks. Half of the tasks stayed between the range of 65% and 156%. The very slow tasks (< 60% of the planned production rate) included Tiling and rockwork on site (40% of planned), Roof sheet metal (43% of planned), Tiling (46 % of planned), Roof carpentry (51% of planned), Plasterboard walls (56% of planned), Services corridor bulkheads (54 % of planned), Plasterwork (56 % of planned) and the Retaining wall natural stone covering (58 % planned). The very fast tasks included the Air circulation machines (450% of planned), Equipment and furniture (290% of planned), Wooden doors (220% of planned), Parking hall asphalt (210% of planned) and the vertical plumbing pipes (210 % of planned). Although the variability of production rates is smaller than in the other case studies, the production rate variability indicated poor reliability of the baseline schedule assumptions.

Both the start and finish dates had huge variability. Because of the large outliers (start date 110 days late, finish date 111 days late), the median gives a more accurate picture than the mean. Even the median start-up delay was 14.5 days late and the median finish date was 20 days late. Half of the range is 5…63.75 for the start dates and 4.25…37.75 for the finish dates. Because the start date of each task refers to starting in the non-critical section, and the finish date refers to the finishing in the critical section, it may be that the start dates were not as strictly controlled as in the other projects. In this project, many of the high start date deviations were caused by the delayed procurement of the cooling beams, which pushed the start dates of many tasks in the first section much later than planned. Interestingly, even though 75 % of the tasks finished late, the project finished on time. Examples of tasks which were significantly delayed from the original baseline included Main Electric Switchboard (111 days), Transformer (102 days), Bottom Sewers (92 days), Sprinkler installations (60 days) and Slab on Grade (77 days). Examples of tasks which finished early from the baseline included Paroc-elements of mechanical room (-18 days), Molding and Hardware (-10 days), Mechanical Ducts (-10 days), Automation work in main mechanical room, and Finishing and Final Cleaning (-9 days). Most of the tasks which finished late were not critical. Many of the tasks which finished early belong to the final parts of the project. For example, Molding and Hardware started 60 days late, but finished 10 days early because of the doubled production rate. Delays were successfully caught up in the last tasks.

PPC varied from 0 % to 100 %, with the average task having 60 % PPC and the median task having 58% PPC. Examples of very high PPC include the air raid Shelters (100%, 1 successful/1 assignment), Cast in place stairs and retaining walls (100%, 2/2), Equipment and furniture (100%, 7/7), Molding and Hardware (86%, 6/7), Door Hardware (100%, 3/3), Pre-cast concrete structure and façade (88%, 70/80), Metal windows and Curtain wall (88%, 7/8), Paroc elements (100%, 2/2) and Room lighting (91%, 10/11). Examples of tasks with very low PPCs included the Electrical installations in the main mechanical room (25 %, 2/8), Mechanical duct insulation (25%, 2/8), Backfilling (0%, 0/1) and Earthworks (17%, 2/12).

Overall, the results show that the baseline schedule was not well implemented. It should be noted that the original approved baseline was used in comparison. The baseline was updated many times during the project. The results show that the non-critical work of the 1st section was not controlled very well, which resulted in consistent delays. All delays were caught up in the final stages of the project.

Table C-4: Baseline results

Variable	%
Planned Continuity	26%
Actual continuity	26%
Actual Location sequence	47%
Deviation: Start-up delay	71%
Deviation: Discontinuity	56%
Deviation: Slowdown	33%
Downstream:Start-up delay	42%
Downstream. Discontinuity	38%
Downstream: Production rate	36%

Only 26 % of the tasks were planned to be totally continuous without breaks. This is because of the selected overall strategy where first section would be done first and then there would be a break before the start of the second section. Actually, 26 % of the tasks were continuous. The planned location sequence was implemented for 47 % of the tasks. This low result is caused by the fact that it was decided later in the process that the first floor would be done last because of the missing tenant information.

Start-up delays were experienced by 71 % of the tasks. This is a very high number compared to the other case studies. It is partially explained by the delay of the structure in the first section, and by delay of the cooling beam procurement and the system wall production, which caused cascading start-up delays to most other tasks. 56 % of tasks experienced more discontinuities than planned. 33 % of the tasks were lower than 80 % of planned production rate. The patterns of the problems caused to other tasks were also different to the other case studies. Start-up delays were more common and were caused by 42 % of the tasks. The discontinuities were caused by 38 % of the tasks. The production rate problems were caused by 36 % of the tasks.

The baseline schedule variables had some interesting correlations. The significant correlations are shown in table C-5.

Table C-5: Significant correlations between OPUS baseline variables

Quantity-based vs. Start date deviation	**-0.36****
Planned discontinuities vs. Working in planned sequence	*-0.299**
Planned discontinuities vs. Discontinuity	*0.267**
Total float vs. Location sequence	**0.381****
Actual discontinuities vs. Working in planned sequence	*-0.311**
Start date deviation vs. Working in planned sequence	*-0.309**
Production rate - start date deviation	**0.413****
Production rate - finish date deviation	*-0.258**
Finish date deviation - PPC	**-0.392****
Start date deviation - finish date deviation	*0.268**
Slowdown - working in planned sequence	*-0.302**
Start-up delay - production rate deviation	*0.293**
Start-up delay - start date deviation	**0.4****
Actual discontinuities - discontinuity	**0.534****
Actual discontinuities - slowdown	**0.523****
Actual discontinuities - DS discontinuity	**0.479****
Actual discontinuities - DS Slowdown	**0.483****
Working in planned sequence - DS production rate	*-0.291**
Discontinuity - DS discontinuity	**0.361****
Discontinuity - DS production rate	*0.307**
Slowdown - DS Discontinuity	**0.599****
Slowdown - DS Slowdown	**0.702****

Interestingly, having a deviation in the start date correlated with a higher production rate, which can be explained by the fact that control actions were taken more often than in the other projects. A late start correlated with a late finish, indicating that many delays could not be caught up. A delay in finish date correlated negatively with PPC indicating that higher short term reliability also reduced the finish date delay compared to the baseline. Interestingly, tasks which were based on physical quantities instead of assumptions tended to start early. Tasks which had less planned and actual discontinuities were more usually implemented in the planned sequence. The same was true with tasks which started earlier. Suffering from slowdowns made it unlikely that the task could be done in the planned sequence. Working in the correct sequence reduced the probability of causing downstream production rate effects.

The start-up delay problems did not have significant correlations to any downstream effects. Tasks which experienced discontinuities often caused discontinuities or slowdowns to other tasks. There were very strong correlations of suffering from slowdown to causing downstream discontinuities or production rate problems.

The results give important insights into production control. All of the deviation types are strongly correlated and suffering from problems leads to causing problems to succeeding tasks. Start-up delays are the only problem types which do not cascade and can be caught up by increasing the production rate. However, the number of discontinuities and slowdowns did not correlate with the finish date, indicating that it was often possible to catch up the delay. The correlation of the discontinuities with working out of sequence raises an interesting question about the importance of following a predefined sequence. This will be explored later in this chapter.

C.6 Reliability of the detailed schedules

The reliability of the detail task planning process was evaluated by comparing the progress data to the detail task schedule of the week before the detail task started in any location. The method of selecting the comparison date has been described in detail in the Methods section (chapter 3). Any updates after the start of production were ignored in this comparison. The variables used in the analysis were the same as with the baseline tasks. In this project, there was sometimes a long delay between the sections, so each detail task with a planned break was analyzed as two detail tasks, one for each section. This approach was used because the detail task planning was also done in two phases. Table C-6 shows the results of the numerical variables.

Table C-6: Reliability results of detail tasks

VARIABLE	MIN	25%	Median	75%	MAX	Mean	STD
Planned discontinuities	0.00	0.00	0.00	1.00	7.00	0.74	1.57
Actual discontinuities	0.00	0.00	1.00	2.00	7.00	1.45	1.58
Quantity deviation	0.56	1.00	1.00	1.00	2.17	1.01	0.11
Production rate deviation	0.27	0.67	0.90	1.32	5.17	1.07	0.68
Start date deviation	-18.00	-1.00	1.00	7.00	82.00	4.29	11.91
Finish date deviation	-27.00	0.00	8.00	17.00	111.00	11.12	18.13
PPC	0%	50%	67%	100%	100%	68%	28%

On the detailed level, the standard deviations and ranges between 25% and 75% quartiles are lower for all variables, except the planned discontinuities, than on the baseline level, which indicates that better information results in better plans. The detail tasks were typically planned to have continuous work, however, the median task had at least one work break. Although the range and standard deviation of the production rates are smaller than on the baseline level, the median is actually lower. This may be a result of wishful thinking that was noticed during the observation of the planning behavior. Although the schedule had a lot of delays, there was a continuous hope of being able to catch up during the production of the next task. Therefore, the production rate goals were higher than for the baseline schedule and performance compared to the targets was on average worse.

Although there were some very high start and finish date deviations, the averages are much better than with the baseline plans and the standard deviations show that there is less variability in them. Even though the performance was better than with the baseline plan, the result of finishing on average 11 days behind the schedule that was planned together with the subcontractor one week before the start of work is by no means a good result.

Table C-7: results of detail tasks

Variable	%
Planned Continuity	74%
Actual continuity	35%
Actual Location sequence	70%
Deviation: Start-up delay	27%
Deviation: Discontinuity	49%
Deviation: Slowdown	41%
Downstream: Start-up delay	23%
Downstream. Discontinuity	35%
Downstream: Production rate	28%

On the detail task level, more continuity was planned than in the baseline. Continuous work was planned for 74% of the detail tasks (26% in baseline) and 35 % of the detail tasks were actually continuous (26% in baseline). The difference in planning is caused by the fact that both of the sections were planned separately, and the work inside the section was planned to be continuous. Start-up delays of more than 5 days were rare (27 % in the detail schedule, 71 % in the baseline). 49 % of tasks suffered from more discontinuities than planned (56 % in baseline). 41 % of tasks were lower than 80 % of planned production rate (33 % in baseline). The result of having more slowdowns on the detail task level than in the baseline is interesting. It may be caused by the fact that the detail tasks were often planned with a higher production rate than the baseline tasks to catch up the delays of the baseline. However, downstream effects caused by tasks were rarer than on the baseline level.

Table C-8: Significant correlations of detail task numerical variables

Planned discontinuities - actual discontinuities	__0.761**__
Planned discontinuities - finish date deviation	__-0.206**__
Planned discontinuities - PPC	_0.173*_
Planned continuity - actual discontinuities	__-0.564**__
Planned continuity - actual continuity	__0.392**__
Quantity deviation - start date deviation	_-0.18*_
Start-up delay - working in planned sequence	_-0.187*_
Discontinuity - working in planned sequence	__-0.229**__
Slowdown - working in planned sequence	__-0.202**__
Start date deviation - finish date deviation	__0.366**__
PPC - finish date deviation	__-0.447**__
Production rate - PPC	__0.252**__
Production rate - finish date deviation	__-0.37**__
Discontinuity - finish date deviation	__0.21**__
Slowdown - finish date deviation	__0.287**__
Slowdown - DS slowdown	__0.547**__
Slowdown - production rate	__-0.251**__
Discontinuity - DS discontinuity	_0.182*_
Start date deviation - production rate	_0.184*_
Start up delay - production rate	_0.163*_
Start up delay - start date deviation	__0.337**__
Production rate - DS slowdown	_-0.157*_
Start date deviation - PPC	__-0.239**__
Finish date deviation - DS discontinuity	_0.185*_
Finish date deviation - DS slowdown	__0.268**__
Discontinuity - PPC	_-0.2*_
Slowdown - PPC	__-0.234**__
PPC - DS discontinuity	__-0.26**__
PPC - DS slowdown	__-0.253**__
Start-up delay - DS Start-up delay	__0.198**__
Slowdown - DS discontinuity	__0.422**__
Discontinuity - DS slowdown	_0.169*_

A higher production rate correlated with a start date deviation and finishing early, and with higher PPC. Correlation was also moderately strong with suffering from a start-up delay caused by other tasks. It seems that the control actions to increase production rate were taken with tasks which started late. Fast tasks also rarely caused downstream slowdowns. Tasks which started early often had more actual discontinuities. Similarly to the other case studies, a start date delay correlated strongly with a finish date delay. Because the detail tasks were typically continuous and of shorter duration than the baseline tasks, it was impossible to catch up start date delays during production. Starting late also correlated significantly with lower PPC. Finishing date deviation correlated with suffering from production rate problems. A late finish also caused downstream discontinuities and slowdowns. PPC had many significant correlations on the detailed level. Suffering from discontinuities caused by other tasks lowered PPC. The same was true for suffering from slowdowns. Tasks with higher PPC caused less downstream discontinuities and production rate problems.

The problems caused by other tasks to a task correlated heavily with problems caused to downstream tasks by the task. Suffering from start-up delay often resulted in causing a downstream start-up delay. Suffering from discontinuities had correlations to causing discontinuities and production rate problems. There were extremely strong correlations between suffering from production rate problems and causing discontinuities and production rate problems to other tasks. These correlations are strong evidence for cascading production problems.

C.7. Analysis of weekly planning reliability

The weekly plan reliability was analyzed by the use of PPC (successful assignments / total assignments). The previous sections have described the PPC averages for both the baseline and detail tasks to find correlations to other variables. In contrast, Figure C-4 shows PPC as a function of time, calculating weekly successful assignments divided by total assignments during the week.

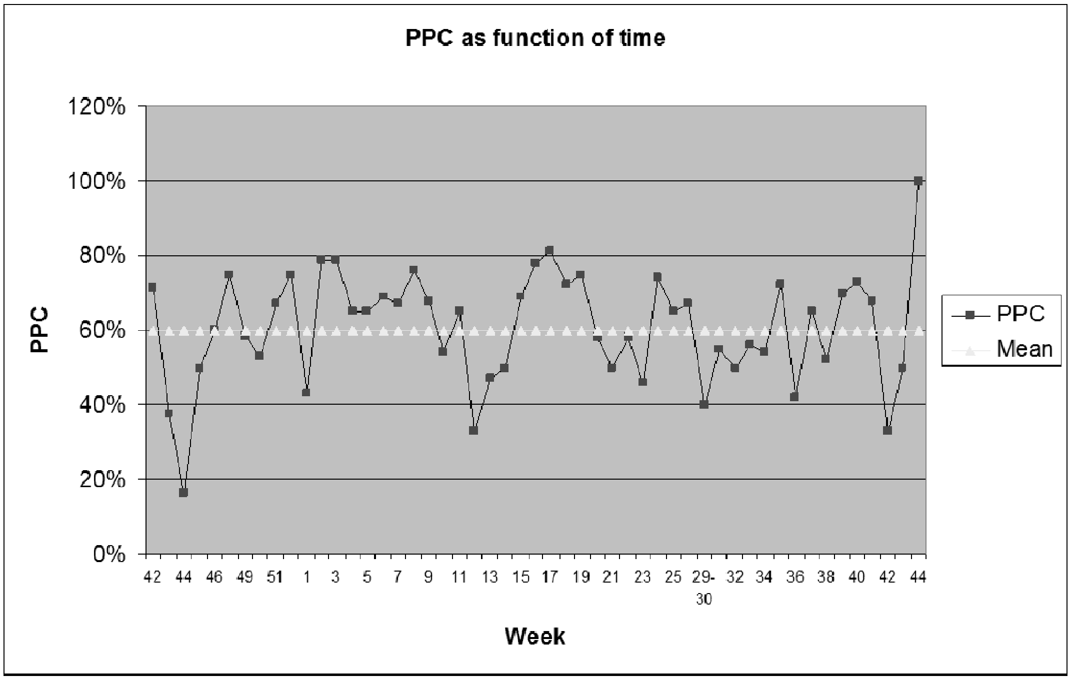


Figure C-4: PCC as a function of time in the OPUS case study

The average PPC was 60%. In this project, there are distinct periods of high PPC and low PPC. Periods of low PPC seem to correspond to start-up delays on the new sets of tasks or holiday periods. For example, low PPC in the beginning of the project (weeks

43 – 45 / 2004) is related to start-up problems of the structure (week 43, 3 failed assignments / 3 planned assignments, week 44 2 failed assignments / 3 planned assignments and week 45, 1 failed assignment / 3 planned assignments) and the slab-on grade (week 43, 5 failed / 5 planned, week 44 7 failed / 8 planned and week 45 4 failed / 7 planned). Th period of low PPC from weeks 12/2005 to 14 / 2005 also has one underlying reason explaining multiple failures. The primary cabling design was delayed, but nevertheless assignments related to primary cabling kept appearing in the weekly plans. Low PPC between weeks 29 to 32 can at least be partially attributed to the holiday season and unrealistic productivity assumptions during the summer.

C.8 Analysis of the problem tasks

In the previous sections, both the baseline schedule and detailed schedules were found to be unreliable. In this project, the baseline plan was of quite good quality, with most of the tasks having quantities. However, the schedule was very tight. The detail tasks were often updated to be faster than in the baseline to catch up delays. In reality, the subcontractors did not often achieve these higher production rates, which led to production problems. The buffers of the production system were used up early on because of a one-week delay in the structure and a four-week delay of the plasterboard walls. Additionally, dependencies were often missing from the system. Also, tasks with no technical relationships slowed each other down when they happened in the same location.

In total, 357 production problems were identified during the project. Because there were 66 baseline tasks, this means that an average task caused 5.4 problems to other tasks during implementation. However, the distribution is skewed. The worst task caused 21 problems (system walls) and many of the tasks did not cause any problems. Of these 357 problems, 33 could be verified with certainty (9%). 166 (46 %) were classified probable and the remaining 158 (44 %) were possible. There were 96 start-up delays, of which 4 were certain (4%), 60 were probable (63%) and 33 were possible (33%). There were 129 discontinuities, of which 16 were certain (12 %), 61 were probable (47 %) and 52 were possible (40 %). There were 132 slowdowns, of which 13 were certain (10 %), 45 were probable (34%) and 74 were possible (56%). Interesting in this project was that slowdowns were often referred to in the memos, for example, by saying that the electrical piping has proceeded by the speed allowed by the plasterboard walls.

In 124 cases (35 %), an alarm was generated before a problem happened. On average, alarms were generated 18 workdays before problems. In the worst case, an alarm was generated on the same day, and in the best case, an alarm was generated 55 workdays before the problem.

38 alarms (31%) resulted in a control action, but the problem still happened. On average, a control action was effective 18 work days after the alarm was generated. In the best case, the control action happened immediately, and in the worst case 45 days after the alarm. The production rate was increased in 32 cases, the plan was changed 6 times. In all of these cases, the control actions were inadequate, because the problem actually happened.

Control actions were effective in cases where an alarm was generated but did not actualize, because of a successful control action. There were 120 alarms which did not result in a problem. Of these, 80 were false alarms. Control actions were implemented to remove 40 of the alarms. Control actions involved increasing the production rate of the predecessor (16 times) and changing the plan (24 times).

These data reveal five interesting classes of cases: 1) problem - no alarm 2) problem - alarm - no control action 3) problem - alarm - failed control action 4) problem - alarm - successful control action 5) false alarm. These cases are explored in more detail in the following section.

C.7.1 No alarm

The 233 cases which resulted in a problem but no alarm was generated were analyzed more closely. Nine groups of cases were found.

Case 1: Missing dependency

52 cases out of 233 cases (22%) had a missing dependency link in the system, i.e. the system did not know that the tasks would cause problems for each other. Similarly to the other projects, the most common reason for these cases were that the project team did not enter any dependencies into the system but instead scheduled by using dates. Often, the dependency had been overlooked by the project team. Sometimes the dependency was not added because when planning the detail schedules the planner did not think that the tasks could ever happen at the same time.

Examples:

- The Paroc elements and roof drains did not have a dependency
- The frames and boards on 1st side and the electrical piping inside walls did not have dependencies, even though they happened very close to each other
- The sauna masonry wall had to be done before the roof work connecting to the sauna - the dependency was overlooked

- The tiling in sauna had to be done before the sauna wood paneling. The tiling should have happened so much earlier that a dependency was not considered during the planning phase

Case 2: Many tasks in the same location

In 65 cases (28%), there were many tasks going on in the same location, and they were slowing each other down. There was no dependency link in the system. In these cases, there was no actual technical dependency, but multiple trades working in the same location did not have enough space to work productively. One or two trades might be able to work with a normal production rate and the others had to slow down. In most cases, the production rate improved when tasks were not in the same location together.

Examples:

- Cable trays slowing down painting in the same area – no technical dependency because the painting could go before cable trays
- The painting slowing down the mechanical corridor ducts in the same area – no technical dependency
- The vinyl floor covering slowing down the electrical cabling
- The mechanical corridor ducts slowing down the plasterwork
- The cooling beam connections slowing down the system walls

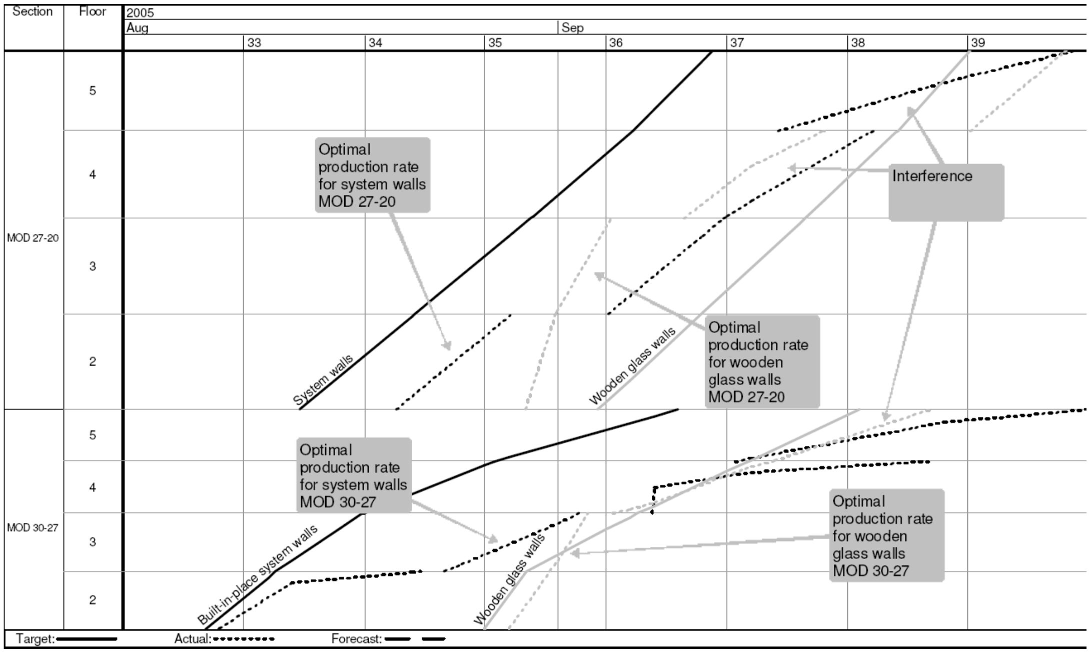


Figure C-5: Example of slowdowns caused by tasks happening in the same location

Figure C-5 above shows a good example of this problem type. Two tasks with no technical dependencies have good production rates when they happen in different locations. However, when they enter the same location, both tasks slow down.

Case 3: wrong dependency in the system

In 2 cases (0.9%), a dependency had been planned, but was incorrect. Mostly, the problems were caused by negative lags. For example, the slab-on-grade was linked to the mechanical ducts in the basement with a Finish to Start dependency with a negative lag of 15 days. In reality, the mechanical ducts were delayed by the Slab-on-Grade much earlier. Similarly, the foundations and structure were overlapping and an alarm was not generated because their planned overlap was too large.

Case 4: Not at the same time in the same location

76 times (32.6%), tasks were suspended or had start-up delays because they could not enter the same location at the same time as another task. In this case there was no technical dependency – the tasks could be done in any order. However, the work space was too small for both to continue at the same time. This type is similar to the productivity loss described in case 2. In some cases, the tasks sometimes prevented each other from working in the same location and sometimes slowed each other down. For example, the plasterwork and mechanical ducts had problems belonging to both of these categories. Many of these problems were related to tasks which require a lot of space and prevent other tasks working in the area – such as the vinyl floor covering.

Examples:

- The mechanical vertical ducts and plumbing vertical ducts could not be done in the same shaft at the same time
- The site tiling and rockwork and support wall natural stone covering could not happen in the same location at the same time
- The primary cabling had to be suspended when the vinyl floor covering entered the same location

Case 5: Problem within the same baseline task

In 13 cases (5.6%), the problems were caused between the detail tasks of the same baseline task. Location-based planning assumes that the same task contains only work done by the same subcontractor, and thus alarms are generated only if another subcontractor is going to have problems. However, in this project the detail tasks of different subcontractors were often planned within the same baseline task and could interfere with each other without generating alarms in the system.

Examples:

- The board on the 1st side, electrical piping and the board on the 2nd side caused problems to each other. There was no alarm because all were in the “Plasterboard walls” baseline task
- The initial pours on the roof interfered with the vapor barrier. There was no alarm because both were part of the “Roofing” baseline task
- The concrete floor pouring interfered with the shaft masonry task. There was no alarm because both were part of the “Concrete floor finishing” baseline task
- The Slab-on-Grade reinforcement interfered with the Slab-on-Grade pour task. There was no alarm because both were part of the “Slab-on-Grade” baseline task

Case 6: Start-up delay caused by plan change

In 7 cases, the plan of a predecessor was changed in such a way that it moved the start date of another task which was supposed to start the next week. Typically, a task had been delayed from the schedule and then the planner moved the start date a lot later, which also moved the start dates of the dependent tasks. Because the system did not know when the delayed predecessor would start, an alarm could not be generated.

Examples:

- The cooling beams were supposed to start, but the planner did not know when they were going to be delivered. The delivery date was updated to the detail schedule just before the succeeding task was going to start. This caused a start-up delay without an alarm.

Case 7: Wrong progress data in system

In ten cases, an alarm was not generated because the system had incorrect progress data. Typically a predecessor had been marked completed even though it was not completed. Sometimes, a predecessor was actually suspended, but the suspension had not been entered into the system and the forecast assumed that work was almost completed.

Examples:

- The foundations were suspended for a long time. The suspension was not entered into the system. Because of this, the forecast kept assuming that the foundations task was going to be finished in the current week and alarms were not generated

- Pouring the deck had been marked completed. The deck was not of the correct height and had to be poured again. This caused problems to the succeeding trades.

Case 8: Over-optimistic forecast

In five cases, an alarm was not generated because the forecast was over-optimistic. The forecast assumed that the first two locations could not be used for production rate forecasting. However, for example the earthworks and foundations were only done in three locations of the project. When the foundations encountered significant delays in the second location, an alarm was not generated because the forecast assumed continuing with the planned the production rate.

The forecast was also over-optimistic when a predecessor had been suspended. The forecast assumed that all the suspended tasks would continue on the control date which led to missing or delayed alarms.

Case 9: Other

Three alarms were not given because of some other reason. All of these problems happened during the weeks when progress had not been updated. It may be that the reason was that schedule was not up to date.

C.7.2 Alarm → no control action

There were 88 cases when an alarm was generated before a problem, but no control action was implemented. Table C-9 shows how many days before a problem the alarm was generated, and whether a control action took place. The table includes all the cases where a problem happened and all the cases where a problem did not happen, but an alarm was correctly generated. False alarms have been removed from the table.

Table C-9: Number of control actions as a function of alarm time before a problem

Days before alarm	No control action	Control action	Total
0	13	3	16
5	18	5	23
10	14	14	28
15	10	9	19
20	12	8	20
25	8	8	16
30	6	8	14
35	3	7	10

>35	4	14	18
Total	**88**	**76**	**164**

The Chi2-test of the data shows that this kind of distribution could have happened by chance, assuming that the variables were independent with a probability of 0.7 %. This result is statistically significant.

Because the time of an alarm before problems seemed to have an effect on guiding the control actions, the reasons for generating alarms ten days or less before problems were examined by looking at 78 cases. These 78 cases also include false alarms. Each alarm was examined and the status of the previous week was observed to see why the alarm was not generated earlier. The cases could be classified into the following groups.

Case 1: Start-up delay in the first location

In 23 cases, the delayed alarm happened because the first location of the predecessor task started too late. For tasks which should have been able to start because all the predecessors were completed, the forecast assumed starting on the control date. This assumption was the reason for delayed alarms.

Example:

In the figure C-6 below, the predecessor task does not have any predecessors. Therefore, the forecast assumes that it can be started on time. When the task does not start, the forecast is shifted forwards every week to match the current date. When the task is delayed enough to affect the succeeding task, an alarm results.

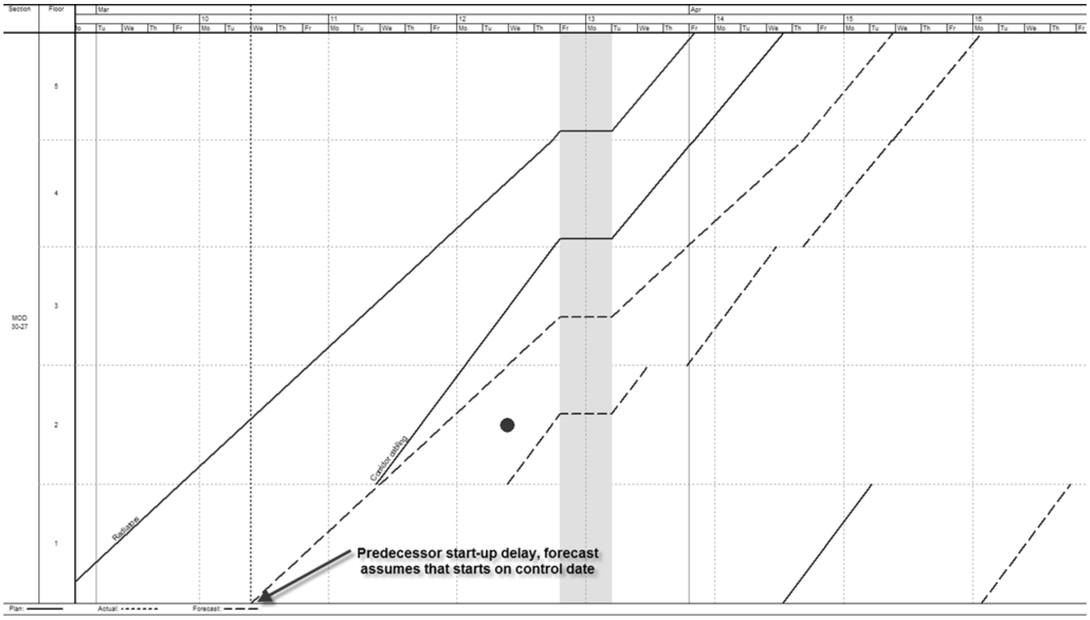


Figure C-6: In case of a start-up delay, the forecast assumes that the task starts on the control date which often resulted in delayed alarms

Case 2: Detail plan updates

In 10 cases, detail plan changes caused immediate alarms. Typically, the alarm was generated when a new dependency was added to the system.

Example:

- A dependency was added between the painting and mechanical ducts. Because tasks were already ongoing and the predecessor was delayed, there was an immediate alarm

Case 3: Errors in the progress information

In 3 cases, there were errors in the progress data which caused delayed alarms. For example, the corridor cabling had been suspended for a long time, but the suspension had not been entered into the system. Therefore, it was forecast to finish on the control date. In reality, the task was not finished and a delayed alarm happened.

Case 4: Sudden slowdown of predecessor

In 19 cases, the predecessor either started slow or suddenly slowed down in the middle of a location. Because the forecast assumes that work continues with the same production rate, this often resulted in late alarms.

Example:

- A predecessor task had a much lower production rate than previously in the last location. The forecast slope is updated only when a location is completely finished. Therefore the alarm was given too late. (figure C-7)

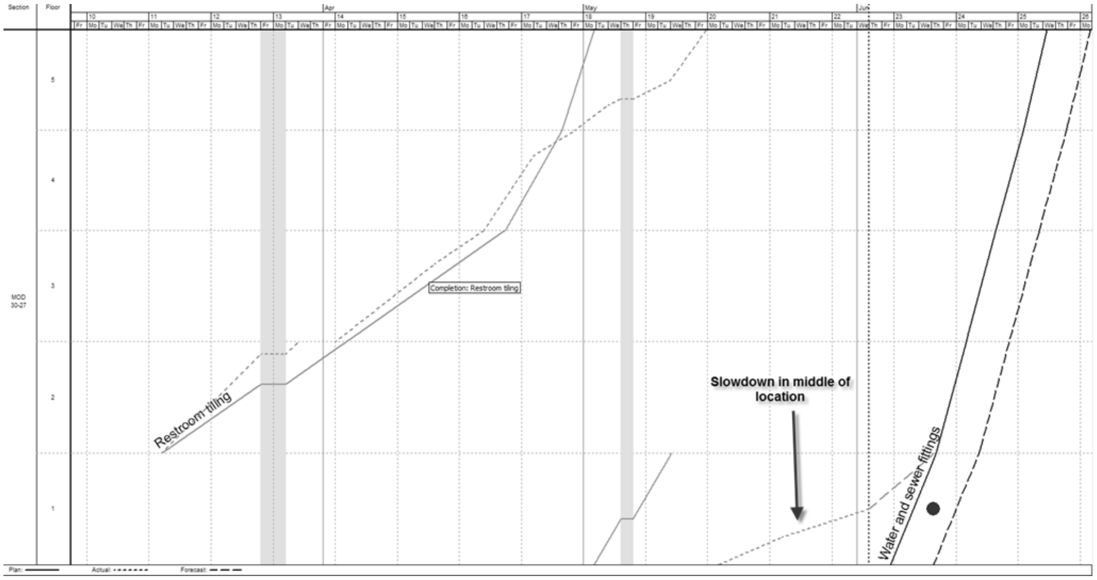


Figure C-7: Delayed alarm because the predecessor slowed down in the middle of a location

Case 5: Suspension of predecessor

In 14 cases, alarms were generated late because the predecessor was suspended and the forecast assumed that the suspended tasks would continue on the control date.

Example:

- The painting had started early and proceeded with a faster than planned production rate. Then it was suspended for five days. Because the forecast assumed that the painting would continue immediately, the alarm was not given on time.

Case 6: Schedule forecast over-optimistic

Three cases happened because of an over-optimistic forecast. The schedule forecasting technique assumed that the forecast could not be calculated based on the first location, because the beginning of the task always had production problems. The vinyl floor covering work started very slowly. The first two locations were finished in four weeks instead of the planned 2.5 weeks. After this, the forecast was updated to use the actual production rate and an alarm was generated.

Case 7: Sudden change of sequence

In three cases, a predecessor either started to work in the wrong location or continued to the wrong location. These cases usually resulted in immediate alarms because it was assumed that the successors would work in the original sequence. For example, the roofing work in this project adjusted the sequence almost weekly. Often, the sequence changes had not been updated into schedule but were revealed through the monitoring process.

Case 8: Out of sequence work

One case resulted from starting a successor out of sequence. The vertical mechanical ducts had been planned to start after the vertical plumbing pipes. The vertical mechanical ducts unexpectedly started first, which resulted in a late alarm.

Case 9: Miscellaneous reasons

In one case, an alarm was generated late because a new crew had been planned to come on site to install the first floor cable trays. The new crew did not come, but the forecast continued to assume that the crew would come on the control date. This case is very similar to the case 2/ start-up delay and the case 4 / suspension. In one case, the successor had started early compared to the baseline. An alarm was not generated before the task was delayed from the baseline schedule. In the final case, a successor started too fast compared to the plans and this caused an immediate alarm.

C.7.3 Alarm → Control action → problem

In 38 cases, a control action took place but the problem still happened. These cases can be divided into 6 groups.

Case 1: Changing or removing a dependency as a control action

In three cases, a dependency was changed or removed as a control action, because the management did not think that there would be a problem. The dependency change removed the alarm. However, the problem still happened. For example, the vertical plumbing ducts in the stairwell room had their logic to the structure changed. The change was over-optimistic and the problem happened later.

Case 2: Control action too late

In two cases, the alarm was removed as result of a control action but the problem had already happened. In seven cases, the control action happened too late and an alarm was not removed. For example, the production rate of the electrical work in the main mechanical room was accelerated right after it had already caused a slowdown to the automation work in the same location.

Case 3: Control action not consistent

In four cases, the production rate was increased enough to remove the alarm. However, the production rate increase was only temporary, and the problem happened again later. For example, the mechanical corridor ducts were temporarily accelerated and the alarm was removed. However, they slowed down again the following week and caused a problem.

Case 4: Predecessor production rate increased but was then slowed down by another task

In one case, the predecessor production rate was successfully increased, but another task caused the predecessor to slow down. The foundations had experienced slowdowns. More resources were added, and the resulting production rate increase was enough to remove the alarm. However, the earthworks task caused a slowdown to the foundations the following week which then caused the problem.

Case 5: Control action too small

In 19 cases, a control action was taken to improve the production rate but the production rate increase was too small to prevent the problem. Typically, the production rate had been too low and it was increased, but it was not increased enough to prevent the delay.

Case 6: Other reason

In two cases, a control action was taken but a problem still happened. These cases were difficult to classify, because they shared characteristics from multiple case types.

C.7.4 Alarm → Control action → no problem

There were 40 alarms which did not actualize because the problems were prevented by successful control actions. The production rate was changed 16 times, and 24 alarms were removed because of a change of plan.

Control action type 1: change of production rate

A production rate increase removed an alarm and prevented a problem 16 times in the project. Three times there was supporting evidence that resources had been added. Other times, the production rate increase was unexplained. In these other cases it is possible that the resources worked overtime to catch up, or there was a factor affecting productivity negatively which was removed.

Production rates were controlled much more in this project than in the other case studies. This is in line with the location-based controlling theory which assumes that the production rate should be the focus of control and any deviations should be solved by control actions – for example by adding resources, working longer hours, or removing any problems affecting productivity.

Control action type 2: plan change

The plan was changed so that it removed the problem in 24 cases. Dependencies were changed in seven cases. For example, the corridor cabling generated an alarm to alert that it would cause problems to the electric generic cabling. After an examination on site, it was decided that the tasks could happen together and the dependency was removed.

In seven cases, the successor start date was shifted forwards to remove an alarm. This was not classified as a start-up delay if the change happened two weeks or more before the task should have been started in the previous schedule.

In two cases, the plan was changed to change the sequence of a successor task. For example, the slab-on-grade was delayed in the second section and the plan was updated so that the masonry walls in the second section started from the top floor instead of the basement. This removed the alarm and the problem.

In four cases, the predecessor detail plan was changed to be more optimistic. This happened three times for the structure. The planned durations were adjusted based on the good progress on the second and third floors. Also, the planned production rate of the second section was adjusted based on the production rate of the first section.

In two cases, an alarm and problem were removed because the successor broke a voluntary safety dependency. The inside pours were planned to happen after two levels of the structure above them were finished. However, work started earlier.

In one case, the plan was changed so that the dependent part of the work was done first. For example, the foundations generated an alarm to alert that it would cause problems to the air raid shelter. However, only part of the foundations was needed to commence the air raid shelter work. As a control action, the plan was changed so that the foundations of the air raid shelter were done first.

In one case, the start date of predecessor was shifted forwards. Because alarms were only generated when a predecessor activity was delayed from the schedule, this change removed the alarm.

C.7.5 False alarms

There were 80 false alarms during the project. These are damaging to the perceived reliability of the alarm system and may lead to a delayed reaction or no reaction to valid alarms. The false alarms were examined to find out their reasons.

Case 1: wrong dependency

In 15 cases, the reason was a wrong dependency. For example, the start of work in the mechanical room was linked to the pre-cast structure with a delay. Actually, the mechanical room should have been linked to the mechanical room steel structure and the pouring of the concrete floor of the mechanical room. In two of these cases, a mandatory lag had been used instead of a buffer. For example, the structure had a link to the elevators with a mandatory lag. In reality, a buffer had been meant. This caused an alarm to be generated, even if the structure was delayed just one day compared to the detail schedule. In two of these cases, the dependency was otherwise correct but the wrong lag had been used. For example, the parking deck was poured in many parts. The thermal and waterproofing had been planned to start when the deck was completely finished. In reality, the work could start after the first part had been poured.

Case 2: Same subcontractor and resources

In 12 cases, an alarm was generated when a task of the same subcontractor and same resource type was going to cause problems to another task of the same subcontractor. Because there is no break of commitment or problems in the handover between subcontractors, these cases can be classified as false alarms. For example, the suspended ceiling bulkheads were delayed and this affected the start date of the first board of the plasterboard walls. Because the same people were doing both tasks, it was an internal problem for the subcontractor.

Case 3: Minor part of scope not finished

In three cases, just a small part of the predecessor was unfinished, and even though the overall dependency was correct, the small part did not interfere with successor. For example, five windows on the fifth floor of the first section could not be installed for some time because of design issues. This did not affect the concrete floor work inside the building. However, an alarm was generated because the predecessor was still unfinished.

Case 4: Same location at the same time but no problem happened

In nine cases, the dependency was valid, the tasks happened in the same location but no problem happened according to the progress data. For example, the furniture installation had a dependency to the molding and hardware. Even though they were both going on in the same location, no problem happened.

Case 5: Tasks should not be in the same location but could be done in any sequence

In six cases, a dependency had been chosen, but in reality the tasks could happen in any sequence – just not at the same time. It often happened that the successor was faster than the predecessor and the sequence shifted. This caused continuous false alarms which were not removed until both tasks had been finished. For example, the suspended ceiling bulkheads had a dependency to the corridor plumbing ducts, but the plumbing ducts were finished before the bulkheads in one location.

Case 6: Wrong progress data

In 17 cases, a false alarm was generated, because the forecast was operating on the basis of false progress information. For example the frames and 1st board of the plasterboard walls had a false alarm to the mechanical ducts. In fact, the frames and 1st board had been finished already. This error was apparent because both electrical pipes and the 2nd board had been marked as finished in the same week.

Case 7: No real problem, subcontractor commitment not threatened

In three cases, there was no real problem because the commitments to the subcontractors were not actually threatened. For example, there was an alarm about the slab-on-grade delay affecting the sprinkler installation. In reality, the sprinkler subcontractor had not been selected, so no schedule had been actually committed to.

Case 8: Meeting memos show that delay was caused by another issue

In eight cases, the meeting memos show that problem was actually caused by another issue.

Case 9: Over-optimistic forecast of a successor

In three cases, a false alarm was generated because the successor was forecast to proceed at the planned production rate. However, the successor started slowly which prevented the problem. Because the actual production rate was used in the forecasting only after finishing two complete locations, a too high production rate forecast caused a false alarm.

Case 10: Forecast start-up delay did not happen for predecessor

In three cases, the forecast of the predecessor start date had shifted forwards and that shift caused an alarm. In reality, the task started on the planned date.

Case 11: Other

One case had a mix of many reasons and was not possible to classify.

C.9. Analysis of the construction phases

Direct observation revealed some evidence of differences between the construction phases. These were also revealed in the other case studies. To evaluate the hypothesis that there was a fundamental difference between the construction phases, the main numerical variables were calculated for each construction phase: Foundations, Structure, Roofing, Façade, Interior construction work, Interior MEP work, and Commissioning. The results were calculated for the production rate deviation, start date deviation, finish date deviation, PPC, each production problem type, and each downstream effect type. The analysis was done only for the detail tasks.

C.9.1 Production rate deviation by construction phase

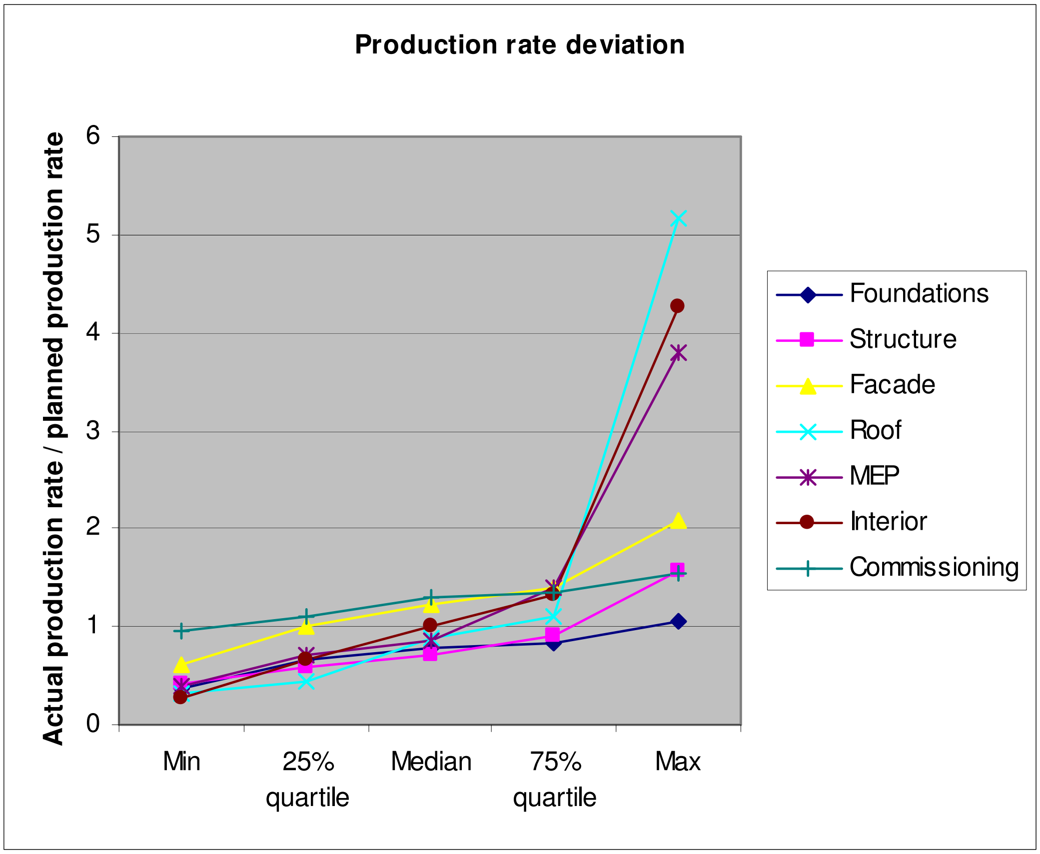


Figure C-8: Production rate deviation for the construction phases in the Opus project

Figure C-8 above shows the range, quartiles and median of the production rate deviation for the different construction phases. Most groups behave similarly between the 25% and 75% quartiles. The structural and foundations tasks are lower than the other groups. The interior, façade, and commissioning have the median on the planned levels or above. The roofing, interior, and MEP tasks have outliers with very high maximum production rates. The commissioning tasks also have their minimum on the planned levels and the median noticeably over the planned levels, which indicates that these tasks at the end of the project were used to catch up the schedule delays and their durations may have been overestimated.

C.9.2 Start date deviation by construction phase

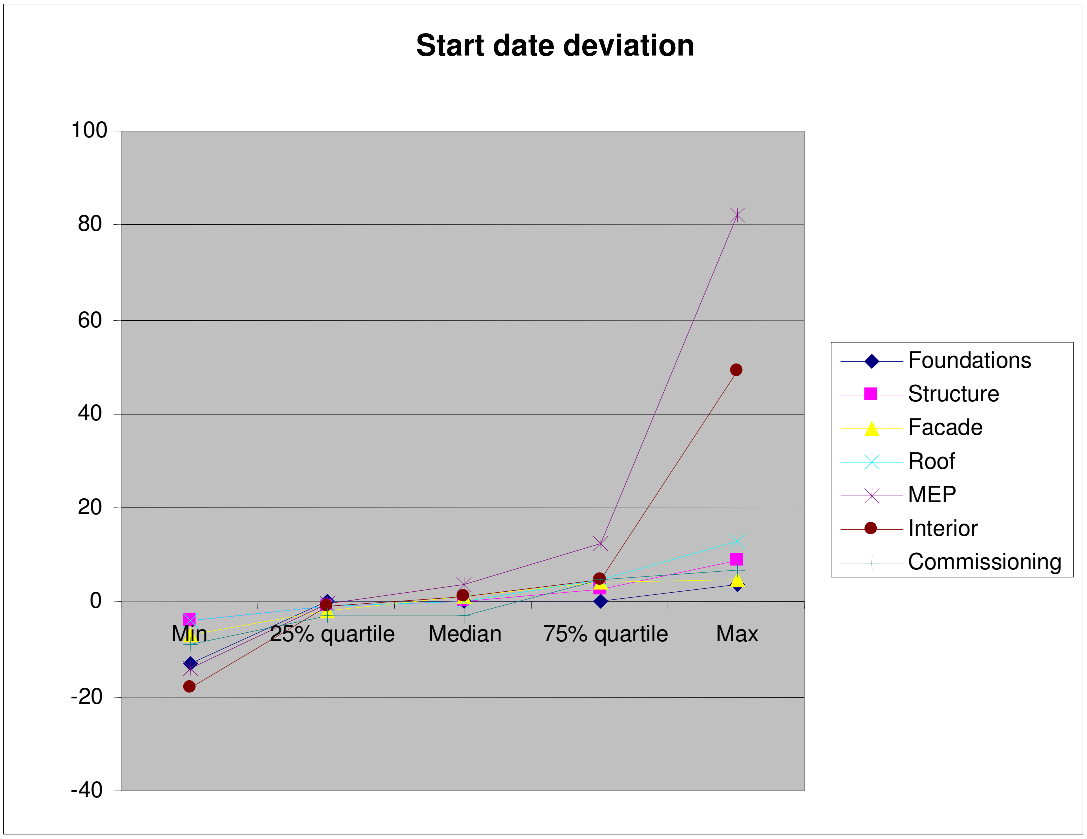


Figure C-9: Start date deviation (actual start date – planned start date)

In the start date deviations (figure C-9), the MEP and interior finishes have extreme deviations in terms of delays. These groups also have the highest delays on the 75% quartile level. Most of the other construction phases performed in the same way, with little or no start-up delays. The results show that the start dates of the finishes and MEP were more poorly controlled than the other construction phases.

C.9.3 Finish date deviation by construction phase

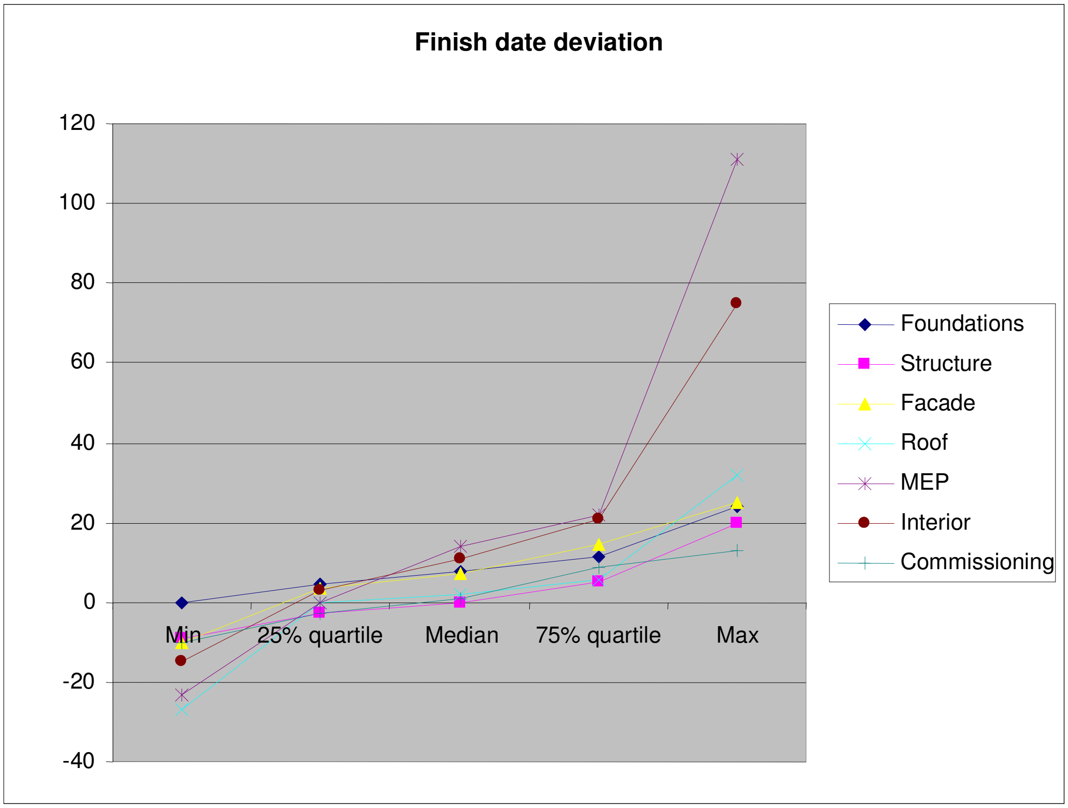


Figure C-10: Finish date deviation (actual finish date – planned finish date) for the construction phases

Even the median tasks had high finish date deviations in this project. Only the structural, roofing and commissioning tasks had median delays close to zero. The MEP and interior tasks underperformed in this analysis on the median, 75 % quartile, and maximum finish delay. Also, the variability in these categories is higher because the MEP and interior finishes, together with roofing, had the smallest minimum delay, finishing 15 to 25 days early. The other phases follow the same trend with a minimum delay close to zero, a median of about 10 days and a maximum of near to 20 days.

C.9.4 PPC by construction phase

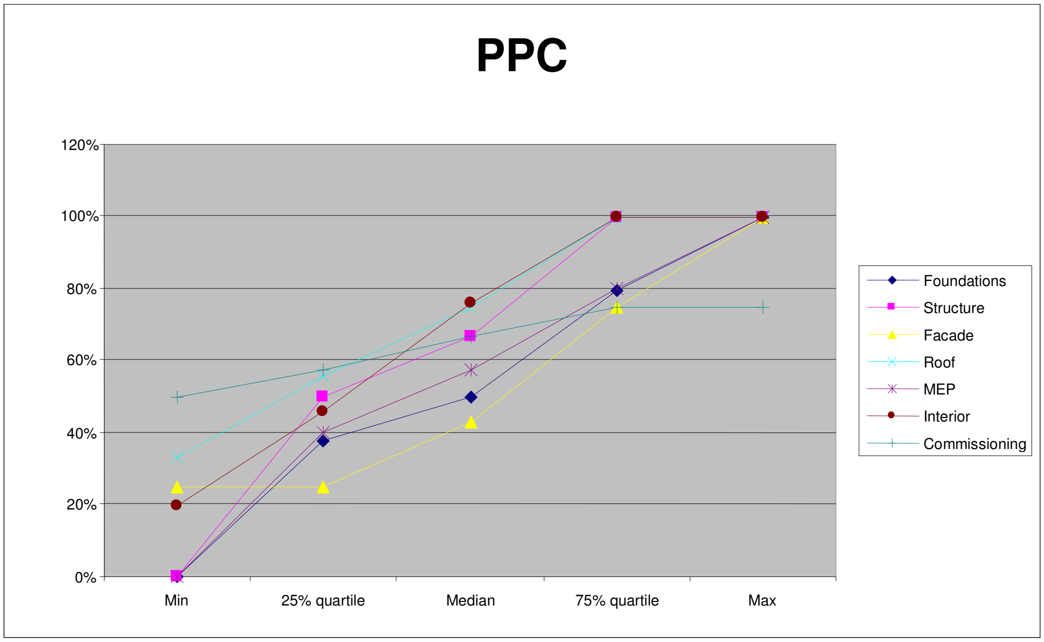


Figure C-11: Weekly plan reliability by construction phase (% of successful assignments / total assignments)

In terms of the weekly plan reliability, the structure, roofing, interior finishes and commissioning had the best results in this project (25% to 75% quartiles). The foundations, façade and MEP had the worst performance. However, each group except the commissioning had very bad tasks with zero or close to zero PPC, and very good tasks with 100% PPC. The interior finishes, structure and roofing groups had 100% PPC for 25 % of tasks.

C.9.5 Start-up delays by construction phase

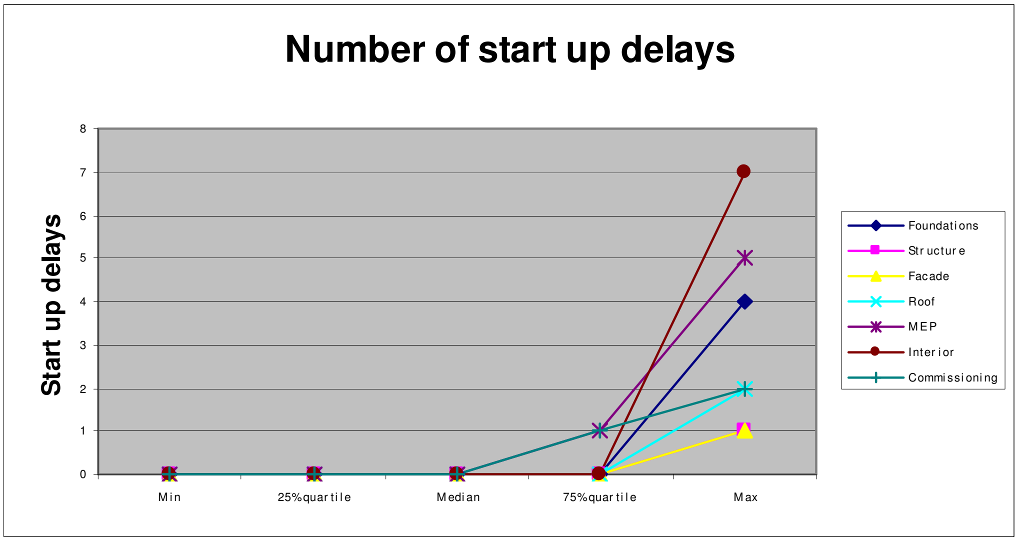


Figure C-12: The number of times a task's start date was delayed by another task by construction phase

Figure C-12 shows how many times tasks could not start on the week they were planned to start because of delays to other tasks. In this project, the start up delays happened only for some tasks (the median number of start-up delays was zero for all the construction phases). Most commonly, the start-up delays were experienced by the MEP and commissioning tasks (over 25 % of the tasks in these phases had at least one start-up delay). Each construction phase had at least one task which had a start-up delay. For the Façade and Structure, the maximum number of start-up delays was one. It may be that the start dates of these tasks were controlled strongly because of their criticality. On the other hand, the worst finishes task had 7 start-up delays which may result from the fact that the first section was not critical and the management's attention may have been directed elsewhere.

Figure C-13 below shows the same results in the opposite way. It shows how many start-up delays were caused by tasks in each construction phase.

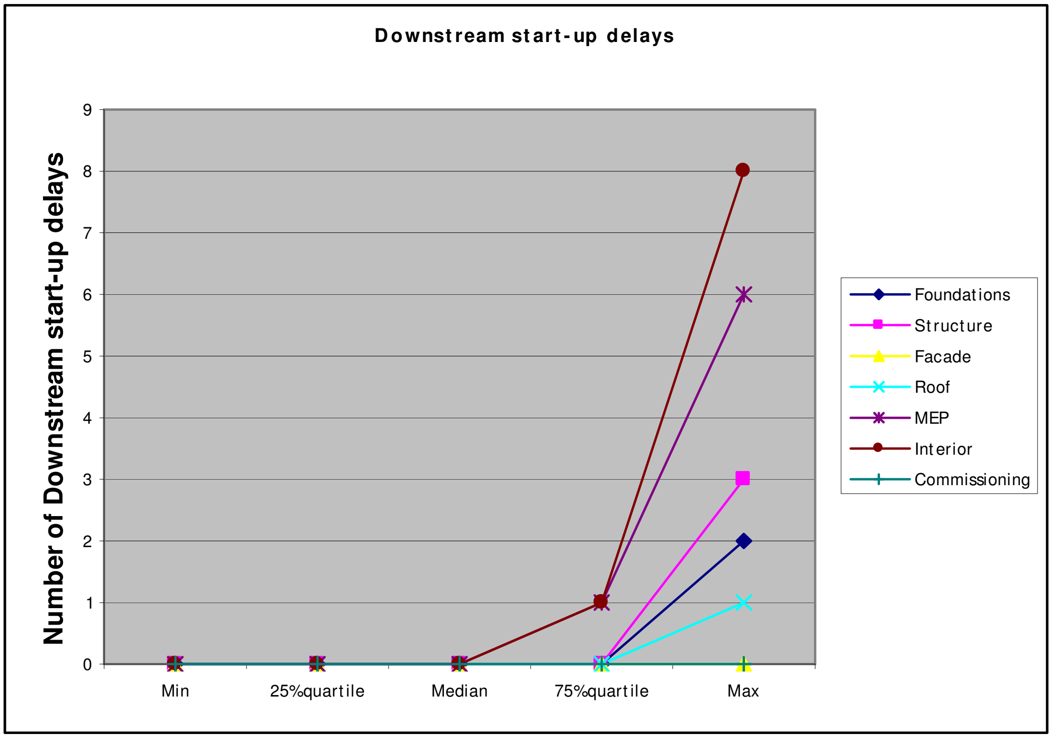


Figure C-13: The number of downstream start-up delays caused by a task

It can be seen from figure C-13 that the interior and MEP work were most often causing start-up delays, and some tasks were causing multiple start-up delays to other tasks. Some structural, foundations and roofing tasks also caused start-up delays, but 75% of the tasks in these categories caused no start-up delays. The façade and commissioning tasks did not cause any start-up delays in this project.

C.9.6 Discontinuities by construction phase

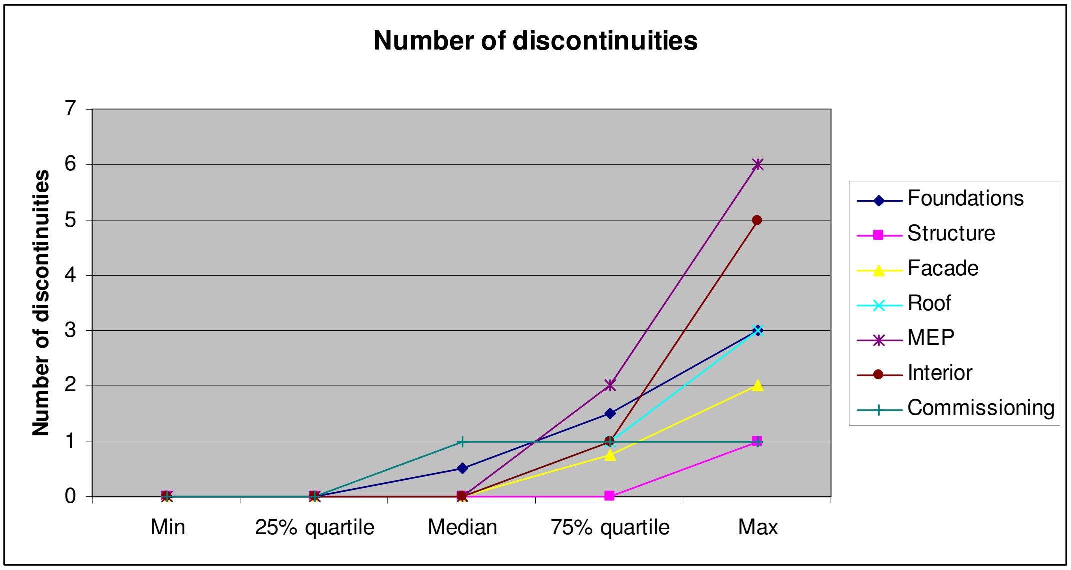


Figure C-14: The number of times a task was made discontinuous by another task by construction phase

Figure C-14 shows how many times a task was made discontinuous by another task. In this analysis, the foundations and commissioning tasks often had one discontinuity. However, the finishes and MEP are clearly different, because although only part of the tasks suffered from discontinuities, the same task could be made discontinuous many times – a maximum of 6 times for the MEP tasks and 5 times for the finishes tasks. Also, the foundations, roof and façade suffered from discontinuities. The structure had few discontinuities.

Figure C-15 shows the same result from another angle. It shows how many times the tasks in a construction phase caused a discontinuity to another task.

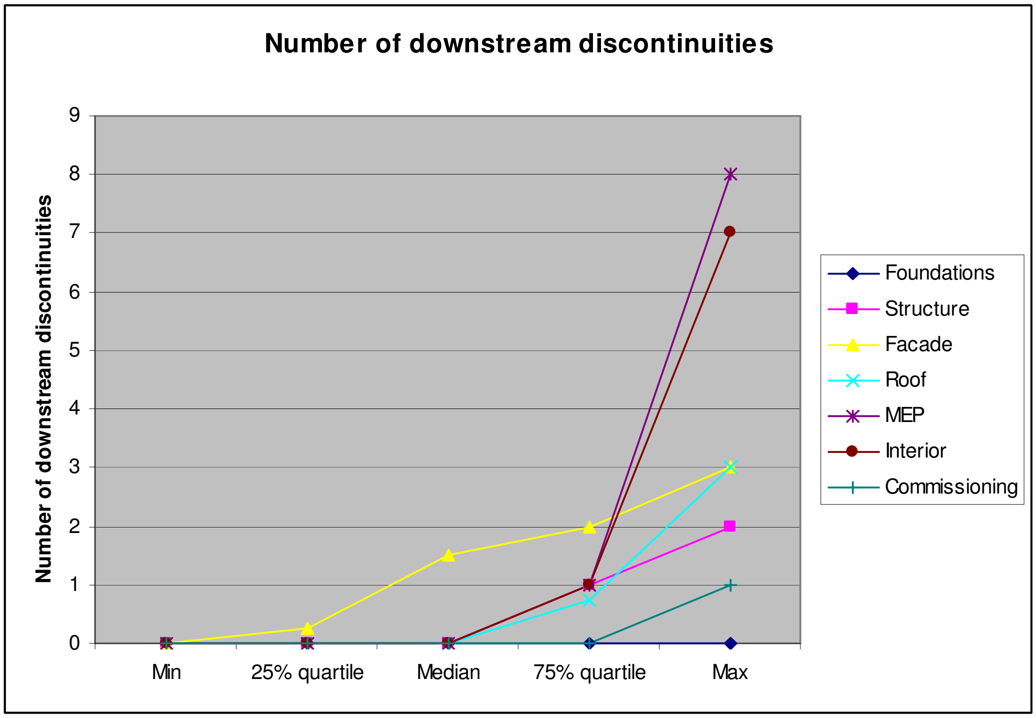


Figure C-15: The number of downstream discontinuities caused by tasks in different construction phases

The results shows that the façade tasks most often caused discontinuities to other tasks. This problem type was also caused by the structural and roofing tasks. Although few interior finishes and MEP tasks caused problems (one problem at the 75% quartile) the maximum number of discontinuities caused by tasks in these construction phases was higher than for the other construction phases.

C.9.7 Slowdowns by construction phase

Figure C-16 shows how many times a task in a construction phase was slowed down by other tasks. In this project, slowdowns concentrated on few tasks (the median number of slowdowns was zero for all construction phases). The interior finishes, MEP and foundations tasks suffered most from slowdowns. In these groups, the worst task suffered from slowdowns multiple times (8 times for the worst MEP task, 6 times for the worst interior task, and 4 times for the worst foundations task)

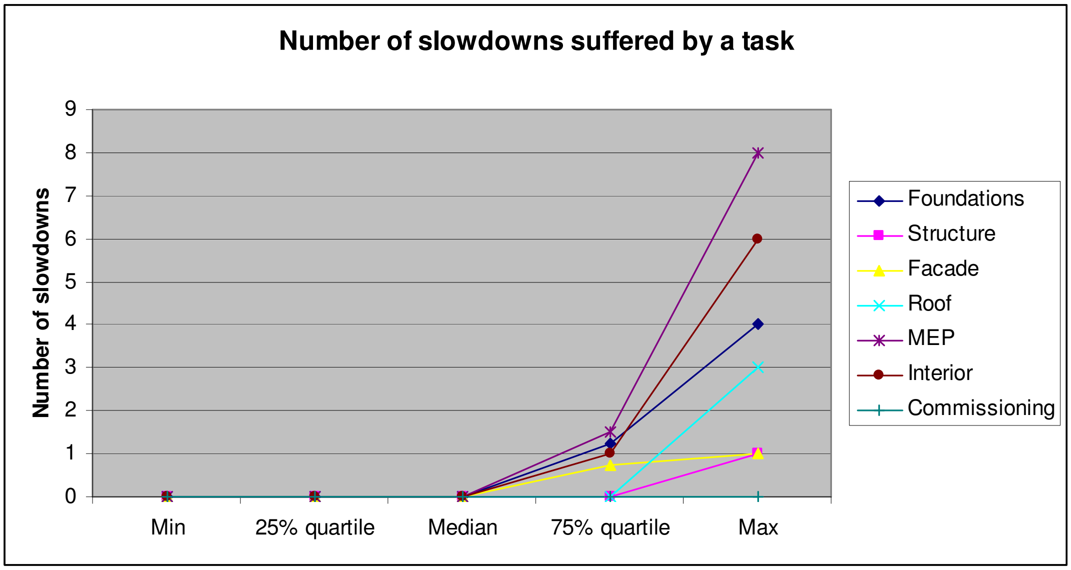


Figure C-16: The number of times a task suffered from slowdown by construction phase

Figure C-17 shows the number of times a task caused a slowdown to another task by construction phase.

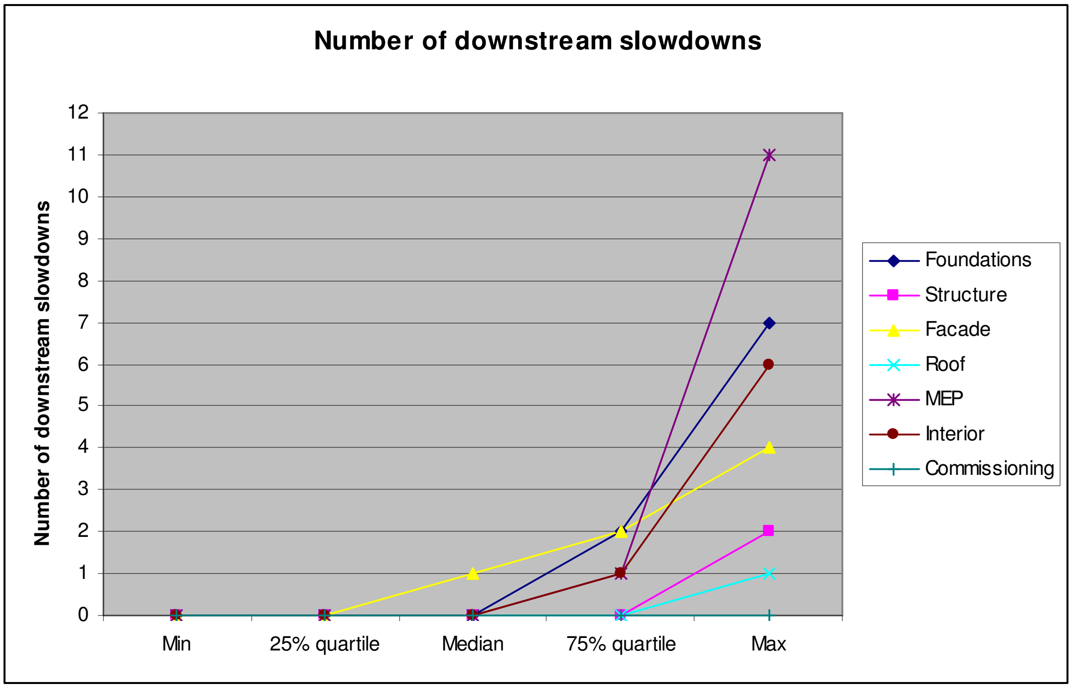


Figure C-17: The number of times a task caused a slowdown to another task by construction phase

The results show that most tasks did not cause slowdowns. The façade was the only construction phase where the median downstream slowdowns were positive (1). The foundations, MEP and interior tasks had a positive 75% quartile and high maximum downstream slowdowns.

C.10 Differences of small locations and large locations

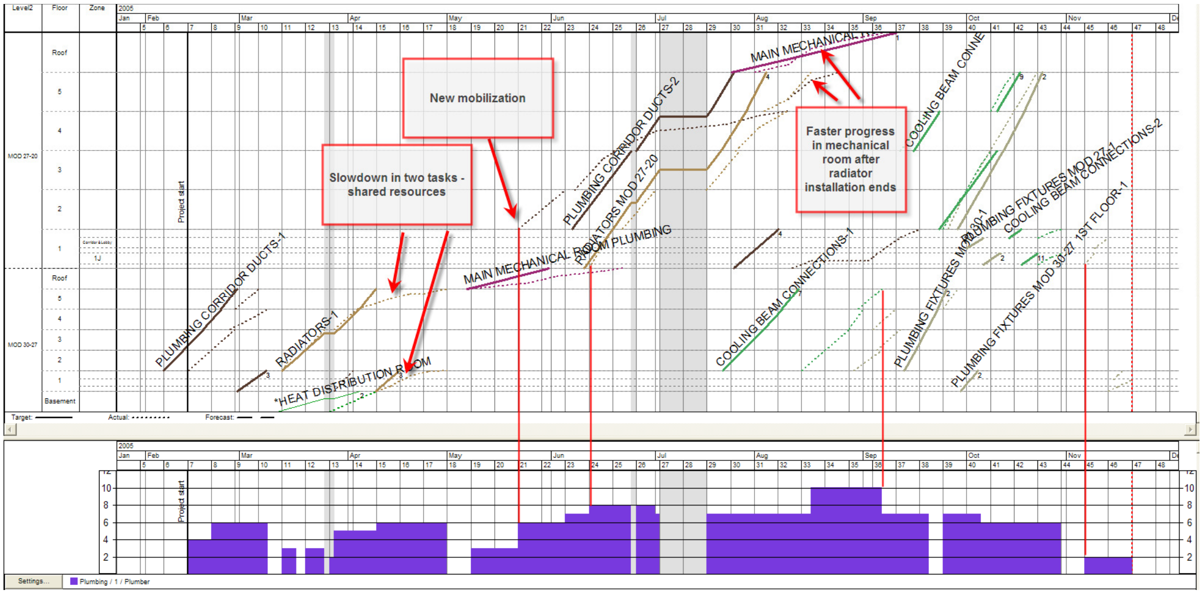
In this project, location sizes were fairly uniform. The smaller section had a floor area of 700 – 780 m^2 per floor and the larger section had 883 – 1,248 m^2 per floor. The difference between the small and large locations was tested by evaluating the number of production problems in the small locations under 800 m^2 and in the locations over 800 m^2. The main mechanical rooms were also considered to be small areas in this project. The areas of the first floor were further subdivided into individual areas and were considered small areas.

The small locations had approximately 61% of the project's man hours and the large locations had 39% of the project's man hours. The small locations had more man hours in this project because of the large work content of the first floor and mechanical rooms. Out of 96 start-up delays, 59 (61%) happened in the small locations and 37 (39%) in the large locations. Out of 129 discontinuities, 72 (56 %) happened in the small locations and 57 (44%) in the large locations. Out of 132 slowdowns, 63 (48%) happened in the small locations and 69 (52%) in the large locations.

In this project, the large locations suffered a disproportional amount of discontinuities and slowdowns. This effect may not be related to the location size but to the fact that the second section had a tighter schedule.

C.11 Analysis of resource use

Direct observation and the number of production problems for the finishes and MEP tasks prompted further analysis of the performance of the individual subcontractors. The actual resource use of the electrical, plumbing and mechanical contractors was compared to the actual progress of their tasks.



New mobilization

Slowdown in two tasks - shared resources

Faster progress in mechanical room after radiator installation ends

Figure C-18: The plumbing subcontractor's actual resource loading and progress

The results of the plumbing subcontractors illustrate the general findings well. Figure C-18 shows the actual progress and the actual resource use of the plumbing contractor. The figure shows that when multiple tasks are happening together with no associated mobilization of new resources, the production rate of both tasks slows down. On the other hand, when a task finishes, the production rate of another currently ongoing task often increases. These resource dependencies are not taken into account by current scheduling practices. Unbalanced resource use is planned instead.

The original schedule for the plumbers had been resource-loaded based on the productivity rate and quantity assumptions. At the beginning of production, the production plan called for the resource loading shown in Figure C-19. The figure shows that balanced resource use has not been considered in the planning even though quantity and resource assumptions have been made for each task. The planned resource profile is very different from the actual resource profile. In actual production, the subcontractor finishes his scope six weeks later than originally planned. Interestingly, the plumbing contractor's actual total resource use is almost exactly the same as planned – the original plan assumed 8,304 man hours and the actual resource use was 8,351 man hours.

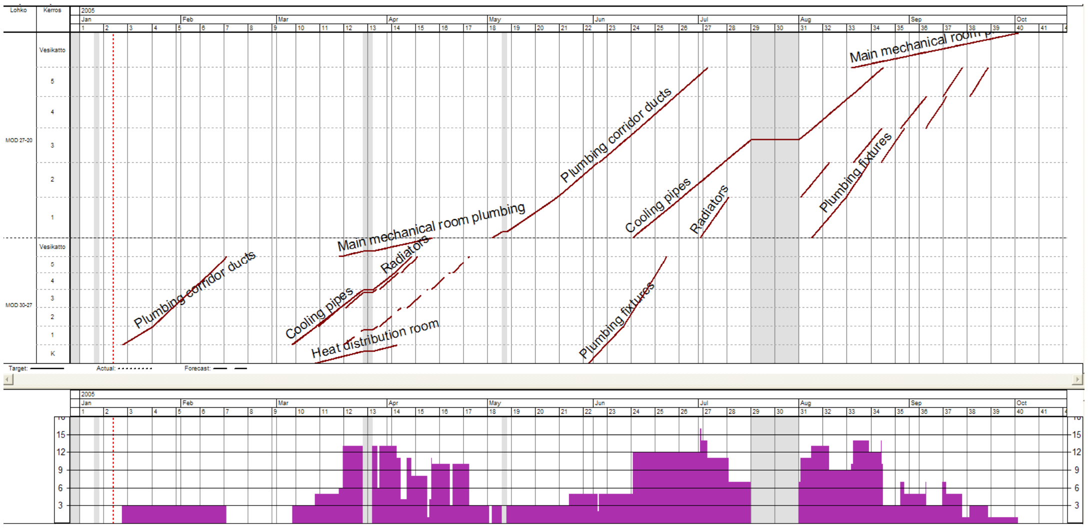


Figure C-19: Detail plan just before start of production

Similar results were found with the electrical, mechanical and drywall contractor. In each case, the actual resource profile was markedly differed from the planned resource profile. The planned resource use fluctuated and assumed the availability of more resources than were actually available.

C.12 Summary of the results in Case Opus

The project was finished according to the baseline schedule, two months before the original contract deadline. However, there was a lot of waste in production. In this project, many of the problems were concentrated in the critical second section. The first section had a more relaxed schedule and had fewer production problems. The reliability of the baseline schedule and the weekly plans was poor. The start dates were especially poorly controlled. However, the production rate targets were achieved by many tasks. The detail tasks were better controlled both in terms of the start and finish dates. Interestingly, the detail tasks had lower reliability in the production rates, which may indicate that the plans were over-optimistic to catch up the baseline delays. In this project, discontinuities of work were a big problem. In contrast to the other case studies, the production problems tended to concentrate on a few tasks. This may be caused by the fact that the level of detail and the number of tasks in the schedule was much larger than in the other case studies.

In this project, many problems identified by the location-based management system were openly discussed in the site meetings and documented. Some of the production problems even ended up in the owner report. The Flowline and control chart views were often appended to the production meeting memos and used as communication tool in the production meetings. It may be that using the reports in the production meetings helped the team to understand that there was a problem and to communicate it. This may also explain the large number of control actions undertaken in this project, and the fact that the overall production rate for the median task was close to that planned even though there were slowdowns during the way (i.e. delays were caught up by the subcontractor).

The detail schedule planning and updating baseline task by baseline task caused problems, because the complete schedule was rarely up-to-date. Concentrating on individual work packages instead of complete construction phases tended to cloud the overall view, especially in terms of the resource loading of the subcontractor trades. For analysis, this presented the problem of not knowing which schedule was committed to by the subcontractor, and which was work-in-progress or even accidentally changed schedule because of the dependencies. For reporting and production management, the continuous updating of the schedule causes a problem because the production plans are constantly being aligned with the actual progress. This gives an over-optimistic picture of the plan reliability.

The success of the weekly plan assignments correlated with the reliability indicators of the higher level schedules. Tasks with higher PPC were produced faster and caused less downstream production problems. On the other hand, PPC was affected by the production problems caused by upstream trades. It can be concluded that removing the production problems caused by other tasks will increase both the production rate and PPC, and this will in turn decrease the production problems caused by the task to downstream tasks.

There was strong evidence of cascading production problems. If a task suffered from slowdowns caused by upstream tasks, it almost certainly also caused either discontinuities or slowdowns to downstream tasks. The MEP and interior finishes tasks were the largest contributors to this cascading slowdown problem.

The problems related to the MEP tasks were analyzed by comparing the planned resource levels to the actual resource levels on site. The results show that even though work was planned to be continuous for many of the tasks, the overall resource loading had many peaks and troughs. The resource peaks in the detail schedules were not matched by an increase in the subcontractor resources in the same period. The same result was found with the other main interior and MEP contractors (mechanical, electrical and drywall). Based on direct observation and a comparison of the planned and actual resource use, it can be said that there is not enough communication between the General Contractor and the subcontractors about the resources they are going to mobilize. This leads to cascading delays when the detail schedule assumes many more workers than are actually available.

The location breakdowns structure of the project worked well until the commissioning phase. All the construction phases used the same locations. The roof was broken down into work areas, and the site work was broken down into the different sides of the building. In the commissioning phase, the dust-free cleaning, testing of equipment, final cleaning and other tasks needed to be done by floor instead of by section-floor. The commissioning had to be done floor by floor, because the mechanical room effect areas did not follow the section boundaries. This caused a big problem, because the first section had been planned to be completely finished much earlier. The production team did not see value in following the actual schedule, because the final phase had to be done one floor at a time anyway, which explains many of the start-up delays in the first section. However, this slippage of the first section led to excessive resource needs in the final stages of the project. Based on direct observation, this issue had major effects on the baseline reliability, detail plan reliability and PPC in this project.

Many problems were identified in the production control system itself. Alarms were often not generated or were generated too late because of over-optimistic forecasting. The alarm system had issues relating to missing or wrong dependencies, over-optimistic forecasts, not generating alarms when there were many tasks in the same location, or when work started in the wrong sequence. There was evidence that the alarms led to successful control actions if they were generated in time. Therefore, the alarm system needs to be developed so that the correct alarms will be generated earlier.