Criticality in Location-Based Management of Construction

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Preface

The present thesis is submitted to the department of Management Engineering at the Technical University of Denmark, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

The thesis is the result of three years of research from January 2010 to December 2012. The research was performed through an industrial PhD program in collaboration with the Department of Management Engineering at the Technical University of Denmark and MT Hojgaard A/S, Denmark's largest contracting company. The research was funded by the Ejnar and Meta Thorsen Foundation and the Danish Agency for Science, Technology and Innovation.

The main advisor was Associate Professor Rolf Niclas Andersson and the company advisor was Lars Fuhr Pedersen. Professor Russel Kenley of Swinbourne University in Melbourne, Australia, contributed to, supervised, and participated in six month of research in relation to the present thesis.

The thesis comprises the research process that explains the coherence between four scientific articles that constitute the study's contribution to the body of knowledge. The thesis also presents the theoretical underpinnings and summarizes the results.

Rolf Büchmann-Slorup

Copenhagen, Denmark.

Foreword

This thesis addresses one of the major problems facing the construction industry; namely, the lack of improvement in productivity.

Wasted time and rework are common signs of sub-optimal production in the construction industry. However, the subsequent delays and budget overruns are not only damaging to contractors and clients, but also restrict the development and quality of the physical infrastructure of the society because they require additional unnecessary financing when refurbishing and constructing buildings. Successfully transforming research results into more efficient construction processes will positively affect jobs in the industry and reduce the cost of running and living in high-quality buildings in the future. Thus, improvements in construction management will not only benefit the parties involved in the building projects, but will affect our entire society.

Research in other industries has contributed by continuously improving productivity, both in large and small increments. The construction industry operates with production cycles of several months and even years, which means that improvements and changes in production planning and management practices take a long time to become common practice, and to effectively contribute to the corporation's bottom lines. The construction industry has, in comparison, only actively conducted a limited amount of research that provides suggestions and knowledge on how productivity could be improved in the industry. This thesis does more than simply question the aforementioned inefficiencies – which is relatively easy and has been done often. Instead, the thesis takes us behind the logic and the existing practice in our industry, on a journey towards new knowledge that can transform construction scheduling and control.

The research results provide insight into the constraints that limit productivity on construction projects, and can be broadly applied in practice. Therefore, the research project benefits not only the involved parties that have supported this research program, but also the society as a whole. The results also indicate the extent of work that is needed to implement and realize a new "best practice" of planning and controlling construction projects in the future, which I see as an important contribution to a new school for contractor's planning and control processes.

Peter Bo Olsen

BIM Manager

English Abstract

The present thesis adds to the current theory of location-based management (LBM). Research has suggested that LBM is better suited than the prevailing techniques for scheduling and controlling construction projects because it takes continuous work flow, resource limitations, and location conflicts into account. The thesis describes how the different constraints in LBM affect a project's lead time, and how the criticality of the activities changes when LBM is applied, in contrast to the prevailing techniques. It is important for construction managers to understand these changes because current techniques fail to provide information about vital limitations in their production processes. The prevailing techniques only take technical constraints into account when determining the criticality of an activity. LBM also includes location, continuity and productivity constraints. Therefore, the prevailing techniques can cause misperceptions of the critical activities on building projects because the constraints that determine the activities impact on project's lead times are not explicitly dealt with. This lack of information can result in disruptive work sequences, ineffective consumption of resources, and, ultimately, unnecessary prolongation of a project's lead times. LBM explicates additional constraints that influence a construction projects lead time, which means that the entire perception of when activities are critical changes when LBM is applied rather than the prevailing techniques. However, the current literature does not include a collected description of what constitute critical activities in LBM. Nor have the implications for scheduling and control efforts of these changes in criticality been described. Accordingly, the present thesis establishes a collected criticality principle of LBM; highlights the implications of this alternative criticality principle to the schedule and control effort on construction projects; and suggests how time buffers should be applied on LBM projects to protect critical activities, compress project's lead times, optimize flow, and minimize resource consumption. The thesis offers three main results that contribute to the current LBM literature and close some of the gaps therein. The thesis conceptualizes the criticality principle of LBM by analyzing the relationship between inherent constraints in LBM and the lead times of projects. The collected criticality principle of LBM is suggested to contain the following aspects:

- Activities or tasks on the longest path or paths through a project's dependency network with zero float are critical.
- Activities or tasks are critical if they are allocated to a location that imposes time delays on activities on the longest path or paths in a project's dependency network with zero float.
- Activities or tasks that cause discontinuity of activities and tasks on the longest path or paths through a project's dependency network with zero float are critical.
- The most critical activity or task is that which has the lowest production rate on the longest path or paths through a project's dependency network with zero float.

The implications that follow from these additional constraints were studied by analyzing as-built production data with the LBM technique from a project that used the prevailing scheduling and control techniques, thus highlighting the differences.

The findings suggest that the combined criticality principle of LBM entails five major differences:

- The number of activities that are critical, and appear to be critical, increases.
- Critical activities can be prioritized by means of the slowest critical task.
- Consequences from slower-than-planned production performance of critical tasks are forecasted more negatively.
- Work crews' flexibility of work sequence through a building is reduced.
- The sensitivity to disturbances and fluctuation in production rates increases.

The last of these points inspired the third part of the research project. Although sensitivity is mitigated by applying time buffers in LBM, buffer management in LBM is treated sparingly in the current literature and no guidelines exist as to how buffers should be placed and prioritized. Therefore, the thesis' final contribution is to offer suggestions regarding the placement and prioritization of buffers in LBM, which was established using theoretical guidelines of critical chain theory and a case study with practitioners. Specifically, these suggestions are that stage buffers and weather contingency buffers should be avoided. Moreover, activity buffers should only be applied to the most sensitive critical tasks, and should otherwise be reallocated; and productivity feeding buffers should be incorporated ahead of the slowest tasks, leaving the project buffer to predominate.

Dansk Resume (Danish Abstract)

Denne Ph.d.-afhandling bidrager til den nuværende forskningslitteratur om *location-based management* (LBM), som tidligere forskning viser, er bedre egnet til tidsplanlægning og styring af byggeprojekter end de teknikker, der almindeligvis anvendes, fordi LBM understøtter kontinuerlige arbejdsprocesser, inddrager ressourcebegrænsninger og hjælper med at undgå lokationskonflikter. Det centrale tema for afhandlingen omhandler, hvordan leveringstiden af byggeprojekter bliver påvirket af forskellige bindinger, som ikke fremgår eksplicit i den nuværende praksis for tidsplanlægning og styring af byggeprojekter. Almindelig praksis tager kun højde for tekniske bindinger mellem aktiviteter og deres respektive varigheder. LBM inddrager udover de tekniske bindinger også lokations-, kontinuitets- og produktivitetsbindinger. Disse yderligere bindinger påvirker opfattelsen af, hvilke aktiviteter der er kritiske og derfor bestemmer byggeprojekters gennemløbstid. Manglende forståelse af de ekstra bindinger skader ofte arbejdsflowet og betyder unødig brug af ressourcer samt medfører unødige forsinkelser på byggeprojekterne. Det såkaldte kritikalitetsprincip, hvilket er en beskrivelse af de bindinger der afgøre om aktiviteter bør opfattes som værende kritiske, er derfor anderledes for LBM end i de almindeligt anvendte teknikker. En samlet beskrivelse af, hvad der bestemmer kritiske aktiviteter i LBM er dog ikke tilgængelig i den nuværende litteratur. Denne afhandling samler og konceptualiserer derfor kritikalitetsprincippet for LBM. I forlængelse heraf undersøges konsekvenserne af de ekstra bindinger, som indføres, når LBM bruges på byggeprojekter frem for de almindelige teknikker. Til sidst udarbejdes retningslinjer for placeringen og prioriteringen af tidsbuffere i LBM da dette også er begrænset behandlet i litteraturen. Afhandlingen yder derfor tre hovedsagelige bidrag til den eksisterende litteratur om LBM. Det første bidrag, en konceptualicering af kritikalitetsprincippet for LBM, beror på en teoretisk analyse af, hvordan de førnævnte bindinger påvirker projekters gennemløbstid, og dermed hvornår aktiviteter skal opfattes som kritiske i LBM. Resultatet og det samlede forslag til kritikalitetspriniciprincippet i LBM er:

- Aktiviteter eller opgaver på den længste sti af afhængige aktiviteter uden slæk i et projekts afhængighedsnetværk, er kritiske.
- Aktiviteter eller opgaver som er allokeret til lokaliteter der tidsmæssigt forskyder aktiviteter eller opgaver på den længste sti af afhængige aktiviteter uden slæk i et projekts afhængighedsnetværk, er kritiske.
- Aktiviteter eller opgaver som skaber diskontinuitet af aktiviteter eller opgaver på den længste sti af afhængige aktiviteter uden slæk i et projekts afhængighedsnetværk, er kritiske.
- Aktiviteten eller opgaven der har den laveste produktionsrate på den længste sti af afhængige aktiviteter uden slæk i et projekts afhængighedsnetværk, er den mest kritiske.

Det andet bidrag, som vedrører de praktiske følgevirkninger som de ekstra bindinger i LBM's kritikalitetsprincip medfører, blev undersøgt ved at analysere produktionsdata med LBM teknikken og dermed vise konsekvenserne af, at de ekstra bindinger bliver vist eksplicit.

Konsekvenserne er, at:

- antallet af aktiviteter der er kritiske og fremstår som værende kritiske stiger;
- kritiske aktiviteter på den længste sti af afhængige aktiviteter uden slæk i et projekts afhængighedsnetværk kan prioriteres ud fra de laveste produktionsrater;
- prognoser af kritiske opgaver vil være mere negative, hvis fremgangen for opgaven er langsommere end planlagt;
- arbejdsrækkefølgen gennem byggeprojektet for de udførende er mindre fleksibel;
- sensitiviteten i forhold til forstyrrelser i produktionen og udsving i produktivitet øges.

Det femte punkt vedrørende øget sensitivitet var udgangspunktet for det tredje bidrag af afhandlingen. Sensitivitet på byggeprojekter er i følge LBM litteraturen afhjulpet ved brug af aktivitets-, fase-, vejr- og projektbuffere. Teoretiske anbefalinger om placeringen og prioriteringen af disse buffere er dog begrænset i LBM litteraturen. Det sidste bidrag i denne afhandling er derfor teoretiske anbefalinger af bufferes anvendes på LBM baserede projekter. Anbefalingerne er fremkommet gennem Critical Chain Theory (CCT) og studie af brugen af buffere på byggeprojekter. Anbefalingerne er, at fasebuffere og vejrbuffere bør undgås. Desuden bør aktivitetsbuffere kun bruges på de mest sensitive kritiske aktiviteter men ellers allokeres til projektbufferen. Produktivitetsbuffere, som introduceres i afhandlingen, bør indarbejdes foran den langsomste kritiske opgave, og projektbufferen bør være den primære buffer.

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List of Appended Papers

1. The first article is entitled *BIM-based scheduling of construction – a comparative analysis of prevailing and BIM-based scheduling processes.* The article was published in the proceedings of the CIB W78: 27th International Conference – November, 2010. Associate Professor Niclas Andersson is co-author.

2. The second article is entitled *Exploring Scheduling Problems in the Construction Industry – A Case Study.* The article was submitted to the Journal of Construction Engineering and Management in January 2012. The paper was requested revised and resubmitted in December 2012, and the work is ongoing.

3. The third article is called *Slowest Task Criticality in Construction Control.* The article was first submitted to the Journal of Construction Management and Economics in June 2012. The article was requested resubmitted in November 2012, and resubmitted in December 2012. Professor Russell Kenley is co-author.

4. The fourth article is entitled *Applying Critical Chain Buffer Management Theory in Location-Based Management.* The article was first submitted to the Journal of Construction Management and Economics in October 2012. The appended version of the article was requested revised and resubmitted in November 2012. A final version was accepted for publication in April 2013.

Part I – Introduction and Point of Departure

Part I introduces the research project by explaining its point of departure and briefly introduces location-based management to provide an initial description of the technique. Part I also specifies the delimitations of the thesis and describes how practical observed problems initially guided the research and subsequently led to the definition of the research questions.

1.1 Introduction

The present research project was initiated by request from a construction company. A divisional manager from a large general contractor wanted to promote research in the company within the field of construction management, and more specifically time management. Time management is one of the central aspects in the successful completion of a construction project, along with economic success, quality, and fulfillment of client's expectations and demands. However, it is generally accepted in the construction industry that managing and coordinating work crews, sequencing of activities, estimating durations, mitigating timely risk, controlling the construction process, etc. is a complex and demanding task in praxis that often results in late completion of projects. Thus, the thesis seeks to provide new knowledge that can be applied to schedule and control construction projects in a world that is seemingly complex to practitioners. The intention of the construction company was to explore new ways of supporting the timely aspect of construction management. The initial purpose was to research building information modeling (BIM) and location-based management (LBM). LBM was eventually prioritized through initial exploratory research that will be described later in Part I. The final aim of the project is to provide knowledge through LBM that explains how successful completion of construction projects is delimited by a series of constraints that are not treated explicitly in prevailing scheduling and control techniques.

Historically, scheduling and control in the construction industry have predominately been performed by means of activity-based methods (Kelley, 1964; Starnes, 1969), such as the critical path method (CPM) and the project evaluation and review technique (PERT), which were introduced in the 1950s by Kelly and Walker (1959) and Malcolm et al. (1959) respectively. These techniques help project managers determine and focus on critical activities, which in turn determines the project lead time. The time float that appear between activities in CPM is analyzed by means of technical constraints and duration estimates (Ferdinand et al., 1963). The techniques have continued to help project managers schedule and control construction project. Contractors use the prevailing techniques for a multitude of purposes; Periodic control of work after start of construction; developing look-ahead schedules; coordination of subcontractors; detailed planning of work prior to construction; schedule impact, claims analysis and tracking of changes; coordination of own trades; estimating and bidding; tracking shop drawings and submittals; calculating payment requests for work performed; design development; operation and maintenance of projects; tracking costs; and materials planning (Galloway, 2006). A good scheduling and control technique is consequently essential to contractors for successful completion of construction projects.

However, the techniques have also met criticism in the construction industry since their introduction. Stradal and Cacha (1982) and Arditi et al. (2002) for example criticized the disregard for the work flow of construction crews in CPM and PERT. Disruption to the flow is undesirable for most construction workers because time is wasted and the turnover rate declines if they cannot work continuously. A common effect of this malpractice is that construction crews leave the construction site to work on other projects, which subsequently entails late return and further disruption to the overall workflow. Another common effect is that crews move to available areas of the construction site without finishing the work started. Working in random areas complicates the control effort and may cause rework because some work tasks is performed before preceding tasks are completed. Further, opening multiple work faces, and failing to close them limits the accessibility to other work crews.

Laufer and Tucker (1987) also addressed the shortcomings of CPM and PERT regarding resource constraints and argued that it is ignored that the same construction crews perform similar tasks. Further, CPM and PERT does not illustrate conflicts regarding simultaneous work in the same locations and productivity problems that occur due to insufficient management of work crews (Russell and Wong, 1993). Neglecting these constraints can cause productivity problems for succeeding crews because, if it is planned that the same crew must work in several locations simultaneously.

The communicative abilities of the prevailing techniques have also been criticized. Koo and Fischer (2000) stated that prevailing techniques does not communicate spatial context and complexities of the project components. Equally, Andersson and Christensen (2007) criticized the ability of CPM and PERT to provide an overview during project control, communicating schedules, and ensure workflow.

Therefore, despite the advantages of the prevailing scheduling and control techniques that allow practitioners to reduce their focus to the critical activities, a lot of criticism remains, which is why other possibilities should be explored. Peer (1974), an important contributor to the LBM methodology, stated that the prevailing scheduling and control techniques are simply not suited for time management in the building construction industry: *It cannot be expected that the use of a technique for purposes for which it has not been developed originally could produce a practical solution to a real situation, which requires a completely different approach.* Peer's (1974) statement refers to the constraints that prevailing scheduling and control techniques excludes, but he regarded paramount for successful timely completion of construction projects. These constraints play a central role to how practitioners view the criticality of activities; that is, how activities affect a project's lead time, and subsequently how projects should be scheduled and controlled. The additional constraint not only ensures that work crews work with optimal flow and in different locations, they affect when activities must be considered critical. Thus, the perception of activities' criticality change when the underlying management paradigm changes. The criticality principle of LBM is different from commonly applied methods such as CPM and PERT. However, a collected criticality principle has not yet been defined in LBM literature similar to that of the prevailing techniques. Additionally, the consequences of the differences in criticality between LBM and the prevailing techniques have not been subject to previous research, although it can have a great impact on how construction projects should be scheduled and controlled; accordingly, the criticality principle of LBM and its effects on the scheduling and control effort on construction projects are the focal point of this research.

Structure of the thesis

The four scientific articles on which the thesis is based are appended. The thesis serves the purpose of collecting the results from the articles, describing how they are interrelated, presenting the research questions and the theoretical underpinnings, describing the research process, and explaining the underlying philosophical considerations of the research paradigm. The thesis is structured in four parts, as described below.

Part I – Introduction and point of departure

Part I starts by introducing LBM to provide insight and understanding of the technique. Secondly, the practical point of departure is presented, which is based on a series of qualitative interviews on prevailing scheduling and control practice in a case company which has provided most empirical content in the thesis. Uncovering this prevailing practice anchored the thesis in the empirical world and inspired the research. However, the research questions were identified in the LBM theory. Thirdly, the path to the research questions is presented, followed by sections on the thesis' delimitations and definitions.

Part II – Theory

Part II presents the theoretical aspects of the thesis. The theory on LBM comprises most of Part II, although theory on activity-based scheduling and control, with emphasis on CPM, is included to contrast LBM. Basic principles are initially presented and followed by more elaborate and detailed aspects of the LBM theory that are relevant for the research questions; namely, aspects that are relevant for the criticality principle and buffer management theory.

Part III – Research Process, Method, and Philosophy of Science

Part III starts by describing the research process through the theory of *systematic combining,* which is based on abductive research principles. Secondly, the epistemological and ontological considerations of the research are presented through theory on qualitative research methods. Finally, the primary method (case studies) is described and discussed.

Part IV – Results and Discussion

Part IV answers the three research questions by summarizing the results from the third and fourth articles and the theory from Part II. The results are discussed with regard to the delimitations, the research paradigm presented in Part III, and critical aspects of the results. Part IV finishes with suggestions for future research and clarification of the claimed contribution to the body of knowledge.

Appendix – Articles

The empirical work of the thesis consists of the four main studies that are documented in the four appended scientific articles. The first two studies guided the project towards formulation of the research questions, while the latter provided the means to answer the research questions. The first study investigated current problems in scheduling through qualitative interviews. The second study continued to explore scheduling problems and included a test with case-based reasoning (CBR) that attempted to address some of the identified problems. Although this attempt failed to provide useful results for the participating practitioners, it did guide the project towards the final research questions of the thesis. The third study dealt with the topic of criticality and the fourth study addressed the buffer management theory of LBM in response to the results of the third study. The main contribution of this thesis is from the third and fourth studies, whereas the first two studies are considered exploratory and as the points of departure.

The thesis includes parts of the articles, but can be read independently. However, some aspects of the thesis are explained in more detail in the articles.

Introduction to Location-Based Management

The theory of LBM is described in detail in Part II; however, a brief introduction is provided here to explain the technique in its simplest form.

LBM is a scheduling and control technique that is believed to offer advantages in building construction compared with techniques such as CPM and PERT, because it includes important aspects of the construction process that are omitted in the prevailing techniques, such as continuous work flow and location constraints (For example Soini et al. 2004). LBM combines production rates, quantities, and resource consumption in specific locations to estimate the duration of tasks. Each task is depicted with *production lines* or *flow lines* that pass through locations over time. The result allows schedulers and managers to evaluate whether construction crews can perform their work undisturbed by aligning rates of production. The following example shows the basic principle and a basic analysis of what LBM can provide.

Figure 1 shows a section of a Gantt chart displaying a building project that is based on the CPM.[1] Gantt charts are commonly used to communicate a construction schedule. Each task is represented by a horizontal bar and the chart illustrates when activities start and finish. Dependencies between the activities are not shown in this example but are defined in the underlying data. Only a minor portion of the schedule is illustrated in the Gantt chart. Similar activities are typically copied and repeated for each location in a construction project, which tends to make the schedules elaborate. Schedules commonly comprise over 1000 activities, making them difficult to manage and communicate.

[1] Refer to Part II for an introduction to the critical path method and Gantt charts.

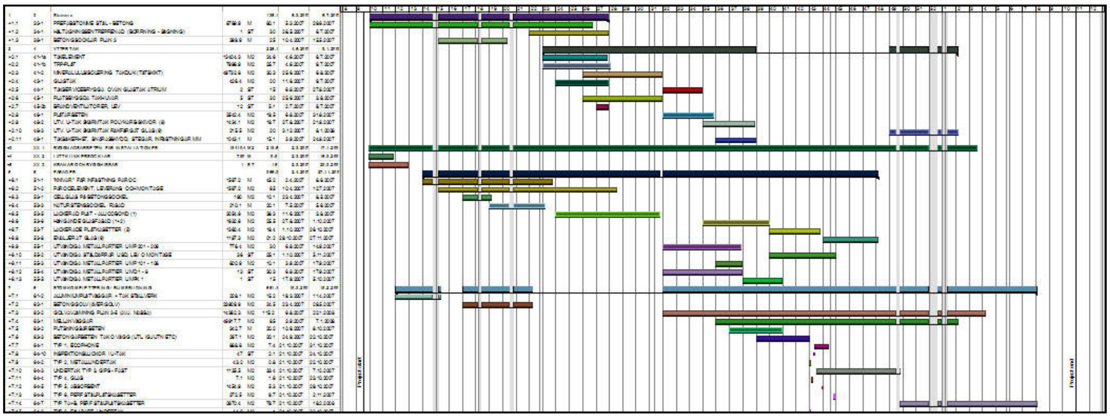

Figure 1: Gantt chart of a building project.

In LBM, similar activities are collected in tasks and displayed as a single line over multiple locations. Figure 2 illustrates the same project as Figure 1, but for the entire project schedule. Each line represents summary tasks of similar activities in their respective locations. Locations run horizontally in location based schedules. The red circle on the left indicates vacant locations where no work is performed at a given time, while the red circle on the right indicates a location in which several activities are performed simultaneously. Working at the same time and in the same location negatively affects the work of construction crews because technical constraints are not respected. Logical dependencies that have to follow in succession fail. For example, suppose that drywalls and paint in a room are completed before the electrical wiring is installed. In this case, the electrician has to drill holes in the drywall, which entails rework for both the carpenter and the painter. As another example, construction crews working in the same location may be limited by workspace. The location-based schedule illustrates areas not utilized for production (left red circle), allowing the project manager to exploit vacant areas of the build site by moving work crews to those locations.

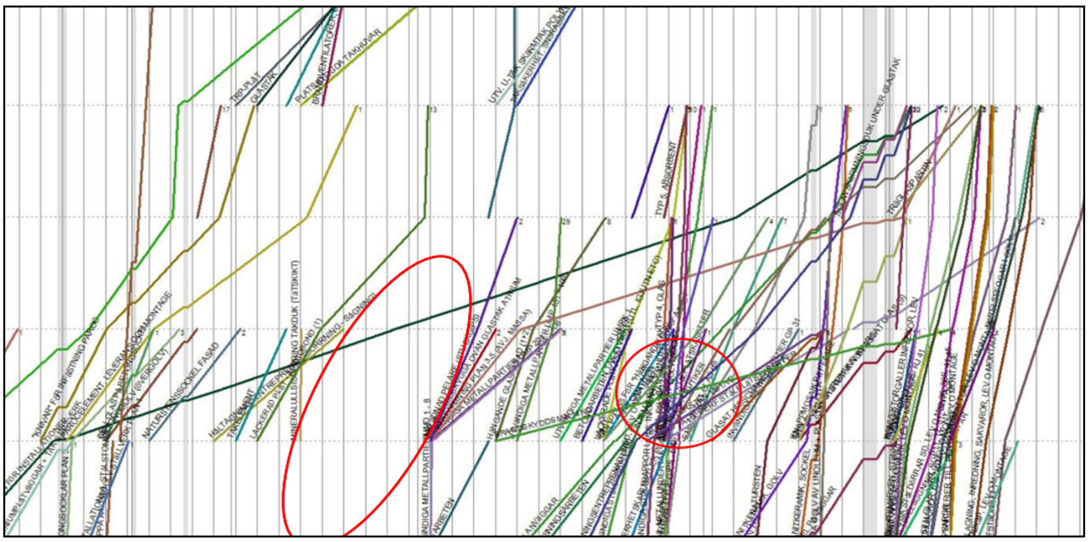

Figure 2: Location-based schedule of the same project as in Figure 1.

The location-based schedule also illustrates productivity problems. The flow lines reveal tasks that are completed at a comparatively slower rate, which not only affects a project's lead-time; it can also result in discontinuous production. A steep gradient of a flow line indicates a high productivity rate. The flow lines also indicate discontinuous work. When a construction crew temporarily interrupts work and leaves the site because of discontinuous or overlapping activities, the construction crew's productivity will decrease and additional coordination efforts on the part of the main contractor will arise in an attempt to get the construction crew back to the site. Several additional analyses may be conducted using LBM and location-based schedules, such as resource distributions, cash flow analysis, productivity forecasts, or Monte Carlo risk analysis. Criticisms of LBM also exist. For example, Flood (2011) questioned LBM's applicability in projects with few similar repeating activities. However, the aforementioned points present the basic differences between LBM and the commonly applied CPM and Gantt charts. Part II presents the relevant intricacies and details of LBM with respect to this thesis in detail.

1.2 State of the art – in the case company

The starting point of this thesis was an investigation of current scheduling and control problems and best practice in a case company. The aim was to identify problems that would ensure justification of the research from a practical point of view. The research process is described in section 3.4. The final research questions were derived from identified gaps in current LBM literature; however, because the research process was initiated and inspired by the identified practical problems of scheduling and control, the problems are presented in this section. The path to the research questions from these practical problems are elaborated in section 1.3.

Most of the empirical data in this thesis originates from the same case company, a contracting company with approximately 5000 employees. The company has an internal design and engineering department and controls several production units, such as carpenters, concrete work, and electrical work. This section describes the general problems faced by the case company with respect to scheduling and control. Additional findings have been added since the initial studies that are presented in Articles 1 and 2, because more interviews and observations were completed.

Construction projects are known for incurring time overruns, and the causes and effects of these delays have been subject of much research (E.g. Mulholland and Christian (1999); Love and Li (2000); Chester and Hendrickson (2005); Assaf and Al-Hejji (2006)). The notion of timely overruns also applies to the case company, although there is no data to suggest the extent of the delays in the case company. Although many scheduling and control problems exist, they all have exceptions. There is a tendency to recognize the problems and state that they have been solved for particular projects. However, despite efforts to solve problems for certain projects, they still largely persist at the case company. Accordingly, the problems described in this section are general and characterize the company as a whole.

The lack of proper scheduling and control signifies a great risk to any construction project. The participants in this case study stated that insufficient scheduling and control often result in busyness and chaotic work processes, which lead to shortcuts being taken in construction methods, leading to rework and sub-optimization of construction crews. The need for work coordination is particularly noticeable in the fit-out phase because this production phase involves the largest number of different construction crews. Further, problems from the early parts of the construction phase cascade through the project and become apparent later in the construction phase. At this stage in a construction project, insufficient work coordination can easily allow the main contractor to lose control over the work, resulting in tight deadlines, resource discontinuities, and rushing to complete work on time. Such reported problems follow from insufficient scheduling and control.

General scheduling problems

Table 1 summarizes the identified overall problems with respect to scheduling at the case company. Each problem is elaborated upon below. The method and tools used for scheduling and control are the CPM, Gantt charts, MS Project, and MS Excel. A description of identified causes to these problems is presented in the following section, which is again followed by problems in project control in the case company.

Problem no.	Problem Description
A.	**Interconnections between schedules** from different project phases are bad or **non-existent** - Time restrictions and schedules from the tender and design phases are difficult to accommodate during the construction phase.
B.	Scheduling is **prioritized low** - Cost is in focus - **There is not enough time** for scheduling during the tender phase.
C.	**Risk analysis** and scenario analysis are **not performed** systematically. Implications of alternative scenarios are not considered.
D.	**Little optimization of activities** regarding sequence, resource consumption, and locations. Too high a focus on milestones.
E.	Scheduling does **not improve systematically** at the company level.
F.	**No criteria** or measure **of quality** for the schedules - schedules vary in quality.

Table 1: Overall problems with scheduling at the case company.

The earliest studies in this research project identified a major gap between phases in the construction project process. The schedules from the tender phase lack analytical details and only represent overall timeframes for the project. The superficial schedules constitute a problem because the company is committed through the tenders to perform projects that have not been planned and analyzed in detail with respect to time. A tendency also exists to expect that construction crews can adapt to anything. The implicit expectation is that schedules or optimizations of the schedule will be successfully implemented.

Although the schedules are sometimes optimized, no follow-up exists to determine whether the improvements were implemented successfully. The expectation of the successful implementation of schedules is also expressed explicitly. The tender department considers the given timeframe holistically in the tenders; however, construction managers are assigned the responsibility for completing projects within the given time.

> *"It is their problem (The construction personnel) whether they can pull it off or not"* ***– Employee from the tender department.***

Thus, a gap exists (Problem A) between the overall scheduling approach in the tender phase and the detailed scheduling in the construction phase. The tender department is distant from the knowledge that resides in the production units. Although the quality of the overall level of scheduling sets the conditions for the detailed level of scheduling in the construction phase, the interconnection between scheduling levels is insufficient. Typically, new schedules are created during the construction phase and only have a limited connection to the schedules created during the tender phase. The schedules created during the tender phase are typically timeframes with little details on actual production methods. A scheduler describes this issue by stating:

> *"The interconnection between the top-down and the bottom-up scheduling is critical. [...] Early decisions are based on the top-down schedule, but this provides an insufficient information basis at the time. The problems that follow will show up in the detailed bottom-up scheduling. The two scheduling approaches should eventually meet, and hopefully correspond. However ... the overall schedule provides an insufficient information basis for the detailed weekly scheduling process."*- ***Scheduler commenting on the scheduling in the tender and construction phases.***

According to the tender department, one problem is that the tender phase is greatly constrained by time (Problem B). Cost estimation is considered paramount, leaving very little time to evaluate processes in detail, estimate task durations, and consider the effects of alternative solutions on project cost and duration. The time restrictions also mean that risk analysis and only minimal process optimization is performed (Problems C and D). Further, no support exists at the company-wide level (Problem E) to improve scheduling and control; subsequently, no requirements or proper guidelines exist for creating a quality schedule (Problem F). As one project manager stated:

> *"There are no company processes securing the quality of the schedules, but some best cases are made available on the intranet." "... [T]he company does not express any explicit rules and requirements regarding the schedules developed in a project."*

The lack of standards, guidelines, and support systems provided by the company impedes the sharing of scheduling knowledge and skills between project managers on the project level.

These are the overall problems identified during the interviews in the case company. The underlying reasons for these problems that appeared through the interviews are elaborated on in the next section.

Causes of insufficient schedules

Table 2 presents the identified causes for insufficient schedules in the case company.

Problem no.	Problem Description
G.	Schedules are based on **intuition and personal experience** - **No decision support systems** exist for scheduling.
H.	**Necessary information is not available** for scheduling purposes early in the project. Design and construction processes overlap but are not coordinated, so inputs to schedules are often missing.
I.	It is difficult to create schedules from available drawings, descriptions, and system requirements - **Input is inconsistent** and unsuited for scheduling purposes, resulting in **information overload**.
J.	**Input** from subcontractors is **not incorporated in the earliest schedules** - Contracts are signed with little indication or analysis of **timely risk**, and construction process is sub-optimized.

Table 2: Causes for insufficient schedules at the case company.

The scheduling process relies on individual knowledge, the intuition, and experiences of the project managers (Problem G), as expressed in this quote from a contract manager.

> *"Scheduling is an inspirational and intuitive endeavor. The principle scheduling input is not provided by explicit figures and facts about the project, instead the choice of relevant production methods, the establishment of activities and their interconnections, assessment of durations etc. rely on personal experience and intuition of the construction manager."*

Thus, the project schedule is a generic production sequence of construction work together with an intuitive understanding of the specific characteristics and scope of the specific project.

The project managers explain that the reliance on generic project information as input to the schedules is a result of the limited availability and reliability of project information (Problem H). The overlap between the design and the production phases, along with insufficient communication and limited coordination of work between the design and the production teams, limits the basis from which the schedules should be created.

However, when information is available, project managers often have difficulty assessing and managing the large amount of information, design documentation, and descriptions. Moreover, the vast number of drawings, project specifications, and contracts, among other documents that comprise the extensive project documentation, is difficult to assimilate and use as a basis for understanding the project and its characteristics (Problem I). Additionally, project managers do not have detailed knowledge and access to information on the subcontracted work of the project, which generally represents a significant part of the total workload (Problem J). Subcontractors are typically procured based on lump-sum contracts in which the overall schedule attached to the contract specifies the delivery deadlines for the respective subcontracts.

Despite these challenges and practice, practitioners create schedules and control projects. However, the use of the schedules also involves significant problems, which are elaborated upon in the next section.

Problems in project control

Some of the problems from the previous section concerning scheduling also apply to project control, although they have different implications. For example, Problem G also applies to project control. Project control praxis is individualized and the tools do not support centralized control, which can entail sub-optimization. Other project control problems are related to both tools and methods, as presented in Table 3, and may be methodological, behavioral, and procedural, as presented in Table 4.

As previously noted, the case company relies on CPM, Gantt charts, MS Project and MS Excel for project control. Table 3 presents the challenges experienced with using these tools and methods, which are explained in the subsequent text.

Problem No.	Problem description
K.	Changes to the **CPM schedules become unmanageable** due to the number of activities in the plans. The plans are **not updated or abandoned entirely**. Updates and **progress reports to the main schedule is lost**.
L.	The **level of detail** in the schedules is often **too high or too low** - Schedules become unmanageable and incomprehensible, or carry to little information.
M.	The output of current schedules is too **complex to communicate**.
N.	**Integration of time, resource consumption** and **cost** is **ignored**. It is time consuming to evaluate alternative solutions.

Table 3: Challenges with current scheduling tools and methods at the case company.

The comprehensive and complex structure of detailed CPM schedules makes managing and controlling the progress of a project difficult (Problems K and L). As one contract manager explained:

> *"If a master plan is too detailed, it will not be utilized as subcontractors lose overview of the plan, as schedules for large projects consists of about 5,000 separated activities."*

One problem is that the activity dependencies in the schedules are typically not created properly. Failure to create the dependencies makes it difficult to update complex schedules. As a result, the complexity, number of activities, and lack of proper dependency networks result in mismanaged schedules. The schedules end up being hung on a wall in the site offices and are only rarely consulted and updated. Therefore, progress data is not fed back into the master schedule. Furthermore, the project manager and the site scheduler are typically the only people to have a good understanding of the entire project plan.

Multiple schedules are created for specific construction crews and are disconnected from the main schedule. Contract managers tend to create their own sub-schedules, which serve only their specific purpose. Using specific schedules for each craft detaches the control data from the main schedule, which again makes the main project schedule unmanageable. The vast number of activities and a fragmented main schedule also cause problems for management when communicating both the plan and the progress to construction crews, suppliers, and other actors (Problem M). One way of communicating upcoming work is by using 2D drawings with colors and deadlines to communicate when selected work must be completed. Figure 3 illustrates an example.

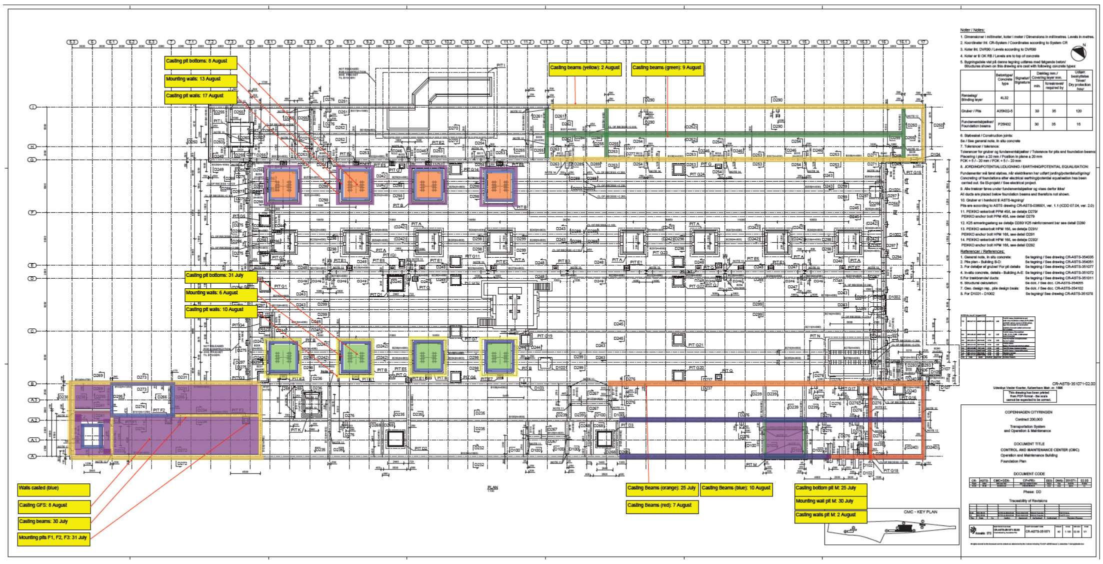

Figure 3: Communication of schedule content. A 2D drawing with dates and colors to indicate upcoming work.

Although cost estimation is considered paramount, the effect of time on cost estimates is largely neglected (Problem N). Inefficient or inaccurate integration of time, design, and cost makes it time-consuming to establish alternative cost and time estimates.

Table 4 summarizes the identified methodological, behavioral, and procedural problems in project control.

Problem No.	Problem description
O.	Detailed and **systemic recordings of performance data** on a weekly basis are **rarely done**.
P.	**Base-line schedules are not used**. **Schedules** are **adapted to match current state**.
Q.	**No forecasts are calculated**.
R.	There is **little active use and understanding of dependencies**, **buffers, lags and float**

Table 4: Methodological, behavioral, and procedural problems in project control.

Progress reports are typically performed, although not systematically (Problem O). The schedules are updated to fit with the current state of the project, rather than indicating progress relative to a baseline schedule (Problem Q). Failure to record the progress restricts the ability to review the production schedules and identify fundamental productivity problems. The lack of a baseline schedule also hinders the company's ability to use the schedules defensively. As progress data are not recorded in a manageable way, the company cannot use the schedules to explain what occurred in a potential trial, for claims or in negotiations with clients of subcontractors.

No forecasts are produced (Problem R). Outlook for future problems are determined by evaluating whether a project is on schedule or behind schedule. The control efforts are primarily reactive. Late projects are typically granted more resources and better managers once they are performing insufficiently, reportedly causing hectic construction sites in which all construction crews want simultaneous access to the same locations. Such access can result in damage to existing work and rework because the logical dependencies between the crafts are not considered or respected. As with the forecasts, little understanding, analysis, or use of buffers, lags, and floats exist (Problem S). The logical dependencies are not thought through in detail and the schedules (typically Gantt charts) become mere indications of how long a task is allowed to take.

Good Control Practice

Many scheduling and control problems have been noted. However, personal efforts and dedication ensure positive results for some projects. Project managers and contract managers who design solutions that fit their purpose produce good scheduling and control solutions. Although most successes are attributed to individuals, some company-wide initiatives are reported to provide positive results.

The lean construction philosophy and last planner system (LPS) (Ballard and Howell (1994); Ballard, 2000) are company initiatives. The interviewees emphasized the importance of the so-called process planning and the LPS in which all concerned actors meet, discuss, and add their professional knowledge to schedules. The involvement and commitment of the various project actors create a strong sense of ownership for the plans and schedules that are established. With a scheduling range of one to two weeks, the LPS focuses on the day-to-day management of onsite activities and contributes to imminent production preparation, committing the involved parties to the plan and providing the greatest benefit to the management of the project.

LBM has also proven its worth on a few projects. However, its use was initially applied as a result of personal initiatives.

Use of LBM in the case company

Location-based scheduling and control has been implemented to a certain extent on a few projects at the case company. By the time that this research project was initiated, however, it had not gained a broad foothold. However, the use of LBM has changed during the three years that this thesis has been underway. Since the 1990s, a handful of people have manually applied location-based schedules to residential projects.

Figure 4 illustrates one of the earliest location-based schedules from the case company, which is combined with a Gantt chart. Thus, location-based schedules have been utilized by a few project managers for many years.

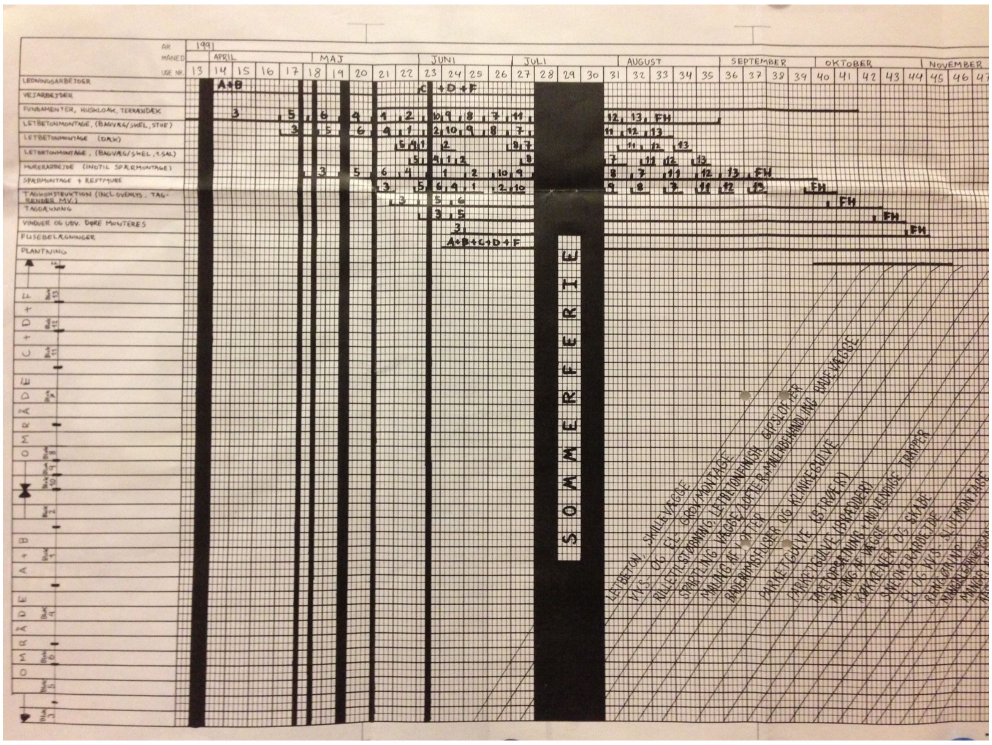

Figure 4: Photograph of combined Gantt chart and location-based schedule from the case company from 1991.

From the start of this project, full implementation and control with modern software was only attempted on two projects, whereas some tenders were submitted with a location-based schedule (however, not strictly in accordance with the prescribed theoretical work methods and processes). Three years later, LBM has found renewed focus at the company level because employees have started to become aware of its advantages. Location-based schedules are now being utilized on many new tenders and some construction projects. The advantages are evident as practitioners find ways to shorten project lead times by identifying locations to exploit, and by coordinating production rates of work crews. However, LBM remains in its infancy at the case company. Cost has not yet been integrated with design, resources, and time. A few cases exist for which quantity takeoff from building information models (BIM models) have provided the basis for the integration of time, resources, and design. However, overall, the schedules are still primarily used for tenders, and few projects are controlled through LBM. The schedules for the tenders are created by drawing the flow lines rather than basing the estimates on model takeoffs, resource estimates, and production rates. Consequently, working with LBM could improve, but the company has come a long way the past three years.

Because some project and contract managers have begun to familiarize themselves with LBM, several observations have been made. The following statement is an observation by a contract manager that, to some extent, encapsulates the problem on which this thesis is focused.

> *Location-based scheduling ensures that locations and resources considered in the logical bindings between activities. The method ensures that locations are utilized as work is allocated to free locations* [and by aligning activities]. *This provides the clear effect that schedules are compressed and resources are utilized better.* ***The general misconception in the company is that this compression is risk-free and a logical redistribution of available resources. The total and free float of the schedule is reduced dramatically when the method is optimized fully.*** *[…]* ***When both the total and free float is removed, it will have the undeniable consequence that any activity that exceeds its buffer zone will affect the project deadline.***

The statement of this alleged misunderstanding touches on both key areas of this thesis; namely, the importance of understanding criticality and buffer management in LBM. LBM operates with more constraints than CPM-based management because it also includes continuous workflow requirements, location constraints and productivity constraints. These constraints change how tasks should be considered in terms of criticalness compared with CPM-based project management; subsequently, they play a significant role in protecting schedules against production delays and fluctuation. The issue becomes a balance between mitigation of risk and controlling projects with comprised schedules. Thus, criticality and buffer management is central to LBM. However, there is limited literature explaining what affects the criticality of activities in LBM including its practical implications and how the critical activities should be protected. These issues will be elaborated upon in section 1.3 and presented in further detail in Part II.

1.3 Motivational problems and the road to the research questions

The identified scheduling and control problems provide the foundation for the remaining research. Some problems have driven the research toward its final focus, whereas other problems are not dealt with at all. The present section describes how some of the problems inspired the research process and which eventually lead to identification of gaps in the LBM literature and the formulation of the research questions.

A CBR system (Aamont and Plaza, 1994) for LBM projects was developed and tested to bridge the gap between the tender and construction phase by reusing parts of relevant similar location-based schedules from prior projects. CBR is a method that helps users identify, obtain, and reuse previous successful solutions. An elaborate description of CBR and the test case can be read in the second article. The intention was to apply basic project attributes (for example, building type, total area, floors) in a CBR system to identify similar projects, from which prior schedules or productivity data could be reapplied. Using these prior schedules should help to more quickly establish a better starting and reference point for the new schedules and to ensure reuse of actual performance data. Consequently, CBR was applied in an attempt to counter Problems A, B, E, and G. However, the attempt failed because of insufficient design content in the tender projects. The CBR system could identify similar previous cases from basic building data. However, the design of the tender projects lacked the details needed to evaluate whether schedules from similar projects could be reapplied. The design of the project in the tender phase was not detailed enough to evaluate if sections of previous sections could be reapplied. Despite the failure to build a CBR system that would support early scheduling, the outcome of the trials and the interviews with participants did underline the inability to easily create schedules that would allow analysis of alternative construction processes, optimize the schedules, and evaluate timely risk. The same aspects were apparent during the interviews with project and contract managers. Schedules take a long time to establish and become superficial. If the schedules become too superficial, they do not support identification of risk and possibilities for optimization. On the other hand, if the activity-based schedules are detailed, they are difficult to establish and especially manage and communicate during project control. A shift was made in the research process, to counter problems like B, K, L, and M that were described in section 1.2. The underlying assumption is accordingly that prevailing scheduling and control techniques fail to provide the means to cope with the complex nature of construction projects and need to be simplified. Complexity is referred to as both organizational and technological complexity as described by Baccarini (1996). Complex organizational structures contain differentiated parts from within and between companies (Baccarini, 1996). Technological complexity includes the variety or diversity of tasks, and the interdependencies between tasks, networks of tasks, work crews, and technical aspects (Baccarini, 1996). Constructing, analyzing, optimizing, and controlling schedules must be simple according to the practitioners in the case company. Yet, despite this desired simplicity, schedules must contain project-specific information and must enable easy control of the construction projects. LBM was assumed to encompass these features because flow lines are placed in parallel in optimized location-based schedules, they include comparatively more information than CPM and Gantt charts, and location-based schedules communicate an entire project on less space. However, the current literature does not describe how these features simplify the scheduling and control effort. In the search for this information, the fundamental constraints that governs a location based schedule were explored which subsequently lead to the study on criticality. Some literature exists on what makes activities and tasks critical in LBM. However, criticality has not been treated collectively in current theory nor have practical implications of the LBM criticality principle been described. This situation led to the study of a collected conceptualization of the criticality principle in LBM equal to that of CPM, including its implications to scheduling and control. The criticality principle of CPM is determined by the technical dependencies between activities and their duration estimates, which form the technical constraints when building projects are constructed. These technical constraints are analyzed in CPM in relation to their duration estimates and effect on the projects lead time. Consequently, a shift was made to researching constraint's impact on criticality in LBM and the implications of this criticality principle to scheduling and control on LBM projects. These two subjects constitute the first and second research questions that will be presented in section 1.4. Other paths could have been chosen and other approaches may have been taken to potentially address the identified problems. For example, this could be done by imposing new roles in the tender department with a focus on the schedules, better education on current tools and methods such as CPM and Gantt charts, or new corporative initiatives with subcontractors, architects, and engineers. Thus, initiatives like Building Information Modeling (E.g. Koo and Fischer, 2000), virtual design and construction (Khanzode et al., 2006) the Last Planner System (Ballard, 2000), Integrated Project Delivery (E.g. Kent and Becerik-Gerber, 2010), concurrent scheduling and engineering (E.g. Love et al., 1998) etc. were considered. However, the choice was made to pursue LBM because it has been a key subject from the original research program.

The criticality principle of LBM is the subject of the third article, which also includes an analysis of effects the LBM criticality principle is applied on a construction project compared with that of the activity-based methods. These effects are described in section 4.2. One of the effects is that schedules typically become more sensitive to fluctuation in production and delays when the LBM criticality principle is applied compared to the criticality principle of the activity-based methods. Buffers are applied on LBM projects to mitigate this sensitivity to disturbances. However, limited literature exists regarding the placement and prioritization of buffers in LBM. This gap in the literature formed the third research question. Consequently, the last part of this research project suggests new theoretical recommendations for the application of buffers. Critical chain theory (CCT) (Goldratt, 1997) was employed to provide reasoning for these recommendations.

The problem analysis and test using CBR is seen as the path to the research questions, whereas research on the criticality aspect and buffer management using CCT is the focal point of the thesis and the contributions to the body of knowledge.

1.4 Research questions

The research questions have been identified through gaps in the literature although they were inspired by the attempt to address the identified practical problems as described in section 1.3. The theory on LBM will first be presented in Part II; however, the research questions are presented here and are as follows:

RQ1: What aspects constitute the collected criticality principle of location-based management?

RQ2: What are the practical implications when the criticality principle of location-based management is applied to schedule and control construction projects, instead of the activity-based criticality principle?

RQ3: How should time buffers be prioritized in projects that are scheduled and controlled with location-based management theory?

All three research questions aim to provide theoretical contributions to the body of knowledge within LBM theory.

1.5 Delimitations

This thesis is placed in the realm of project management. It focuses on project time management; specifically on schedule development and control. Figure 5 provides a holistic overview of project management according to the Project Management Body of Knowledge (PMBOK, 2008). Many other aspects of project management influence scheduling and control of projects, including risk management, human resource management, cost management, etc. Despite these influences, the research is delimited to scheduling and control. The research also addresses buffer management in LBM as a part of schedule development and control, although it is not mentioned explicitly under these topics in the PMBOK (2008). Buffer management regards analysis, control, and mitigation of risk (PMBOK, 2008). Buffer management, and more precisely the placement of buffers, is treated as a part of schedule development and control in this research.

Theoretical management concepts like batch sizes, bottlenecks, cycle time, work in progress etc. is closely related to LBM theory. Despite these concepts with advantage are made explicit in flowline views, they are not treated explicitly in this thesis.

Definition of activities, sequencing, duration estimates, and resource estimates are important prerequisites when establishing and controlling schedules, although they are not treated explicitly in the thesis. The results regarding criticality and buffer management in LBM projects presuppose that these aspects are performed properly, even though interviews and observations in the case company revealed that this often does not occur.

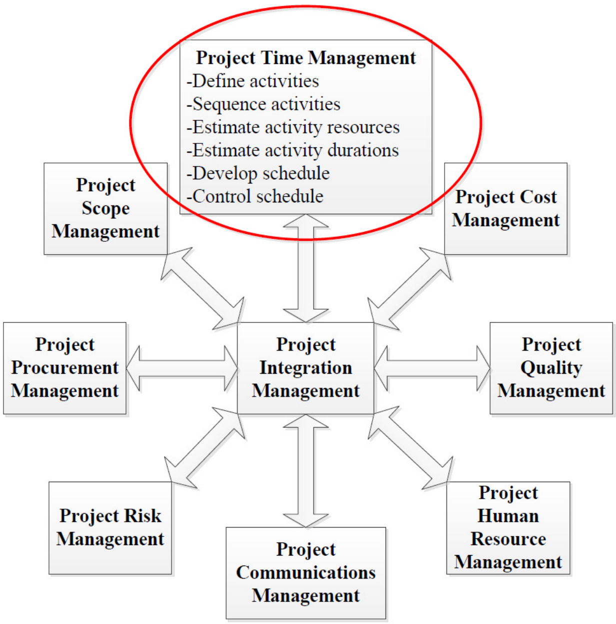

Figure 5 General content of project management according to the Project Management Body of Knowledge, 2008. Primary focus is on schedule development and control.

LBM is a methodology that includes both a tool and a technique. The governing LBM tool or LBM project management software in the case company is VICO Schedule Planner. However, as the criticality principle and buffer management of LBM are central topics, the present study treats LBM as a scheduling and control technique.

Scheduling and control in project phases

Scheduling and control is viewed in relation to the different phases of construction projects in this thesis. The thesis is delimited to the tender, design, and construction phases of building projects. There are many different models that seek to reduce the complex processes of a construction project into a simple model. The two main project phase models in this thesis are illustrated in Figure 6 and Figure 7. Design-build projects (Figure 6) and design-bid-build projects (Figure 7) have both been included as cases in the thesis. The diagrams in Figure 6 and Figure 7 are idealized. Especially, the design process in design-bid-build projects are experienced to evolve in the construction phase even though descriptions, technical drawings and 3D-models are supposed to be complete. The thesis operates with two simplified distinctions. Scheduling in this thesis is commonly referred to, as either scheduling in the tender phase or in the construction phase without making accurate statements on the underlying project type. Scheduling in the tender phase is characterized by having defined the overall processes, in order to communicate milestones to construction crews or clients. Scheduling evolves and becomes more detailed in the initiation of the construction phase where a detailed project schedule is developed, from which five-week look-ahead schedules and two-week coordination schedules are derived. The scheduling processes in the tender and design phases are typically detached from the construction phase, as described in section 1.2, although subcontractors are involved to provide input on some projects. This thesis assumes that scheduling and control processes are intertwined in the construction phase.

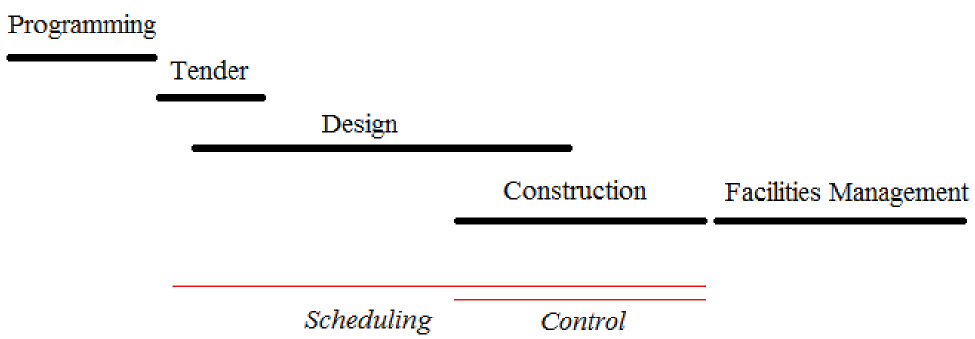

Figure 6: Design-build project phase model.

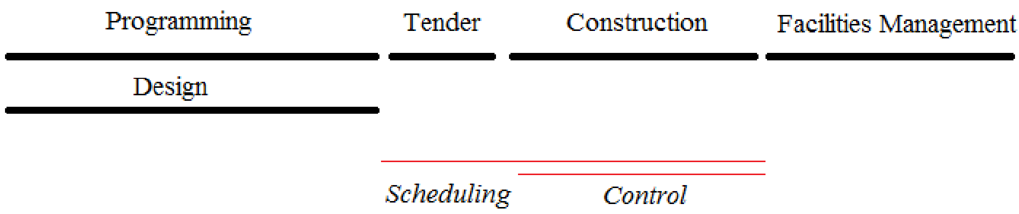

Figure 7: Design-Bid-Build project phase model

Delimitations of the identified problems

Many of the identified problems in scheduling and control that were identified are not addressed by the thesis. These include:

Scheduling:

F. **No criteria** or measure **of quality** for the schedules - schedules vary in quality.

G. Schedules are based on **intuition and personal experience** - **No decision support systems** exist for scheduling.

H. **Necessary information is not available** for scheduling purposes early in the project. Design and construction processes overlap but are not coordinated, so inputs to schedules are often missing.

I. It is difficult to create schedules from available drawings, descriptions, and system requirements - **Input is inconsistent** and unsuited for scheduling purposes, resulting in **information overload**.

J. **Input** from subcontractors is **not incorporated in the earliest schedules** - Contracts are signed with little indication or analysis of **timely risk**, and construction process is sub-optimized.

Construction Control:

N. **Integration of time, resource consumption,** and **cost** is **ignored**. It is time-consuming to evaluate alternative solutions.

O. **Detailed and systemic recordings of performance data on a weekly basis are rarely done.**

P. **Base-line schedules are not used. Schedules are adapted to match current state.**

Q. **No forecasts are calculated.**

R. **There is little active use and understanding of dependencies, buffers, lags, and float**

The problems that pointed toward a need for a simplified scheduling and control technique (Problems B, K, L and M) must be seen as a starting point and motivation for the research rather than the subject of the research. No direct attempt has been made to provide specific solutions for the problems.

Other delimitations

The thesis is delimited by the following primary aspects, which have arisen throughout the research process that is explained in section 3.4.

- Focus on the construction industry. Only building construction, including both new construction and refurbishment projects. Although this thesis is delimited to building construction, LBM is commonly applied to linear projects such as highway projects (See for example Johnston (1981).
- The research has been performed from a general contractor's point of view. Views of clients, engineers, architects, and building product manufactures were not included.
- The main empirical foundation is based on interviews, observations, and data from the same major contracting company.
- The thesis only includes project time management, which is a part of project management.
- LBM theory is the focal point of the theoretical aspects, although it is supplemented by CBR, CCT, and theory on activity-based scheduling and control methods. The theoretical foundation does not include generic project management theory, and is only described in the context of the construction industry.
- LBM is applied and researched as a technique for scheduling and control rather than as a tool that supports these processes. The application of LBM is the focus. VICO Schedule Planner has been utilized as the LBM tool in the case company and by the researcher.
- Cost and quality considerations are not treated as integrated parts of the time dimension, and mathematical aspects are not included.
- Many types of buffers exist, such as material buffers and monetary buffers. However, this thesis is delimited to time buffers.

Section 4.4 discusses the implications of some these delimitations to the results.

1.6 Definitions

This section defines the commonly applied concepts for the terminology used in this thesis.

Location-based management (LBM): LBM is a production control system that integrates planning, scheduling, and control (Kenley and Seppänen, 2010). Tasks are defined by production rates and resource consumption and quantities, whereas the placement and interrelated dependencies of tasks are defined by technical dependencies, locations, and continuity requirements.

Tasks and activities: In LBM, the word *activity* denotes a single work action in a single location. Tasks are an *aggregation of activities in multiple locations* (Kenley and Seppänen, 2009).

Cases: Cases are used as a common term for the subjects of study. In this research, cases are confined to a single company and its supply chain, a company, or a single construction project. The scope of each case is defined in section 3.4.

The term *case company* refers to the same contracting company throughout the thesis. The case company has annual revenue of €1.2 billion and employs 5000 people. The case company has an internal design and engineering department and controls production units of carpenters, concrete, and electrical works.

Time buffer: The definition of a buffer is from Kenley and Seppänen (2010):

The additional absorbable allowance provided to absorb any disturbance between two activities or tasks as a component of the logical connection between two tasks.

Project management: Project management is defined *as the application of knowledge, skills, tools, and techniques to project activities to meet the project requirements (PMBOK, 2008).*

Criticality – This thesis distinguishes between *criticality* and the *criticality principle*. The word criticality is used to describe whether a task or activity affects a projects completion time, should they be delayed. A criticality principle is defined as the collection of constraints that determine whether activities or tasks should be considered critical or not within a given management paradigm.

Scheduling: The word *scheduling* refers to a process that includes definition and sequencing of activities, duration estimating, resource allocation and establishment of the schedule by means of a technique and a tool (PMBOK, 2008).

Control: Control refers to the collected process of monitoring progress of a project, comparing the progress with the plan and initiating corrective actions.

Part II – Theory

Part II contains a brief description of the theory behind current, *activity-based* scheduling and control theory, and an elaborate description of LBM theory. Activity-based scheduling and control theory is included to provide a contrast with the theory of location-based management (LBM). The distinction between the two methodologies is introduced, followed by a more detailed description of LBM.

2.1 Activity-based versus location-based scheduling and control

Kenley (2004) were the first to divide construction scheduling and control into two main methodologies: activity-based methodologies and location-based methodologies, respectively. The critical path method (CPM) and the program evaluation and review technique (PERT) are the predominant activity-based methods. Activity-based methods depend solely on technical relationships; that is, dependencies between activities in the schedules governed by technical constraints. Kelly and Walker (1959) first introduced CPM and the U.S Navy introduced PERT (Malcolm et al., 1959). Given the origin of CPM and PERT in the aerospace and military industries, the methods focus on the earliest possible completion (Birrell, 1980). This focus has been found suited for many complex projects; consequently, it very early has found widespread use in the construction industry (Kelley, 1964; Starnes, 1969), and where it has helped project managers, in particular, prioritize the many activities that they must control during a construction project. The methods assist by highlighting the activities that should be considered critical; however, the methods have attracted criticism when applied in a construction project context, especially on projects of a repetitive nature. Peer (1974) pointed out that network methods or activity-based methods such as CPM do not *include any algorithm, calculation, or consideration for solving the practical organization problems of the on-site production process*. Peer (1974) also criticized the fundamental assumptions in activity-based methods when applied in construction projects. The assumptions that unlimited resources are available and that personnel can be hired and fired freely are erroneous. Activity-based methods were never intended for projects that are sensitive to resource limitations and continuous workflow because the methods originated in the aerospace and military industries. Work continuity was defined by Russell and Wong (1993) as the postponement of the start of an activity until continuous work is guaranteed. Peer (1974) found that a lack of attention to flow and resource optimization contributed to the neglect of scheduling and control in the construction industry because the schedules did not support site management needs. Plans were merely updated and adjusted as projects progressed (Peer, 1974). Peer (1974) stressed the need for an integrated system that would ensure work continuity and balance of the entire process. Arditi and Albulak (1986) found similarly to Peer (1974) that construction crews tend to avoid Gantt charts and network schedules in repetitive projects because these methods do not include resources, although resources constrain projects to the same degree as the time dimension does. Russell and Wong (1993) criticized CPM for lacking work continuity and learning effects, and stated that multiple crewing strategies make the use of traditional network approaches difficult. Arditi et al. (2002) stated that the CPM algorithm simply does not contain elements that *ensure a smooth procession of crews from unit* (Location) *to unit with no conflict and no idle time for workers and equipment*. Consequently, scheduling for construction projects should not be limited to *time-wise performance* (Flood, 2011). More types of constraints than purely technical ones exist. Location constraints and continuity constraints should also be considered when scheduling and controlling construction projects.

Arditi et al. (2002) also criticized activity-based methods because they are difficult to manage on repetitive projects, due to discrete management of similar activities in different locations. The scheduler is forced to manually change the activity for each location in the entire schedule. This aspect is elaborated on in section 2.7. In contrast, distinct advantages exist from using location-based methods on projects with a repetitive nature, and are reported to be as follows (Kankainen and Seppänen, 2003):

- *Compressing the schedule using place division and overlapping production in sections*
- *Increasing productivity, shorter waiting hours, and less hurried work*
- *Use of resources can be planned to be continuous and level, resulting in lower costs (Yang 2002) and less deviations in production*
- *Graphical and easy to use*

The term location based-management

The location-based methodology contains numerous methods that only differ slightly, albeit in important aspects, from modern LBM. These include line of balance scheduling, linear scheduling method, vertical production method, repetitive project model, velocity diagrams, time space scheduling method, construction planning technique, time Location Matrix Model, disturbance scheduling and horizontal and Vertical logic scheduling (Lutz and Hijazi (1993); Harris and Ioannou (1998).

Kenley (2004) suggested the term *location-based planning*. Later, Kenley and Seppänen (2010) combined location-based planning with *location-based control* to form the *location-based management system* (LBMS). LBMS covers both scheduling and control, and is referred to as LBM in this thesis. In short, LBM strives to obtain continuous work throughout the project, avoid a situation in which construction crews work in the same areas, ensure flow of resources, and synchronize tasks to a common production rate.

Before LBM is presented in further detail, the fundamentals of the activity-based methods that play a vital role in LBM are presented.

2.2 Activity-based scheduling and control

This section describes the basics of CPM scheduling because it is essential to LBM and, more specifically, to the topics of criticality and buffers. In particular, *float* calculations are important for understanding both CPM and LBM. LBM partly builds on the same type of logic as CPM and the two techniques have accordingly been treated in close relation (See for example Hegazy, 2001). However, CPM is also described because it is a commonly applied scheduling method in the construction industry, and is therefore used to contrast LBM.

As mentioned previously, Kelley and Walker (1959) introduced CPM in the late 1950s. The purpose of CPM was to manage by exception, which allowed management to impose corrections only when deviations occurred to the plan (Kelly and Walker, 1959). CPM was originally used by the US Navy together with PERT to plan and schedule complex one-of-a-kind projects (Cooke-Yarborough, 1964). Since then, CPM and PERT has dominated planning, scheduling, and control in the construction industry. As mentioned in section 1.1 and section 2.1, CPM and PERT have faced a great deal of criticism concerning the disregard for work flow, resource constraints, communicative abilities and spatial context (Stradal and Cacha, 1982; Laufer and Tucker, 1987; Koo and Fischer, 2000; Andersson and Christensen, 2007). Many researchers have also attempted to provide solutions for the short comings of the original CPM and PERT techniques and suggested new applications for it. For example, the resource leveling problem (e.g., Galbreath, 1964; Lu and Li, 2003; Kim and de la Garza, 2005) and the optimization of cost and time relationships (e.g., Siemens, 1971; Leu and Yang, 1999) have been subjects of research for many years. The same applies to the communicative abilities of CPM and Gantt charts, which Koo and Fischer (2000), for example, addressed by studying the advantages of linking CPM schedules with 3D computer models of building components. CPM and PERT has also provided the foundation for improving health and safety procedures (Kartam, 1997) and flow optimization through lean construction principles (Huber and Reiser, 2003) and the like. More specific challenges for CPM were studied by Hegazy and Menesi (2010), who also provided an overview of research that counters challenges and seeks to improve the technique. A great deal of effort has been invested in the prevailing scheduling and control techniques. However, this thesis focuses on LBM theory. CPM and PERT are mentioned to compare the central themes of the research to prevailing techniques, and because parts of LBM relies on the same basic logic regarding dependencies and criticality.

Cooke-Yarborough (1964) provided a simple explanation of CPM. First, all activity dependencies are graphically represented by an *arrow network diagram* or *activity-on-arrow diagram*.[2] The arrow network diagram contains arrows that represent activities and nodes indicating the start and end times of activities. Second, all activities are attributed with estimated durations. Third, the *float*, or spare time, between activities is calculated. The determination of float is key to the critical path. The critical path is the longest string of dependent activities that contains no float, which in turn determines the shortest project lead time (e.g., Wiest, 1981).

[2] Similar diagrams exist, such as the activity on the node diagram. Although the representation is different, the aim of both diagrams is to identify float and determine the critical path.

Consequently, the critical path informs the scheduler of the activities that should be considered critical to the completion of the project. Originally, PERT did not focus on identifying a critical path because it builds on a probabilistic approach, which means that any string of activities in the dependency network in principle can become critical (Van Slyke, 1963).

Float

Float is essential to CPM because it determines the critical path. Similarly, float is important to LBM because some aspects of the criticality assessment are based on float. Float arises from constraints. CPM only takes technical constraints into account, whereas additional constraints of work continuity, locations, and productivity apply in LBM. Technical constraints describe dependencies between activities that cannot be ignored; for example, painting cannot be completed before walls have been erected and primed. Float begins to emerge when the different activities are given durations and logically connected.

Cooke-Yarborough (1964) provided a simple example (Figure 8) to explain the concept of float and, ultimately, the critical path. Figure 8 contains six activities in a dependency network (activities A through F). Each arrow represents an activity, but the arrow length and direction have no significance except to illustrate logical links between the activities through the nodes. The circles are nodes that all have unique numbers. The duration of activities are shown below the activity name. The square boxes represent the fastest aggregated production time through the activities. The longest duration of any activity to the same node determines the aggregated duration. Therefore, the project cannot be completed faster than the duration in the last squared box by node 5. The process of determining the earliest start times is known as the forward pass. The round boxes indicate the latest time at which each activity can start. These times are found through a backward pass in the chain of activities by subtracting the activity duration from the prior node.

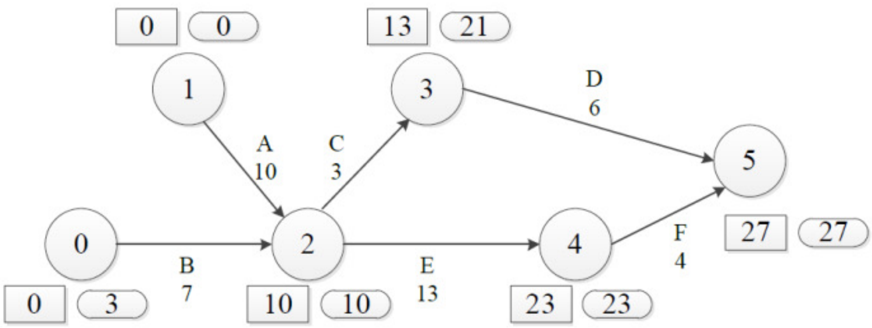

Figure 8: Example adapted from Cooke-Yarborough (1964) of activity on arrow diagram.

Float or spare time arises between activities because different activities in the same sub-network can have longer lead times. For example, suppose that activity D has a duration of six days and starts on day 13, but it does not have to finish before day 27. Accordingly, activity D may finish as early as day 19, which leaves eight days before it has to finish, according to activity F. Float is accordingly determined by subtracting the earliest start from the latest start. There are three different types of float: total float, free float, and independent float.

- **Total float** is the spare time that becomes available if preceding activities start as early as possible, whereas succeeding activities start as late as possible. Accordingly, total float is an indication of the maximum amount of time that an activity can be delayed without delaying the project.
- **Free float** is the spare time that becomes available when preceding activities start as early as possible and succeeding activities also start as early as possible. Thus, free float indicates the length of time that an activity can be delayed without disturbing succeeding tasks if they begin as early as possible.
- **Independent float** is the spare time that becomes available when preceding activities finish as late as possible and succeeding activities begin as early as possible. Independent float indicates the minimum amount of spare time available. The previous example had no independent time available.

The critical path of activities contains no total float. Activities with no total float have neither free float nor independent float. Delays in any of these activities will delay the project. In the previous example, activities A, E, and F should according to the CPM criticality principle be considered critical because they contain no float.

Gantt charts

CPM is commonly used with Gantt charts or bar charts because they are a simple way to illustrate planned work. These charts were introduced by Gantt and Taylor in the early 1900s (Clark, 1922) and are commonly used in the industry to communicate schedules by illustrating horizontal bars that represent start and finish dates. The Gantt charts, which illustrated planned work and were used to control production, were considered an aid for any type of management (Clark, 1922). A simple representation illustrates both planned work and actual performance (Figure 9). The number under each day indicates planned production and the thick line represents actual production in terms of the percentage of planned work that is complete. Although the graphics have changed from the start of the 1900s and more features have been added, such as interconnecting dependencies and the ability to assign resources, the principle remains the same. The charts allow a manager to draw a line to indicate how much of the planned work has been performed, and therefore illustrates the percentage of planned work that is complete, similar to what is commonly used today.

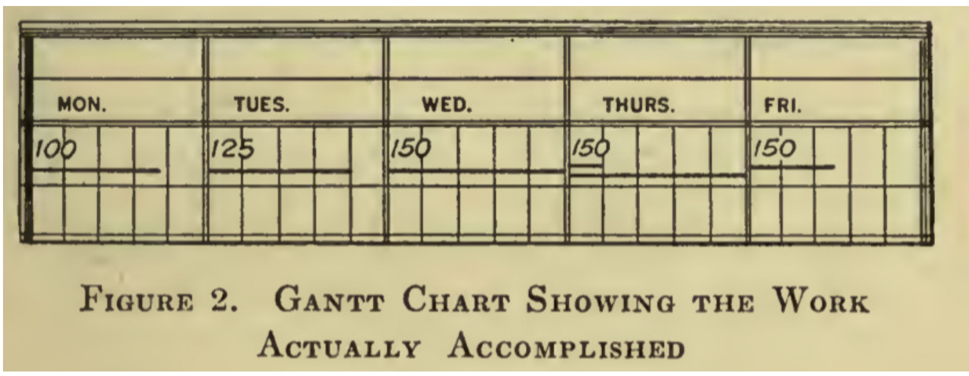

Figure 9: Early Gantt chart taken from Clark (1922) - no copyright pending.

2.3 Introducing location-based management

The location-based methodology has received repeated attention since its earliest use in the 1930s with the construction of the Empire State Building (Kenley and Seppänen 2010). However, none of the location based methods that were listed in section 2.1 have gained the same foothold in the construction industry as CPM and PERT. The main contributors to LBM include Lumsden in the 1960s, Selinger and Peer in the 1970s, Mohr in the late 1970s, Russell in the early 1980s, Kankainen in the late 1980s, Arditi in the 2000s, and Kenley and Seppänen in the 2000s and 2010s (Kenley and Seppänen 2010). LBM was largely developed from the line of balance (LOB) method and the flowline method. The historical development of these methods is not presented in detail. Only decisive points to LBM are included to retain clarity in this representation. Russell and Wong (1993), Arditi et al. (2002) and Lucko (2008) made important contributions that converted LOB and flowline to a location-based system that included algorithms for computation. In addition to the focus on work continuity, their work also emphasized varying location sizes that enabled a more sophisticated and easier use of the methodology. This approach formed the foundation of the collected system of LBM, which in particular was influenced by Kenley and Seppänen in the 2000s and 2010s. Some of the latest contributions to LBM involve linking location based schedules with 3D computer models into so called 4D models, which according to Jongeling and Olofsson (2007) provides enhanced understanding of the spatial configuration of building projects. The use of 4D models with LBM and the mathematical aspects are however beyond the scope of this thesis.

LBM is especially based on the fundamentals of LOB and the flowline methods which therefore are presented first.

2.4 Early development of line of balance and flowline

Originally, LOB and the flowline method were primarily graphical depictions of production tasks. They used quite similar mathematics. However, whereas LOB uses two lines to illustrate the start and finish of a task, flowline only uses one. The two methods also differ in how they represent the performed work. LOB shows accumulated production over time, whereas the flowline method shows locations or work areas on the vertical axis.

Line of balance

The Goodyear Company originated LOB in the 1940s and the US Navy further developed the method in the 1950s (Arditi et al., 2001). The National Building Agency in the United Kingdom developed the use of LOB for construction purposes (Lumsden, 1968). Their focus was planning and controlling projects that entailed construction of similar houses. Lumsden's point of departure was that projects with repetitive work entail a *natural rhythm*[3] and that deviation from this rhythm ultimately wastes both time and resources. In addition to creating a method that accommodates this rhythm or repetitive activities, the intention was to combine time, cost, and resource requirements. The inclusion of these requirements was a major difference to the commonly applied CPM technique, which focused solely on time. However, network techniques such as CPM were significant to LOB. The logic networks formed the starting point for LOB, but LOB exploited similar activities in different locations and dramatically reduced the number of necessary networks. Consequently, the initial driver for the development of LOB was a reduction in administrative effort because large projects with many repetitions require several thousand activities. In addition, the objective of exploiting repeating activities is to ensure that resources *move through the project in a continuous manner to maintain and keep a balanced labor force fully employed* (Lumsden, 1968).

The basic components of LOB that need to be considered initially are as follows:

- Time (x-axis)
- Line of balance quantities (y-axis)
- Logical dependencies between activities
- Start and finish times for each activity
- Production rate of each activity
- Resource requirements

The initial step is to determine the logical dependencies between activities. This determination is done through a unit network in LOB, which is based on the activity on arrow approach. The unit network analysis was simply incorporated into LOB because it provided a useful feature for determining the logical sequence between activities.

[3] The natural rhythm of an activity is defined as the optimum rate of production that a crew of optimum size will be able to achieve (Arditi, 1988).

After determining the logical relationships between activities, the basic LOB diagram can be depicted. Figure 10 illustrates a very simple LOB diagram. The figure shows four activities that are performed over nine months to create five units (Lumsden, 1968). The four tasks are started as soon as possible and only one work crew is allocated to each task. Each task is depicted with two lines. One line indicates the start date, while the other indicates the planned finish date. The four tasks are performed in their natural rhythm. I.e., they are performed within the time that they are expected to take given that only one crew works on each activity. This principle is key to LBM. Although LOB displays the number of units produced and not locations, it represents the same overall principle. Figure 10 indicates how the work would be performed if only one crew was assigned to each task. However, this would signify considerable waiting time for the faster task C, which constitute waste in the schedule.

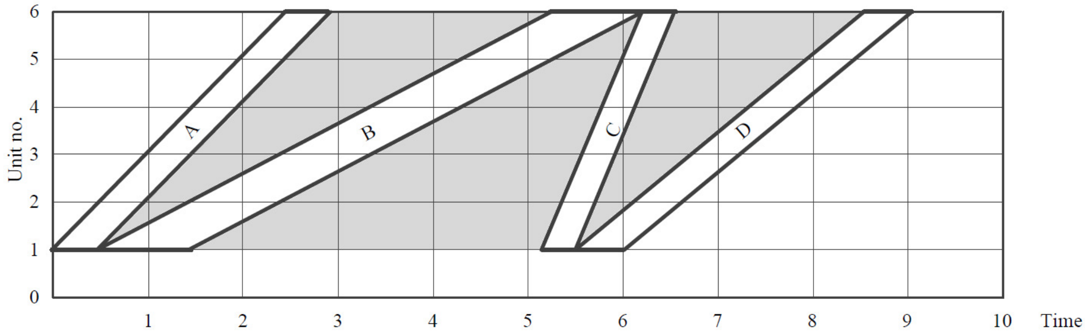

Figure 10: Line of balance diagram. Unaligned tasks. (Lumsden, 1968)

The management of resources is vital to LOB because they are used to *balance out* the tasks by adding additional crews to slower tasks. The aim is to find a multiplier that causes all tasks to align. Each task is simply given the number of crews it requires to reach the same production rate. Aligning tasks can minimize production time. However, constraints such as cost and resource availability, can limit the production rate of some tasks that therefore cannot be aligned completely. Figure 11 and Figure 12 show this principle. Figure 11 shows a partially balanced schedule and Figure 12 shows a fully balanced schedule.

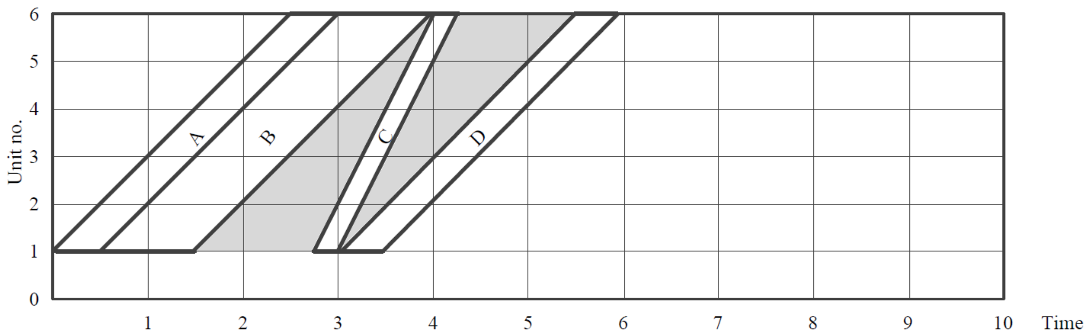

Figure 11: Line of balance diagram. Semi-balanced tasks. (Lumsden, 1968)

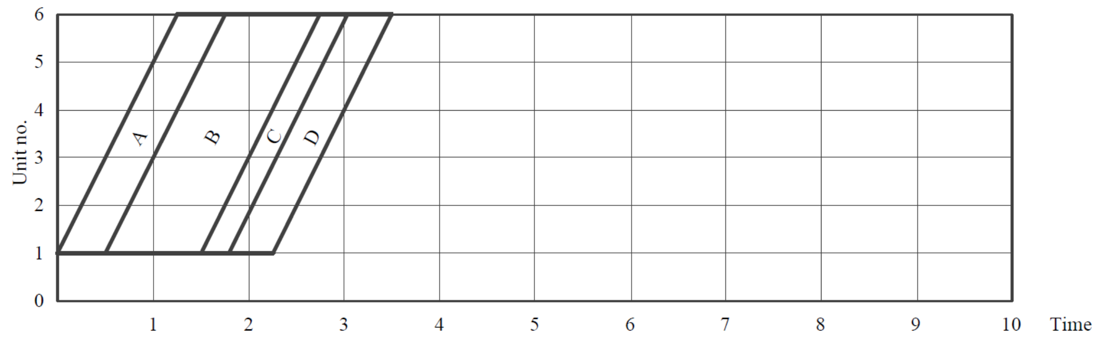

Figure 12: Line of balance diagram. Fully aligned tasks. (Lumsden, 1968)

The alignment and optimized placement of tasks are important subjects for this thesis because they affect the criticality of each task. The fully aligned schedules contain no float which is important to the subject of buffer management.

This concept explains the basic first steps of the location-based methodology. However, the LBM methods presented later in this chapter have progressed substantially since these first thoughts. One important difference is the alternative way that flow lines are presented through the introduction of the flow line method.

Flowline

Peer (1974), together with Selinger (1980), was one of the first contributors to the flowline method, which constituted a new way of handling and displaying activities in construction projects. One important point made by Peer (1974) was that scheduling and control in the construction industry should aim to complete projects in the shortest possible time that is compatible with financial limitations. The fastest time is not necessarily the most economical. Nor is the relationship between available resources and construction time necessarily linear. Yet, Peer (1974) based his work on assumptions of linearity and made the point that the optimum amount of resources varies between the different tasks. Peer (1974) produced a construction planning process for the location-based methodology that contained many current elements of LBM and provided the following construction planning steps.

1. Break down the project into constituent component processes.
2. Divide realization of these processes between adequate production crews.
3. Define technological connections between the crews and activity categories.
4. Decide on the flow line that should dictate the progress of the project given financial or resource limitations.
5. Estimate the resulting construction time and decide on the number of production units that should be employed in parallel.
6. Balance the progress of noncritical flow lines with that of the chosen critical one, aiming to achieve working continuity.
7. Within practical limits, check the possibility of shortening construction time by introducing planned breaks in continuity or changes in crew size.
8. Analyze the entire process in terms of time and duration of activities and produce a plan.

Compared with activity-based methods, the principle of pacing or accelerating activities to form parallel flow lines is essential to the LBM technique. In particular, steps 4–7 are important to LBM and the topics of this thesis. E.g. Article 3 centers on the reasoning behind steps 4 and 6 because they influence how critical activities are perceived in LBM, but are described sparingly in current literature. Thus, Peer (1974) addressed the topic of criticality. Peer (1974) argued that construction project planning is not *a problem of determining an incidental critical path from arbitrarily fixed activity durations*. Instead, it is a matter of choice that is typically affected by technical, procedural, cost, and resource restrictions. As many tasks as possible are aligned to the same production rate because this will produce the most condensed schedule while enforcing continuity requirements and thus ensuring economical production. Despite Peer's (1974) planning steps and comments on criticality, the topic was never treated in much depth, and the importance and reasoning behind the focus on the slowest task has not been treated in great detail in the LBM literature since.

Figure 13, Figure 14, and Figure 15 illustrate a similar situation to that provided by Lumsden (1968), but in the flowline view. Instead of depicting two lines for start and finish, as with LOB, the flowline method uses only one line. The beginning of a line indicates the start date for the entire task. Each intersection with a section (horizontal lines from the y-axis which is locations in modern LBM) indicates the start and finish date in the given section. This is the way in which current LBM also is depicted. Figure 13 illustrates a project with four activities, all with individual production rates. In this example, Activity D becomes discontinuous because the preceding activity C is slower. Figure 14 shows a situation in which all four activities are accelerated to the fastest possible production rate. However, this situation might not be desirable because task A is now limiting tasks B and C which become discontinuous. The principle described by Peer (1974) suggests that activities, B, C, and D should be accommodated to the production rate of activity A, as illustrated in Figure 15. However, such an accommodation makes all tasks critical, which is key to the third research article of this thesis, and is subsequently treated in greater depth in section 2.7.

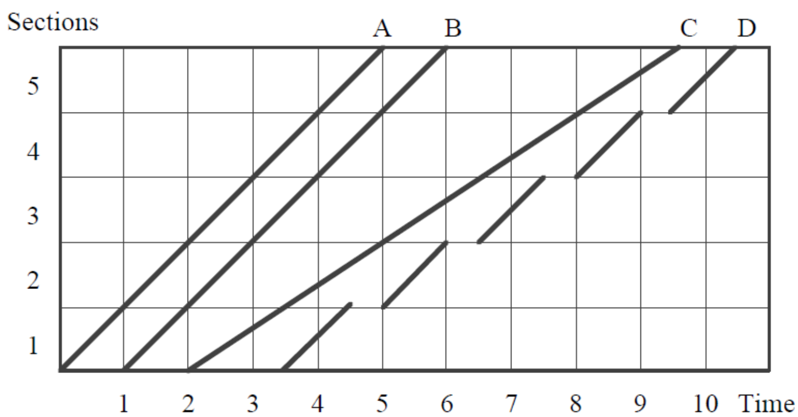

Figure 13: Flowline diagram. Task D is forced to be discontinuous due to slow progress in task C. (Peer, 1974)

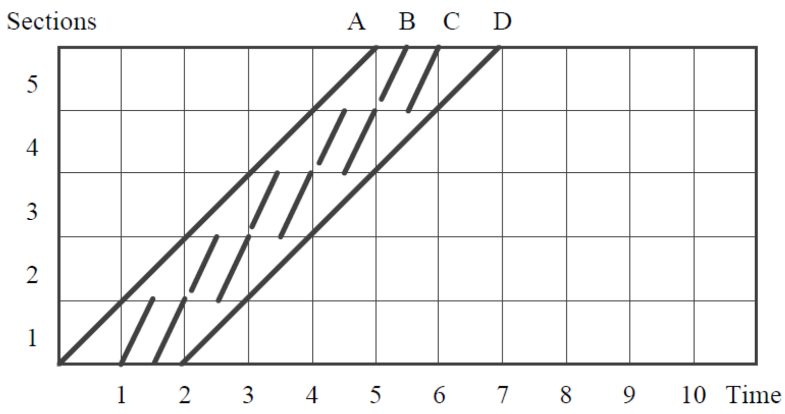

Figure 14: Flowline Diagram. Tasks B and C are discontinuous as all tasks are performed as quickly as possible. (Peer, 1974)

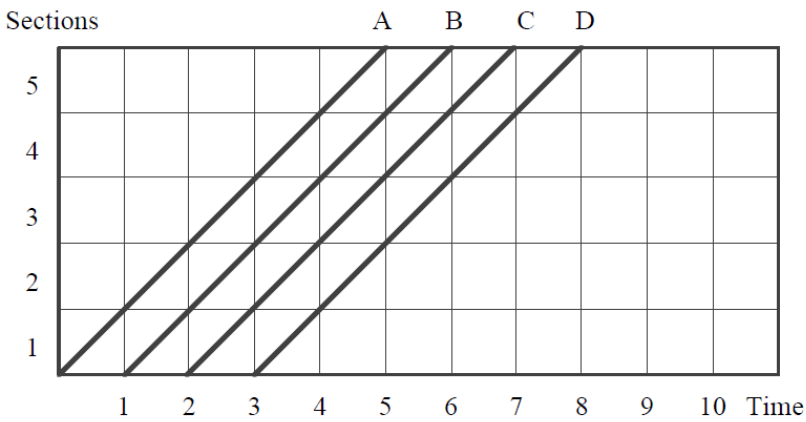

Figure 15: Flowline diagram. All four tasks have similar production rates to ensure continuity. (Peer, 1974)

As previously mentioned, the LOB method was not originally intended explicitly for the construction industry and was developed as a general method. Accordingly, the y-axis in the diagram indicated *cumulative quantity produced*. Similarly, the units of Peer's (1974) flowline diagrams were *sections*. Birrell (1980) introduced location analysis to construction project planning and represented the initial steps in the location breakdown structure, now an essential part of LBM. Section 2.6 describes the location breakdown principles.

As the preceding presentation might suggest, the location-based scheduling methodology was primarily used as a graphical representation until, Russell (1985) Reda (1990), Sarraj (1990), and Russell and Wong (1993) amongst others, began to articulate its mathematics and algorithms more thoroughly. For example, Chrzanowski and Johnston (1986) wrote that the linear scheduling method *is essentially graphical; it cannot be adapted to numerical computerization as readily as network methods*. Russell and Wong (1993) suggested a turn toward a more sophisticated scheduling and control system that furthered the methodology by making these numerical computations possible. While the mathematics and algorithms are beyond the scope of this thesis, the continued development of LBM is described in the following section.

2.5 Continued development of LBM

Russell and Wong (1993) contributed to the location-based methodology by developing new *planning structures* to combine the advantages of CPM with what they called linear scheduling. In other words, the planning structures are types of activities that include the following:

- Continuous activities (work with a specific continuous sequence through the project's locations)
- Ordered activities (work that has to be performed in a specific location sequence but can then be discontinued after each location)
- Shadow activities (work that can be performed in the first available location sequence with no requirements of continuity and resource limits)
- Cyclical activities (activities that have succeeding activities in the same location that, in turn, constitute a predecessor for the first activity in the next location)
- Non-repetitive activities (typical CPM activity)

By explicitly defining these five types of activities, Russell and Wong (1993) enabled easier scheduling of work continuity and work in ordered location sequences between similar activities in different locations.

Russell and Wong (1993) emphasized the repetitive nature of projects by also abandoning the earlier assumption that all tasks should be continuous. By applying the technique, they learned a lot about what location-based methodologies did not provide at the time. They summarized these findings and explained the attributes that had to be added to create an effective location-based management system regardless of whether the projects have a repetitive or non-repetitive nature. They identified the following nine attributes (as reformulated from Russell and Wong (1993)).

1. The activity types or planning CPM structures, including capabilities for projects of a repetitive nature, must be included mathematically in location-based management methodology. The methodology must encompass two extremes, one for pure CPM scheduling and one for pure flow lines.
2. The terminology of CPM should be applied in location-based management methodology to simplify the understanding for new users.
3. It must be possible to vary production rates.
4. The Finish-Start, Start-Start, Start-Finish, and Finish-Finish precedence relationships must be available. Relationships between locations must also be included.
5. Work continuity should be an option, but not a requirement. Work continuity is defined as the postponement of the start of an activity until continuous work is guaranteed when construction crews move between locations.
6. The concept of work location must be defined generally. The methodology should be able to handle major areas, off-site areas, on-site locations, and micro-locations.
7. The activity structure should include work continuity constraints, unlimited predecessor and successor relationships, location ordering, crewing (multiple or variable), preplanned work interruptions, and variable production rates.

8. Updating algorithms should capitalize on repetitions in projects and allow changes to work location, orderings, crewing, and precedence relationships.
9. Multiple representations of plans and schedules must be available to provide optimal means to illustrate the data and to satisfy practitioners' personal preferences. These representations should include a linear planning chart (time-space diagram), network diagram, bar chart, and matrix chart.

Most of these additions have been incorporated in current LBM software and the attributes had an obvious effect on modern LBM. Russell and Wong (1993) also included dependencies between locations and, consequently, a location breakdown structure in their considerations. Section 2.6 elaborates on these concepts.

Arditi et al. (2002), who introduced the *flexible unit network* and *multilevel LOB diagrams*, made another important contribution by identifying the need to modify LOB to handle *complicated activity relationships and concurrent activities* because the technique was found difficult to use on complex projects with many trades or tasks. In particular, estimating production rates and creating unit networks proved difficult. Accordingly, Arditi et al. (2002) attempted to simplify the LOB method and make it suitable for computations and suggested that activities should be able to move in time within the logical constraints of LOB. Consider the example they provided through the unit precedence diagram in Figure 16. If activity 5 is a successor to activity 1, a predecessor to activity 6, and can be constructed concurrently with activities 2 to 4, then activity 5 can be constructed from the finish time of activity 1 to the finish time of activity 4. Activity 5 will only consume float during this time gap. This solution might seem obvious to the trained scheduler, yet it is an important theoretical contribution to location-based methodology and is important to this thesis because it affects the criticality of activities.

Arditi et al. (2002) also introduced a breakdown structure of the unit networks. They created unit networks in *main activities, sub-activities,* and *sub-sub-activities.* This feature is mostly important for usability issues because networks can be handled at different levels of detail, simplifying the use and reuse of unit networks.

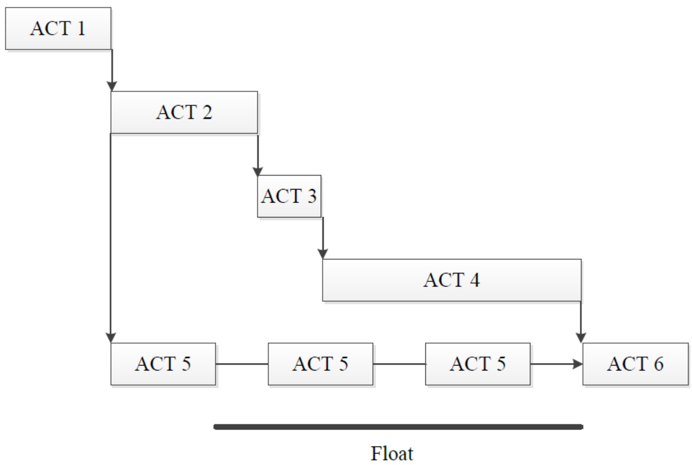

Figure 16: Unit precedence diagram. (Arditi et al., 2002)

2.6 Current location-based management

Some important advances in the LBM theory, which have not yet been described in Part II, include the location breakdown structure, quantities, resources, production rates, and layered logic. These topics will be presented in the present section.

Location breakdown structure

The location breakdown structure is an important part of LBM because it affects how resources flow through the building, and help making location constraints explicit. A location constraint ensures that an activity does not share any work locations of its predecessors or successors (Russell and Wong, 1993). The location breakdown structure is a theoretical and hierarchical description of a project and allows schedulers to allocate and group activities or tasks across locations. The location breakdown structure provides flexibility in schedules because the allocation of activities and tasks depend on the performed work. For some crews, working and thinking in terms of floors or buildings is more logical (such as concrete slab pours), whereas other crews prefer to work and think in terms of apartments or rooms (such as wood floors installation). While projects can be broken down in any suitable way, a building is usually broken down into logical segments or parts represented by physical constraints, although this is not necessary. The only requirement is that the topmost hierarchical levels include every logic sub-location. For example, a project's topmost hierarchical level could be *buildings*, then *staircases*, and then *apartment* (Figure 17). Projects rarely contain more than three or four levels because adding too many becomes unmanageable.

Generally, the purpose of each level is different (Kenley and Seppänen, 2010). The highest level controls the overall production sequence. By changing the sequence on the upper levels, the scheduler can determine how the overall flow of production should progress. Because the highest level is typically independent structures, the structures can be planned to be constructed simultaneously or sequentially. The midlevel locations are typically staircases or floors that need to be completed before construction crews continue with the next midlevel location. The lowest hierarchical level is locations in which only one crew can work at a time (Kenley and Seppänen, 2010); these are typically rooms in building construction, but can also be locations such as hallways and minor floor areas.

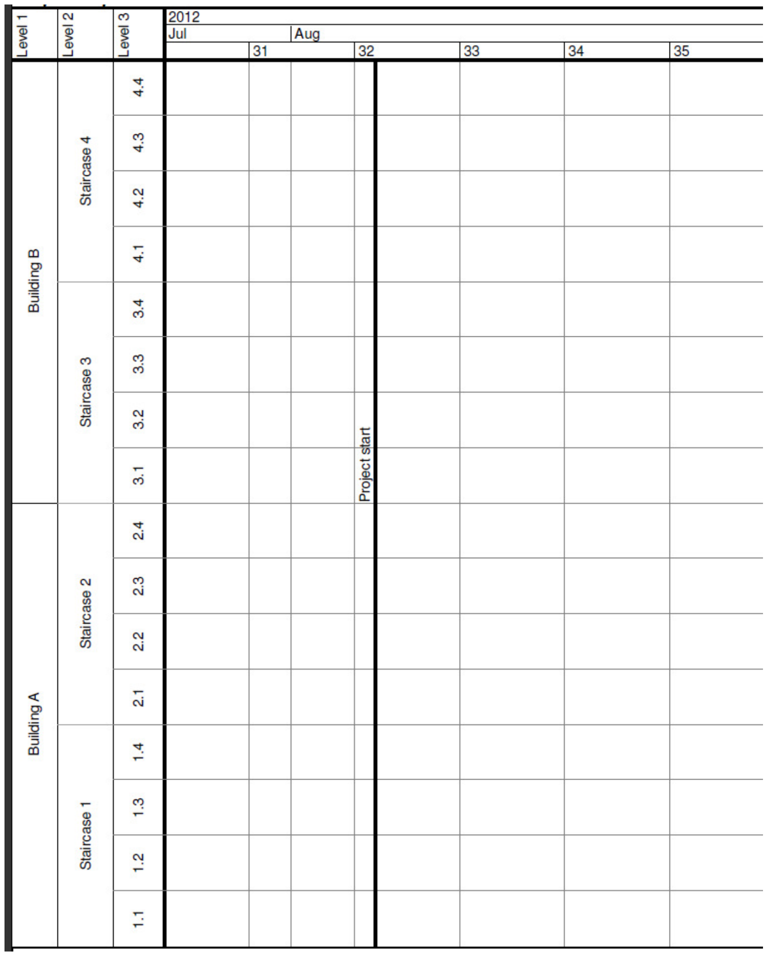

Figure 17: Principle example of a location breakdown structure - division in *buildings, staircases,* and *apartments.*

Quantities, resources, and production rates

Location-based quantities are important in LBM because activity and task durations are calculated from them, implying that some tasks will take longer to complete in some locations than others (Figure 18). Seppänen and Kenley (2005) stated that location-based quantities enable managers to plan continuous work flow with even or balanced resource use. Failure to realize this issue can create productivity problems because crews that follow a slow task cannot initiate their own task.

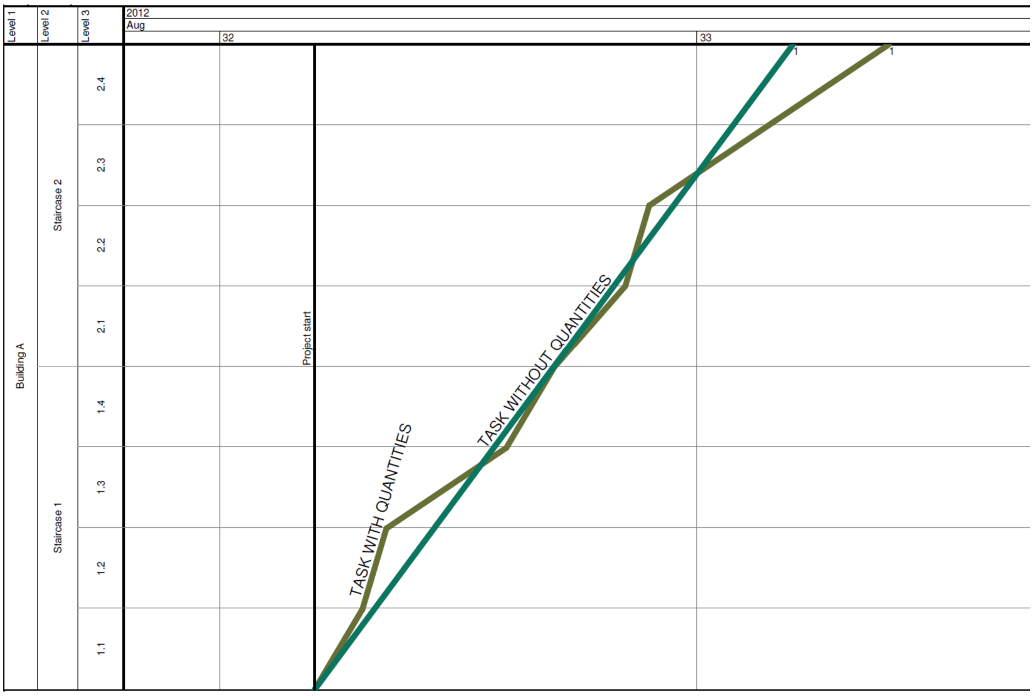

Figure 18: Task with and without quantities.

The quantities are allocated to locations in the location breakdown structure and, subsequently, to activities and tasks. Binding quantities to locations in the plan shows what needs to be performed before a crew has finished a task and can continue to the next location (Kenley and Seppänen, 2010). Quantities are grouped in a *bill of quantity* if the following statements are true (Seppänen, 2009):

- A single crew can perform the work.
- The associated activities or tasks have the same dependency logic.
- The work can be completed in one location before moving on to the next.

Quantities are typically derived from a 3D model of the building or entered manually by analyzing construction drawings. When the quantities have been determined and distributed across locations, knowledge of resource availability and production rates can be combined to produce the flow lines for the location-based schedule.

Note that practitioners also use LBM without entering location-based quantities, particularly during the early project phases. Quantities are not strictly necessary to complete a location-based schedule. A plan can be illustrated merely using assumed durations. However, such an approach is undesirable because it results in a schedule based on guesswork (Seppänen and Kenley, 2005). Flow lines are produced from estimated production rates and work merely as an intended plan or target. Excluding quantities results in greater risk in the schedules. Establishing the schedule without using the logic that ties it to the design can cause project leaders to oversimplify the schedule and fail to notice vital productivity issues from changes in quantities as the project evolves through time.

Resources or crews that perform the work are designated with a consumption rate or a production rate, such as the amount of m, m^2, m^3, or pieces that crews can produce per unit of time. The production rate should be determined for each item in the bill of quantity. Durations can be determined once quantities and production rates have been established. A crew for a particular task can be assumed to be created to suit the needs of each task, whereas the number of workers in a crew varies for different types of crews. However, the number of crews can affect the duration of a task. The reduction or increase in crews to particular tasks is an important feature of LBM because flow lines can be altered to ensure production flow, avoid location conflicts,[4] and level out resource consumption throughout the build site.

Production rates are used by particular crafts such as concrete works. However, most construction companies do not have a complete set of production rates that can be applied to a schedule (Seppänen and Kenley, 2005). Although it is not common practice, some Finnish construction companies have produced a common database of production rates.[5] Either the project manager or a member of the tender group commonly practices using an approximated duration estimate (Seppänen and Kenley, 2005).

Production rates and resource consumption are the cornerstones of LBM and are of central importance to this thesis. The aim of LBM is to ensure flow for each construction crew. Yang (2002) tested the importance of flow and suggested a 30 percent cost saving when resources can work continuously.

Layered Logic

Layered logic describes the different types of dependencies that exist in LBM across locations and between activities and tasks. It is different from the logic in activity-based methodologies given the addition of locations, but also because of the requirement or aspiration for continuous workflow. However, some dependencies are similar to those of CPM. Kenley and Seppänen (2010) described the five layers of logic that can occur with LBM:

1. External logical relationships between activities across locations
2. External higher-level logical relationships between activities driven by different levels of accuracy in the location breakdown structure
3. Internal logic between activities within tasks
4. Phased hybrid logic between tasks in related locations
5. Standard CPM links between tasks and different locations

Layer 1. The first layer describes dependencies between similar activities across locations (Figure 19).[6] The dependency only needs to be defined once and is then copied to all relevant locations. This logic not only simplifies the workflow and

[4] A location conflict is a term that describes a situation in which two different work crews want to or need to work in the same location.

[5] It is now possible to purchase a generic database of production rates to supplement a contractor's own knowledge until a company-specific database is established.

[6] Red arrows indicate critical dependencies and blue arrows indicate non-critical dependencies.

reduces the amount of repetitive work; it also ensures a link between each discrete activity in CPM. This logic affects the way projects are controlled and how progress is forecasted. In CPM, forecasts are based on the initial duration estimates for each location because tasks are treated discretely. The advantage of this method is that forecasts in LBM are based on actual production rates from completed locations of a given task, which arguably provides a more realistic forecast. The discrete treatment of tasks and effect on forecasts is described in section 2.9.

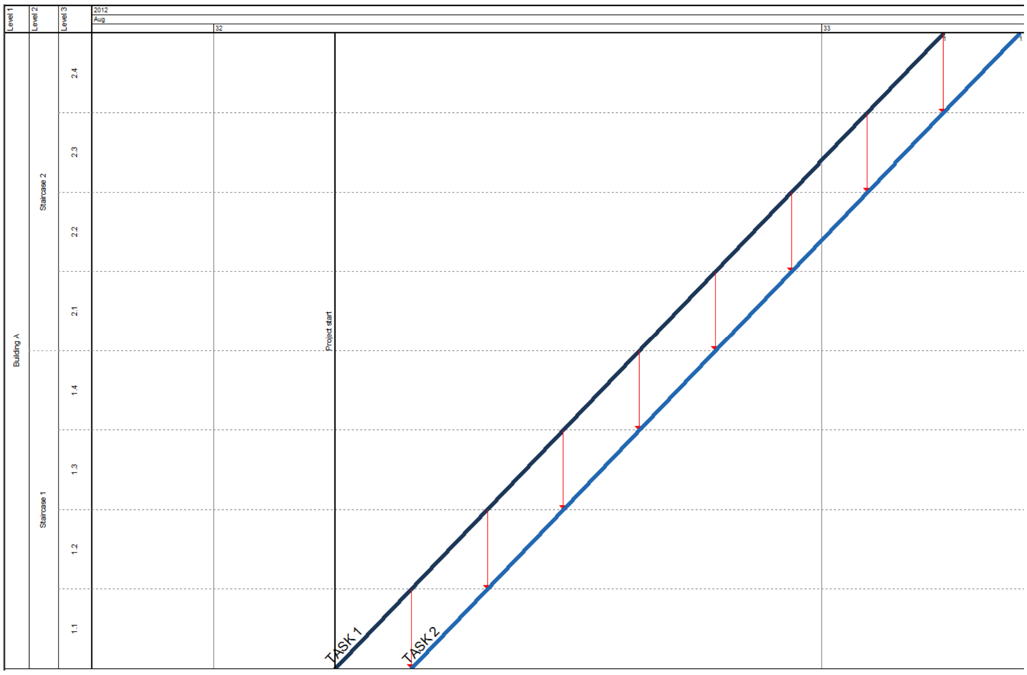

Figure 19: Layer 1 logic.

Layer 2. The second layer describes dependencies that occur between activities or tasks designated on different layers of the location breakdown structure. One task (such as balcony installation) might be defined at an apartment level, whereas another task may be defined by building or sections of a building (such as facades) (Figure 20). By defining the accuracy level of both tasks, the tasks can be connected at the relevant hierarchical level. The layer 2 logic is used to link tasks that are performed at different parts of the location breakdown structure. Figure 20 shows a situation in which balconies only have to be installed for two apartments in each staircase. The task of installing balconies has a Finish-Start relationship with the task of setting up the facades. In this case, the facades can be set up for one staircase at a time. The *Balconies* task is defined at the apartment level, whereas the *Facades* task is defined for each staircase.

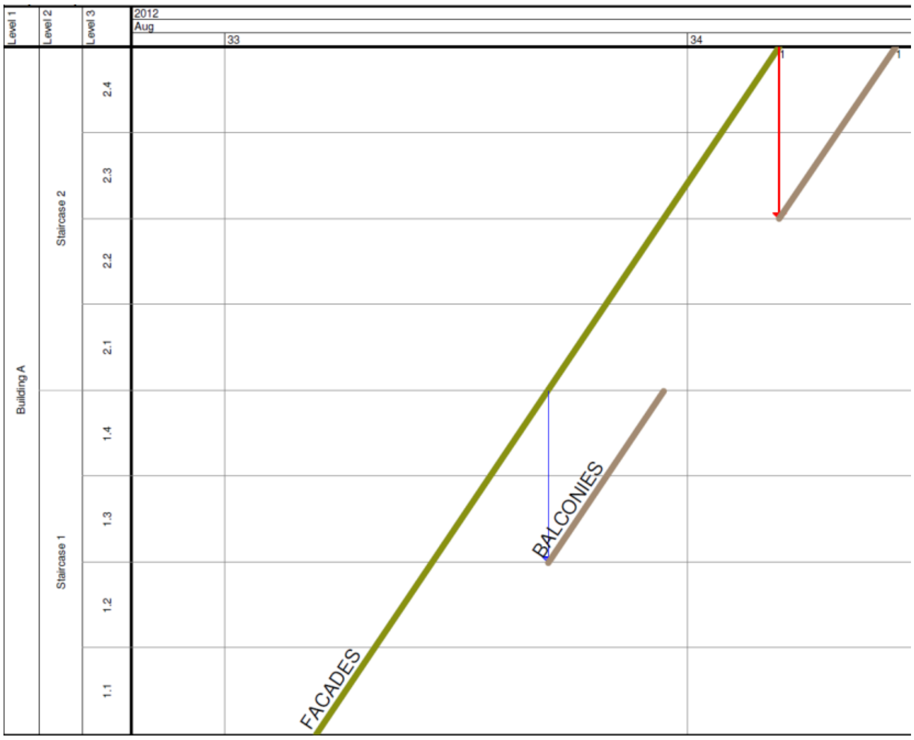

Figure 20: Layer 2 logic – Dependencies between different layers in the location breakdown structure.

Layer 3. The third layer is the internal logic that exists between the single activities within a task. This logic describes whether the task is continuous or discrete across its locations. One fundamental aspect of this logic is that crews completely finish one location before moving on to the next one. Furthermore, a forced continuous task will not be initiated before the entire task can be completed without colliding with any of the preceding task's locations. Task 4 in Figure 21 (left) starts later than possible in the first locations. This is because the last locations cannot be completed before task 3 is complete, given a Finish-Start dependency at the lowest hierarchal location level. Figure 21 (right) shows a similar situation, despite task 4 now being relieved of the continuity requirement. This change enables work to start earlier in the first locations. However, neither the project management nor the construction crews gain anything from the discontinuity if only one crew is available for task 3. The construction crew will have to halt production and wait until the preceding task 3 is completed in the given location, which can cause construction crews to leave the build site and raise the risk of late returns. Figure 21 also reveals that the finish date remains the same for task 4 regardless of whether it is continuous or discontinuous. No gain is made from rushing the tasks by starting each as early as possible. Discontinuity of a task is only desirable if multiple crews are available and a slow task has to be accelerated. Given the situation in Figure 22, task 6 is slower than tasks 5 and 7. If the crew cannot finish a location faster by adding another crew, the task can be split and two crews can work in every other location. Thus, task 6 can be accelerated by splitting it and allowing two crews to work on it simultaneously.

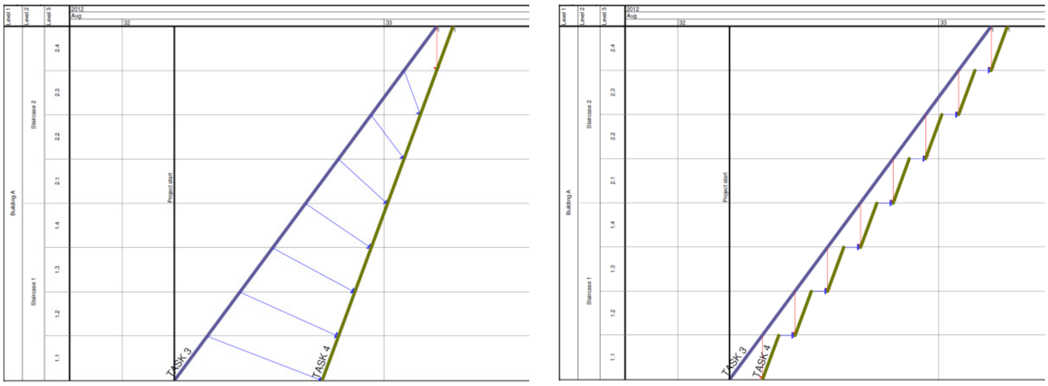

Figure 21: Continued (left) and discontinued task (right).

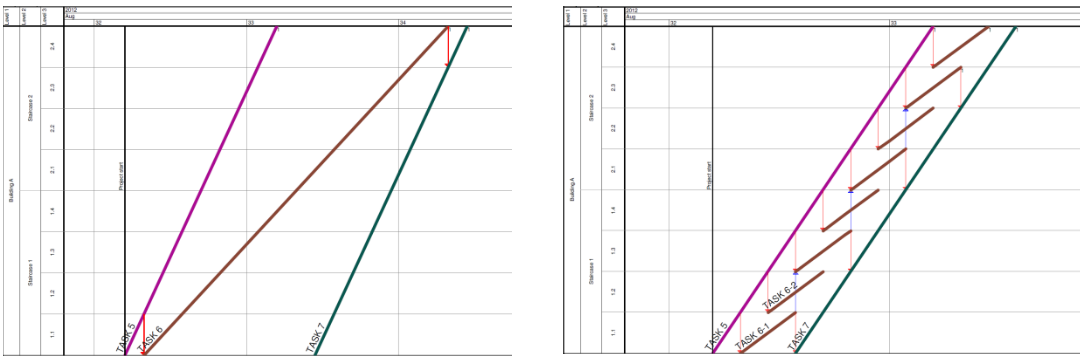

Figure 22: Task 6 continuous with one crew (left) and task 6 split with two crews (Right).

The layer 3 logic also describes the sequence for the performed work. A task can be performed in any sequence throughout the locations. However, generally, a preferred direction of work exists that is governed by the overall construction sequence of the project. However, some crews prefer to work horizontally across a floor (facades, for example), whereas other crews might prefer to work vertically (such as during structural work). Different parts of projects can be performed in different sequences across and throughout the project. Independent tasks need not be hindered if they are completed in different sequences. However, a series of tasks (such as those occurring during the fitout phase) would benefit from following the same sequence of production to avoid location conflicts and unfavorable workflow that can prolong production time.

Layer 4. The fourth layer of logic is used to schedule lags[7] between activities. This technique is commonly used for cyclical activities that are repeated throughout a series of low-level locations. The logic introduces a lag that depends on finished locations. This *location-lag* is similar to a time lag, although it works horizontally in a location-based schedule. Kenley and Seppänen (2010) exemplify this technique with in-situ concrete slabs. Consider a situation in which concrete is poured in a

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[7] A lag is the required fixed duration of a logical connection between two activities or tasks (Kenley and Seppänen, 2010).

high-rise building during the *formwork, rebar*, and *concreting* tasks and the successor *interior work* task. Because the concrete has to set, accessibility is limited to one floor above and two floors below. The formwork on the next floor cannot begin until the lower level can support it. Similarly, the two lower levels must be temporarily propped until the concrete can carry its own weight, which is modeled with a location lag of +1 and -2, respectively. A +1 lag means that a lower level location must be finished before a higher level location can be started. A -2 lag means that two higher level locations must be finished before a lower level location can be started (Kenley and Seppänen, 2010). Figure 23 illustrates this situation.

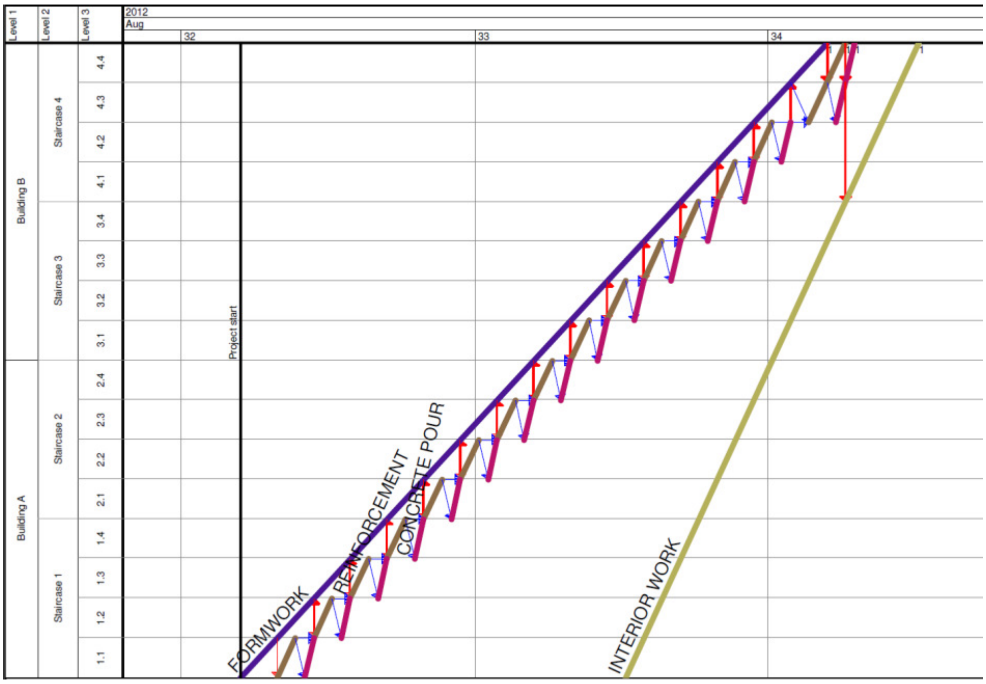

Figure 23: Location lags of +1 from *Concrete Pour* to *Formwork*, and -2 location lag from *Concrete Pour* to *Interior Work.*

Layer 5. The fifth layer is used to enforce special constraints across locations and between and within tasks that are not covered by the other layers. Layer 5 logic entails simple dependencies that combine any activity or task in any location. The essence is that this logic overrides any other logic; for example, if a task has the requirement of continuity, the layer 5 logic overrides it and makes it discontinuous. Figure 24 shows a situation in which a layer 5 logic dependency requires a task (task 9) to start after a specific location in another building has been completed. The layer 5 dependency between tasks 8 and 9, together with the layer 1 *finish-start* relationship in the second building, is stronger than the continuity requirement of task 8. Accordingly, task 8 becomes discontinuous in the latter locations because task 9 is faster.

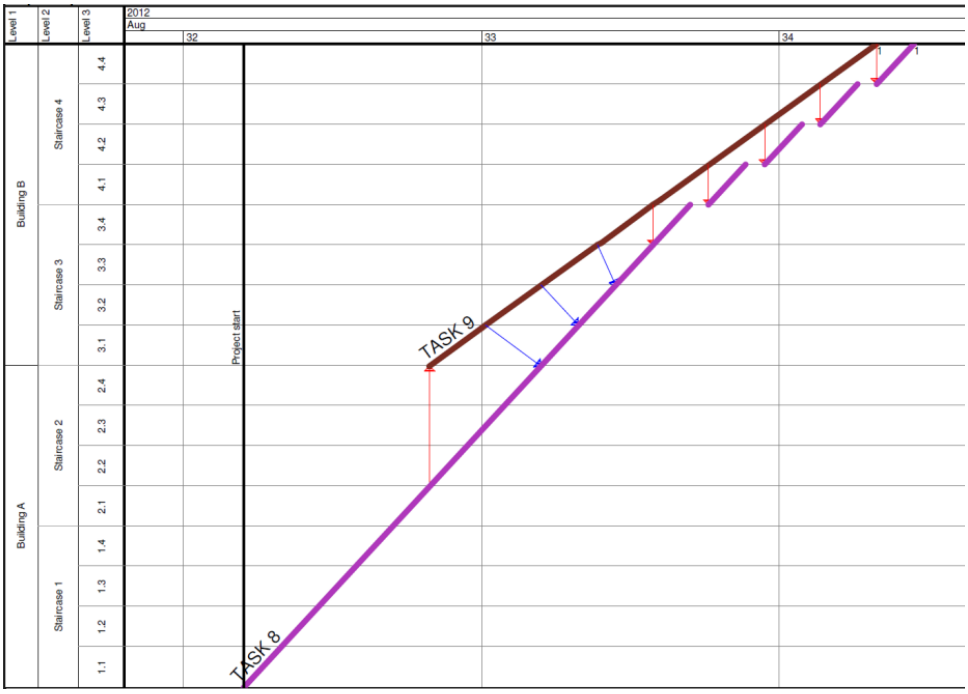

Figure 24: Layer 5 logic. Dependency across structural independent locations.

2.7 Criticality

The concept of criticality is essential to this thesis and is the cornerstone of the third article. Consequently, the content in this section is similar to the description in the third article. Flood et. al. (2006) described that the progress of work on a project is determined by constraints on the system. The topic of criticality is consequently defined by the inherent constraints in LBM and their impact on a projects lead time. As defined in section 1.6, criticality describes whether a task or activity affects a project's completion time if that task or activity is delayed. A criticality principle is defined as the collection of constraints that determine whether activities or tasks should be considered critical within a given management methodology. The constraints that constitute the criticality principle in LBM are described in fractions in the current literature and only relate to the criticality principle sparingly. A collected criticality principle in LBM theory is not present in the current literature, equal to that of CPM. The different parts that affect the criticality of tasks or activities in LBM are described in the present section, whereas the suggested collected criticality principle of LBM is presented in section 4.1. Consequently, the purpose is to present the theory that was identified to conceptualize the criticality principle of LBM and, in so doing, answer RQ1.

The criticality of activities and tasks might seem unambiguous, but it depends on the applied management method and the phase of the project in which it is applied. In other words, the criticality principle is different in LBM than with activity-based methodologies. The criticality of tasks must also be viewed in light of project phases; namely, whether a building is being planned or constructed. The environment is static when projects are planned, whereas controlling projects is dynamic and ever-changing. Therefore, the ability to quickly determine critical tasks is important because project managers must constantly prioritize their focus during the construction phase. The underlying constraints of the criticality principle do not change in accordance with the project phases, only its application.

Criticality in activity-based methodologies

The introduction of CPM brought the advantage of focusing the control effort on projects. By identifying the critical path in a project, managers are able to reduce the number of activities that should be given special attention (Cooke-Yarborough, 1964). The critical path is a set of linked precedence relationships in a logic network that have zero float (e.g., Wiest, 1981), which define the longest path from the first node in a project to the last node, as explained in section 2.2. When projects are controlled, the criticality principle supports project managers in prioritizing tasks that lie on or close to the critical path.

When a CPM project suffers inadequate production performance, monitoring the project reveals that the critical path will exceed the planned duration. A commonly used method is to state the planned date as fixed and calculate backwards, revealing negative float for tasks on the critical path. Indeed, when the delay is long enough, many tasks may have negative float. Thus, a project manager will assess that all of these tasks are now critical and will consider accelerating production as a control action across all of these tasks. Not all methodologies use this approach in application (it is software dependent), but it is a useful method for highlighting management's response.

Koo et al. (2007) noted that CPM is restricted to the concept of time-criticality and fails to inform about enabling or impeding precedence relationships and whether activities can be relaxed; in other words, whether the constraints of an activity are flexible or inflexible. Such logic is tacit knowledge, known by individuals but not apparent in the CPM schedule. Yet, information on these constraints is vital for a project manager's perception of criticality and can determine actions when scheduling and controlling projects.

Van Slyke (1963) also provided a criticality principle for one of the activity-based methods. Working in PERT, Van Slyke (1963)defined the criticality of an activity as the probability that it will fall on a critical path. Criticality of paths was not originally an inherent part of PERT because its stochastic approach to scheduling prevents the ability to determine the longest path through deterministic values. However, Van Slyke (1963) introduced the concept of criticality in PERT to provide project managers with a measure that indicated the relative importance of activities, enabling them to prioritize their work effort. Instead, Elmaghraby (2000) focused on critical activities because they should be more interesting to project managers, as every path in PERT can be potentially critical. Most paths have a probability greater than zero of being critical because durations are determined stochastically. This example indicates that the concept of criticality depends on the applied method.

Criticality in location-based methodologies

Similar to CPM, time float is an important concept to criticality in LBM. The float in a schedule partly describes whether tasks are critical or near critical (Kenley & Seppänen, 2010). Tasks with no float are regarded as critical because any delay in them will delay the project. Tasks with little float are considered near critical, whereas tasks with high float can absorb delays and are considered non-critical. The total float of a non-critical task indicates the amount of time that the task can be moved without delaying the project. However, only the free float is utilized in order to respect continuity and location constraints. Float can act as a time buffer for non-critical tasks and is used to protect succeeding tasks against delays (Kenley and Seppänen, 2010).

Kenley (2004) also treated the topic of float in relation to delays and stated a series of question that must be asked in LBM regarding delays:

- Does the delay disrupt the flow of a continuous activity?
- Does the delay impact on the flow of any following activities?
- Does the delay impact on the commencement of any following activities?
- Does the delay lead to the delay in project completion if flow is maintained?
- Can the delay be absorbed by interfering with the flow or pace of following trades such that the project is not delayed?

Although the questions were not stated explicitly in regard to the term criticality, they suggest the emphasis on flow and task continuity when considering float and delays in LBM.

An additional type of float exists in LBM. Harmelink and Rowings (1998) described the concept of productivity float in LBM as they introduced the *controlling activity path* to LBM. The result provides project planners with information about where production rates can be decreased without affecting the project duration, and illustrates the segments of the tasks that must be planned and controlled carefully. One entire continuous task might not be critical for all locations and at all times. Therefore, Harmelink and Rowings defined controlling segments by specifying critical vertices on controlling tasks, thereby dividing tasks into critical and non-critical sections. Further, they established a principle for controlling activities in linear scheduling modeling, which is branded the controlling activity path. Harmelink and Rowings (1998) argued that the absence of criticality in linear scheduling is one reason why the location-based methodology has gained little influence in the construction industry.

Harris and Ioannou (1998) described a concept similar to the controlling activity path of Harmelink and Rowings (1998). Using the repetitive scheduling method (RSM), Harris and Ioannou (1998) described how the controlling sequence of RSM is different from the critical path because it includes the demand for resource continuity and may include both critical and noncritical activities in terms of float (Harris and Ioannou, 1998). RSM includes the concepts of control points and a control sequence. An activity is considered critical even if it does not affect the project's completion time, given that it ensures continuity for subsequent tasks.

The slowest task is critical

Carr and Meyer (1974) do not explicitly treat the concept of criticality, instead explaining that the slowest activity in a line of balance (LOB) schedule is critical because any reduction in productivity will delay the project. Thus, if all activities have the same maximum production rate, then all activities are critical (Carr and Meyer, 1974). However, the project will be vulnerable to disturbances if all tasks are aligned with the same production rate because changes to some tasks will have a significant effect on later tasks if no float is incorporated in the schedule (Carr and Meyer, 1974). Production buffers are used to protect tasks from local disturbances (allowing time for local control actions); however, systematic errors in production require systematic control actions. Section 2.8 further elaborates on the use of buffers.

Further, Peer (1974) stated that one important step in construction planning is to balance the production rates of non-critical flow lines with the critical ones in order to achieve work continuity, as mentioned in section 2.4. Failure to align production rates can cause either waiting time for some crews or discontinuous work, as described in section 2.4. According to Peer (1974), the slowest flow line will dictate the pace of remaining tasks in a fully optimized and aligned location-based schedule. However, Peer (1974) did not account for other aspects that make activities and tasks critical when scheduling and controlling projects from the LBM methodology. Nor did he elaborate much on the reasoning behind the importance of the slowest critical task. Some descriptions of constraints and aspects such as the importance of the slowest task are accordingly present in current literature. However, a collected criticality principle similar to that of CPM does not exist. The impact of the constraints on a project's lead time including the reasoning behind and importance of the slowest task has not been related collectively to criticality. Accordingly, the criticality principle of LBM has not been defined collectively in the current literature. This led to the formulation of the first research question. Further, because no collected criticality principle exists, no current literature describes how the principle differs from the activity-based method and how it can affect the scheduling and control effort. This led to the formulation of the second research question.

The association of the inherent constraints in LBM to criticality of activities and the importance of the slowest critical task is presented in Part IV, which also describes the effects on the prevailing scheduling and control efforts.

2.8 Buffers in location-based management

The use of buffers in LBM is another important topic in this thesis, and should be seen in continuation of the discussion on criticality. The discussions about criticality introduced the notion that fully optimized location-based schedules are highly sensitive to disturbances, as all flow lines will align and any delay on any task will cascade through the network of activities and tasks (Jongeling and Olofsson (2007); Seppänen (2009)). The following section is similar to the description in the fourth article.

Kenley and Seppänen (2010) defined a buffer as follows:

The additional absorbable allowance provided to absorb any disturbance between two activities or tasks as a component of the logical connection between two tasks.

In this instance, it is important to distinguish between buffers and float. Float (See section 2.2) may be used as a time contingency that incorporates flexibility for non-critical tasks (Uher, 2003). Although float is not technically a buffer, it is a significant contributor to the inherent risk in a schedule and can be utilized as time contingency in some circumstances. Whereas float arises due to technical constraints in a schedule, buffers are purposefully incorporated into schedules as absorbable allowance.

Current LBM theory only incorporates free float. Kenley (2004) stated that the concept of total float fails when location-based scheduling is applied. Considerations of total float become irrelevant because of the requirements of continuous work and resource constraints. Consequently, the concept of float is limited to free float. Kenley (2004) defined free float as *the amount of time that an activity may be delayed without affecting any other activity.* In contrast, *total float is broader and includes any delay that would not delay the entire project* (Kenley 2004). Thus, the protective features in LBM include buffers as well as free float, but it is important to distinguish between the two.

According to Kenley and Seppänen (2010), a task should be provided with a significant buffer if:

- The predecessor to a task has high variability
- The work is planned to be performed continuously
- General knowledge of a subcontractor is limited if they have multiple internal or external jobs
- The locations are small (smaller locations entail higher sensitivity and, thus, greater risk, although small locations can be used to optimize a schedule and reduce lead time); and
- Tasks have little or no float (if they are critical).

In contrast, Kankainen and Seppänen (2003) suggested that only activities and tasks with high sensitivity should be given time buffers. The allocation of buffers to sensitive tasks should be determined in collaboration with subcontractors (Seppänen et al., 2010).

Seppänen and Kankainen (2003) stated that LBM emphasizes minimization of disturbances by allowing buffers between activities and by creating collective activities. For example, buffers are used to protect against unforeseen events and productivity fluctuation. Multiple types of buffers exist in LBM. Lumsden (1968) defined two types of time buffers for line of balance scheduling that still apply in LBM: activity buffers and stage buffers. Additionally, LBM includes location buffers (Russell and Wong, 1993) and project buffers.

Activity Buffers

Lumsden (1968) defined an activity buffer as *an allowance included in each activity time estimate to cater to, for example, random differences in productivity, for receiving and dispatching components, and recreational breaks.* The activity buffers protect the flow and continuity of individual tasks against disturbances, and are not supposed to absorb major recurrent faulty productivity estimates. Activity buffers are applied to each activity in order to protect against minor incidents and fluctuations in productivity. Lumsden (1968) provided the following simple example to explain the extent to which an activity buffer protects tasks in LOB.

No. of units: 50

No. of crews: 1

Activity duration (50 repeating activities within a task): 24 hours

Buffer for the entire task: 16 hours

Actual activity performance: 26 hours per unit

Overrun per unit: 2 hours per unit

Maximum no. of protected units by the buffer: $\frac{\text{16 hours (buffer)}}{\text{2 hours per unit (overun)}} = 8 \text{ units}$

Thus, subsequent activities after the eighth unit will be delayed. Consequently, the cost of the buffer should be compared with the cost of a time delay and analyzed in the context of cash flows. The link with cash flows is outside the scope of this thesis, although it will be briefly presented in the latter part of the present section.

Stage buffers

Stage buffers are used between major stages in projects to protect against unforeseen events such as the weather. The buffers are used to protect continuous workflow and succeeding tasks. Figure 25 illustrates how stage buffers are applied to a project. In this example, the buffer between the first and second stage will increase because stage 2 is completed at a slower rate than stage 1. Contrarily, the buffer between stage 2 and stage 3 diminishes for the later units because stage 3 is completed at a faster rate than stage 2. Figure 25 is an example from Lumsden (1968) and is shown in LOB. The principle is the same in LBM, although it is depicted with one line per task. The stage buffer is intended to be used between substructures. Contractors can speculate on accelerating different stages to build up buffers before subsequent stages. The extent of stage buffer size can be assessed similarly to the example given for the activity buffers. However, the use of stage buffers must also be compared with cash flows quantified.

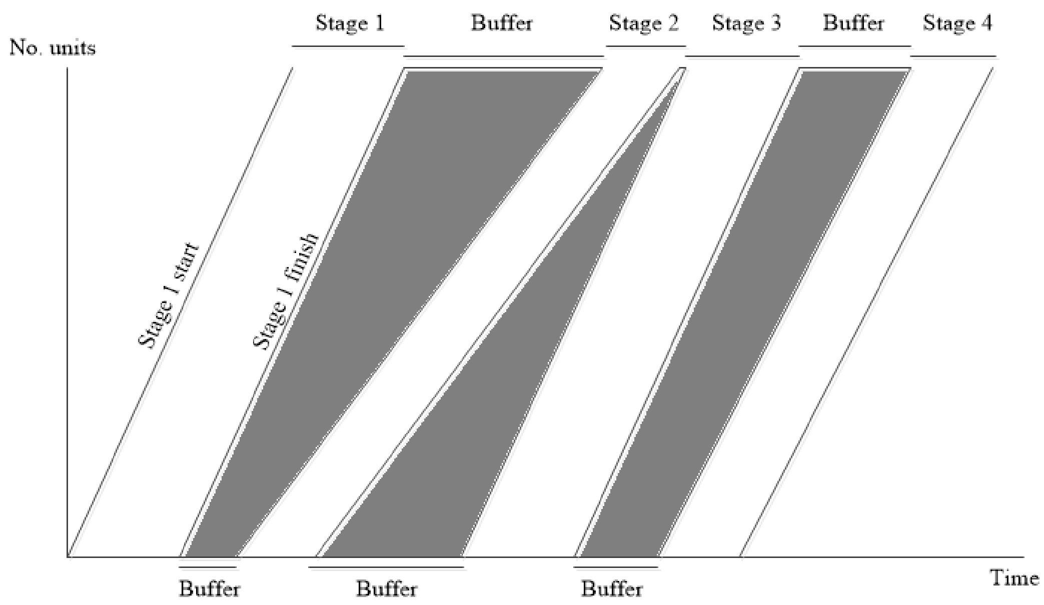

Figure 25: Stage buffers in a LOB diagram. Lumsden (1968)

Location buffers and project buffers

LBM also contains location buffers (Russell and Wong, 1993), as mentioned previously. Location buffers represent available work places at which crews can work if they encounter problems in other areas. With location buffers, crews can continue working despite unforeseen incidents at specific locations. The location buffers are depicted horizontally in the LBM diagrams.

The final buffer that LBM utilizes is project buffers. Project buffers are applied at the end of schedules to protect the final deadline from delays.

Size of buffers

Kenley and Seppänen (2010) stated that it is easy to size buffers if all tasks are aligned because the buffers remain constant for every location. If a two-day activity buffer is allocated to a task, the buffer size will be two days in every location. Therefore, the buffer size of an entire task only prolongs the project’s lead time by two days, regardless of the number of locations. It is more difficult to size buffers if quantities vary across locations because the amount of required performed work differs significantly. Kenley and Seppänen (2010) stated that buffers are always necessary in LBM if variability exists in the production system. A complete lack of buffers creates sensitivity in the system because delays propagate through each remaining work process.

A larger number of time buffers indicate less risk because the buffers absorb delays. However, consumed buffers also inevitably prolong a project's completion time. Buffer sizing should be determined by comparing the expected cost of delays to the additional cost of operating the site and other expenses that follow from the extended lead time the buffer imposes to the project (Lumsden 1968). Figure 26 shows the principle idea, which links the cost of a buffer to cash flow. A buffer simply delays the start of succeeding tasks, which should minimize the cascading effects of the predecessor. The break-even point (dots in the intersection between cost line and income curve) moves because the construction company has to finance the project for a longer period.

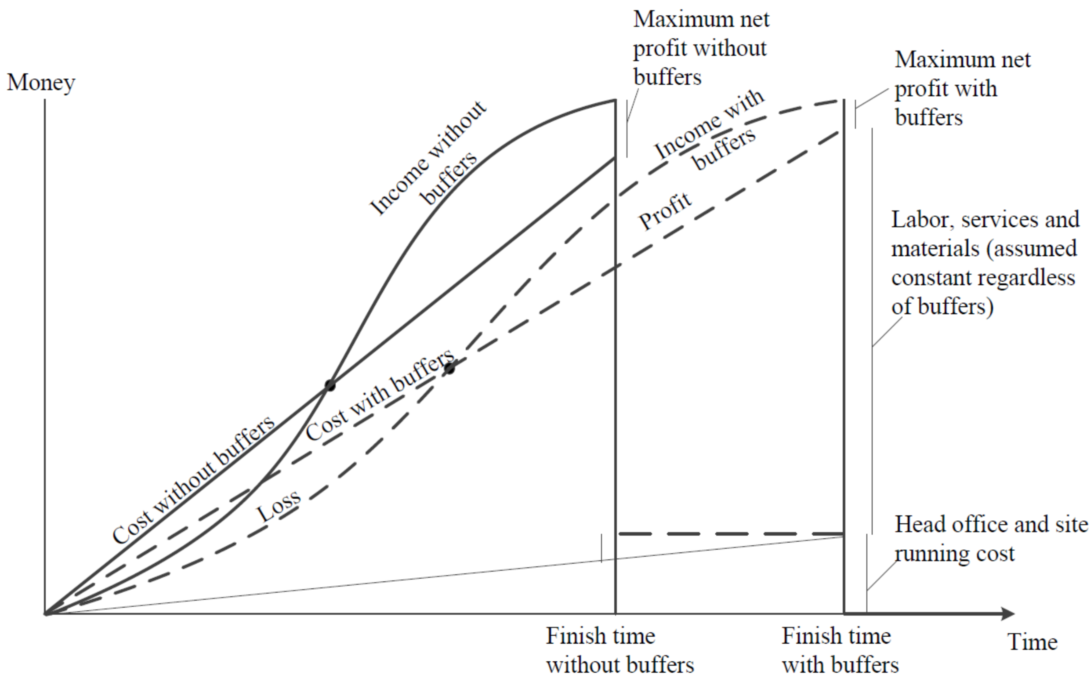

Figure 26: Influence of buffers on cash flow (adapted from Lumsden, 1968).

Sensitivity

Reducing activity buffers can significantly increase sensitivity in schedules to fluctuations in productivity, which can result in discontinuous work. Therefore, a key issue is to determine the sensitivity of each critical task.

Kenley and Seppänen (2010) presented a procedure for determining the sensitivity of tasks and activities. The procedure is based on Monte Carlo risk analysis. In other words, the schedule is simulated thousands of times to determine the sensitivities within a schedule. The procedure from Kenley and Seppänen (2010) is as follows:

1. *Align and optimize the schedule and define critical activities.*
2. *Define the variability associated with each task.*
3. *Run the simulation.*
4. *Observe expected cost and risk level. If the risk analysis is satisfactory then stop. Otherwise, continue to step 5.*
5. *Allocate available buffers to the critical tasks.*

6. *Increase the buffer size for tasks with a high probability of interference, including non-critical tasks. (The sum of buffers allocated to the critical tasks should be less than or equal to the total project buffers.)*
7. *Go back to step 3.*

This procedure provides a basic method for evaluating the sensitivity of critical tasks and ensuring that activity buffers are only allocated to the most sensitive activities.

Advantages and disadvantages

Seppänen and Aalto (2005) stated that time contingency is needed when project schedules are created with a rough level of detail, because they provide flexibility. Imposing additional time contingency will however constitute potential waste that can prolong a project's lead time. Lumsden (1968) also recognized this disadvantage of buffers, but argued that the cost of buffers is low compared with the cost effect on the project if multiple activities are affected by delays. Lumsdale (1968) summarized the advantages and disadvantages as follows:

Advantages:

- Each task is buffered by virtue of the difference in time between the standard performance and the target allowance.
- Activity buffers protect the project work flow at the activity level; in other words, microscopically.

Disadvantages:

- The planned project duration is increased.
- Consistent achievement during initial stages creates the temptation to bring forward subsequent work, which is associated with some risk because the buffer will lose its effect if subsequent tasks are started early. The previous example showed that a small overrun of two hours per unit consumed the entire buffer and protected only the first eight units. Therefore, it is dangerous to start subsequent work early.
- The activity buffer does not protect against major delays such as bad weather.

According to Lumsden (1968), the last of these disadvantages should be countered with stage buffers.

Buffers in this thesis

The work with buffers arose from a need for guidelines in fully optimized location-based schedules. Although LBM contains theoretical recommendations for the type of buffers that can be applied, a gap exists because there are no recommendations for prioritizing the placement of these buffers. This gap, along with criticisms from critical chain theory on the application of buffers such as those in LBM, provided the third research question (Section 1.4), which is addressed in the fourth article of this research project. The theory on CCT is elaborated below, but is explained in greater detail in the fourth article.

Critical chain buffer management theory

Critical chain theory (CCT) is a management theory that was forged from the theory of constraints (Goldratt, 1988) by Goldratt (1997). CCT provides theoretical considerations on the application of buffers. Although Kenley (2004) and Seppännen (2009) have suggested that CCT be explored in relation to LBM, CCT has not been applied in a LBM context. The CCT operates with several key subjects in relation to buffer management. The CCT argues that the buffer management equal to that of LBM is ineffective in protecting projects and causes buffers to become inherent waste in the projects. In short, CCT recommends that activity duration estimates be reduced to a confidence level of 50 percent and that deadlines and milestones be removed to counteract tendencies towards procrastination. In other words, the estimates should have a 50 percent assumed chance of being meet, and deadlines should be removed to ensure that work is not performed slower than possible. In addition, the *critical chain* of activities should be protected from non-critical chains with *feeding buffers* and the project deadline should be protected with project buffers. The CCT also focuses on protecting the bottleneck task, which in this research is related to the subject of criticality. Further details and reasoning behind the recommendations can be found in the fourth article.

2.9 Control with location-based management

A significant difference exists between scheduling and control in location-based methodology with respect to flow lines. Schedulers strive to make parallel lines with a distance that fulfills the requirements of time optimization (short distance between the lines) and risk reduction (buffers). In contrast, controlling projects is a different matter. Russell and Wong (1993) acknowledged this concept in their tests with construction companies in Canada.

We were quickly disabused of the notion that real-life projects followed the nice, neat parallel lines of a pure flow model or for that matter, the precision portrayed by the traditional network diagram (Russell and Wong, 1993).Consequently, the typical straight lines in the schedules are an ideal to which practitioners can strive in the dynamic and ever-changing environment of construction control.

Kenley and Seppänen (2010) suggested an overall control process that is illustrated in Figure 27.

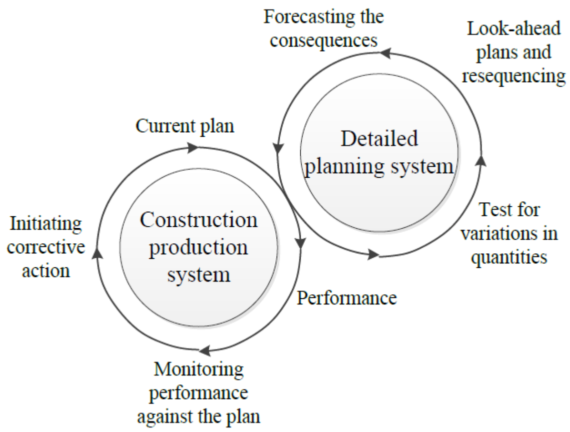

Figure 27: Control process from Kenley and Seppänen (2010).

The aim of the LBM control process is to *assess the progress of activities against target acceptable date ranges and to assess the effect of time variations on the network through recalculations* (Kenley and Seppänen, 2010), as well as to forecast performance problems and evaluate the feasibility of alternative control actions (Seppänen and Kenley, 2005) and then implement them. Progress reporting and forecasting are two important aspects to this thesis and are elaborated in the following sections.

Progress reporting and management

Seppänen and Kenley (2005) noted that there are three reasons for recording actual performance:

1. To evaluate the immediate need for control actions
2. To learn the correct production rate for future projects
3. To estimate the productivity effects of control actions, deviations, and process improvement initiatives

Seppänen and Kenley (2005) suggested a hybrid system that combines percent plan complete (PPC) and the flow line method. This combined approach exploits the benefits of both approaches by allowing practitioners to record progress in PPC for larger locations when tracking completed units for small locations. Such recording is important because performance measurement is typically linked to the payment plans for both contractor and construction crews, which may cause optimism in the PPC data recording. Tracking and focusing on completed units or locations prevents the PPC from being manipulated in favor of either contractor or construction crews.

During progress management, planned production rates are adjusted to the actual production rates by increasing or decreasing resources. Such adjustment supports continuous production and ensures better forecasts.

Forecasting

Forecasting is especially relevant in relation to the third article on criticality, as the layer 1 dependencies (see section 2.6) between activities in activity-based methods affect the perception of criticality.

The forecast in LBM is different from an activity-based forecast because it uses previous production performance metrics to estimate future performance. The justification for this link is that the same resources produce approximately at the same rate in similar locations. The weight given to the performance in the last location is three times that of its predecessor, which is common in location-based control. This means that the latest performance has the greatest impact on the forecast of a task, which should arguably provide a more realistic forecast than using original planned estimates to forecast future performance. Figure 28 illustrates a situation in which three tasks (tasks 10, 11, and 12) are linked by Finish-Start dependencies on the third level in the location breakdown structure. The thick lines indicate the planned durations, while the dotted lines indicate actual performance and the dashed lines indicate the task forecasts. The example shows the effect of tasks 10 and 11 starting late. Task 11 was even started in the second location before the first location was completed. The dashed lines for tasks 10 and 11 show that the progress is expected to be slower than planned given the actual performance in the first locations. Figure 28 also shows how task 12 is forecasted to become discontinuous if no preventive actions are taken. Task 12 cannot retain its continuity given the delays in tasks 10 and 11 if the task must start as early as possible.

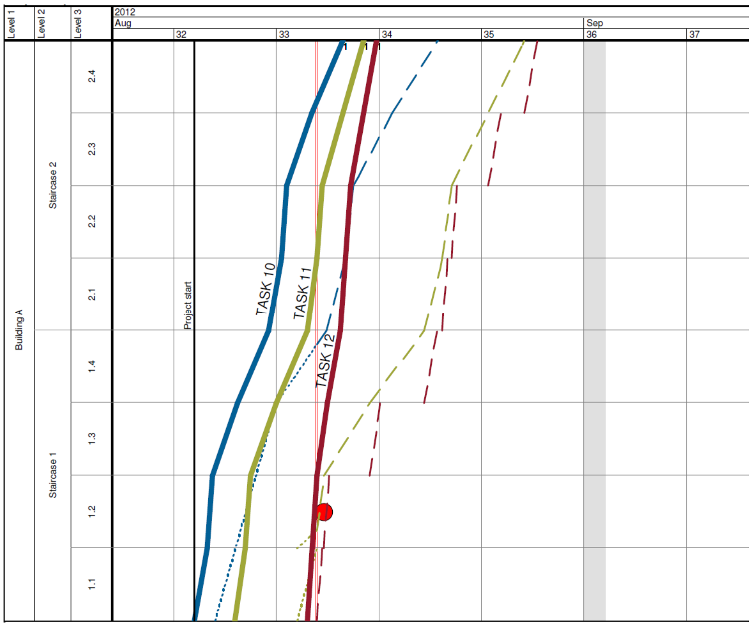

Figure 28: Location-based forecasts.

The forecasts in LBM are important to the practical implications of the recommended criticality principle of LBM, which is described in section 4.2

Causes of delays and control actions

Seppänen and Kankainen (2004) researched construction projects to comment on the types of causes for delays encountered by a location-based controlled project. Although these causes might also apply in activity-based schedules, Seppänen and Kankainen (2004) defined generic causes for delays in the LBM terminology that include the following:

- Start-up delays
- Slow progress
- Working at multiple locations at the same time
- Wrong completion order, which causes flow problems

Kenley and Seppänen (2010) later added the following three causes to the list:

- Quantity changes
- Discontinuities in general
- Production prerequisites (such as insufficient design project)

If the progress of a project fails to follow the location-based plan, several countermeasures may be implemented. Possible control actions include changing the amount of resources on a task, working overtime, changing location sequences, splitting locations into smaller sections and adding crews, producing simultaneously in the same locations, or removing technical dependencies (Seppänen and Kankainen, 2004; Kenley and Seppänen, 2010). Kenley and Seppänen (2010) provided a procedure for evaluating the seriousness of deviations. The following list suggests how activities and tasks may be ordered in terms of criticality:

1. Temporal proximity to *interference point*:
    a. Calculate the number of days to the interference point.[8]
    b. Compare the safe reaction time allowance; in other words, the expected time needed to implement safely corrective actions.
    c. If the interference point is closer than the safe reaction time allowance, go to step 2; otherwise, go to step 3.
2. Calculate the seriousness of the interference:
    a. Find all tasks and locations that will be affected by the interference.
    b. Find the minimum total float of locations affected by the interference.
3. Forecast the total float of the activity itself.

This procedure suggests the importance of float calculations and criticality when controlling in LBM.

[8] An interference point is a point in time at which subcontractors for subsequent tasks are forced to work discontinuously.

Part III – Research Process, Method, and Philosophy of Science

Part III explains the way in which the research was conducted and the principle philosophical underpinnings of the research; that is, the epistemological and ontological considerations. Therefore, the purpose of Part III is partly to describe the research process and partly to explain the theory of science behind the empirical findings and results.

3.1 Introduction

Bunge (1985) argued that the gap between philosophy and technology is being partially bridged by making scientists more aware of the philosophical presuppositions, hypothesis, basic concepts, procedures, and implications of their own research. The philosophy of science has shifted towards a more sociological approach, in which *facts are said to be the creation of researchers, who would act only in response to social stimuli or inhibitors; there would be neither norms nor objective truth* (Bunge, 1985).

The purpose of this section is to present the ontological, epistemological, and methodological considerations of this research project. The objective is to ensure consensus on the premise upon which the project is created and to comment on the quality, validity, and rigor of the research. These elements are necessary in all research, but they cannot be analyzed and justified without knowledge of the applied ontology, epistemology, and methodology. Part III contains the following parts:

- Terminology
- Research process – systematic combining and abductive logic
- Discussion of socio-technical research
- Relationship between purpose and research typology
- Governing research paradigm – constructivism
- Governing research methodology – qualitative research
- Discussion of primary method – case studies
- Discussion of trustworthiness in constructivist research

Selection of and explanations for specific orientations to the project are made after each theoretical topic has been described.

3.2 Terminology

This section briefly introduces the most significant terms in the philosophy of science in order to express how the terms are applied and understood in this thesis.

Research paradigm – The word "paradigm" is used in many ways. Masterman (1970) identified 21 meanings used by Thomas Kuhn, who coined the term in 1962 (Kuhn, 1962). Because no consensus has yet been reached in the scientific community regarding the use of the term, the present work uses the following definition from the Oxford English Dictionary (2012): *A world view underlying the theories and methodology of a particular scientific subject*.

Methodology – A methodology contains the valid methods with which to execute the research in a research paradigm. Guba (1990) described this term by asking: *How should the inquirer go about finding out knowledge?*

Method – A concrete practice for carrying out research.

Ontology – Ontological considerations regard how a scientific discipline views the existence of the observed. Ontology deals with the nature of reality (Guba 1990). The difference becomes distinctive in different research paradigms and is an underlying philosophical consideration of what entities the discipline believes should be observed. In social research, for example, the central question is whether social entities should be considered as objective entities or social constructs (Bryman 2012).

Epistemology – Epistemology deals with common understandings within a discipline of what knowledge is and what can be known (Bryman 2012). Guba (1990) asked: *What is the nature of the relationship between the inquirer and the known?*

3.3 Research Process - Systematic Combining

Case studies are the primary research method in this research project, which originated with no predetermined goal. Consequently, the standardized subsequent phases of natural science research did not support the advantages of case studies, as new findings constantly affected the direction of the research. The research process diverged from strict deductive (development and test of propositions from theory) and inductive research processes (generation of theory from data) to accommodate a more iterative process of combining theory and empirical observations, as described by Dubois and Gadde (2002). Because case studies develop over time, the author of the present thesis continuously increased his understanding of the observed by addressing the research environment and the theory. As Dubois and Gadde (2002) put it, *Theory cannot be understood without empirical observation and vice versa*. Theory and empirical observations have been combined repeatedly to contribute to the researcher's understanding. Accordingly, the interrelatedness between theory and empirical observations in this research has not followed predetermined phases in the research process. Dubois and Gadde (2002) referred to this *abductive* process as *systematic combining*.

The main purpose of systematic combining is to comment on and improve theory. However, testing theory is also a part of the process. Figure 29 shows the driving model for this process. The model centers on matching theory, cases, the boundaries of the empirical world, and the research framework. It encourages an open process that combines data and analysis in recurring events with no initial predetermined goal. The goal becomes apparent as theory is understood and empirical observations are made and analyzed. Systematic combining relies on multiple data sources and encourages triangulation. Methods such as interviews, quantitative data, and reports have applied in this research in order to inform the research process from more than one angle and to provide a more elaborate and convincing case study as recommended by Yin (1994).

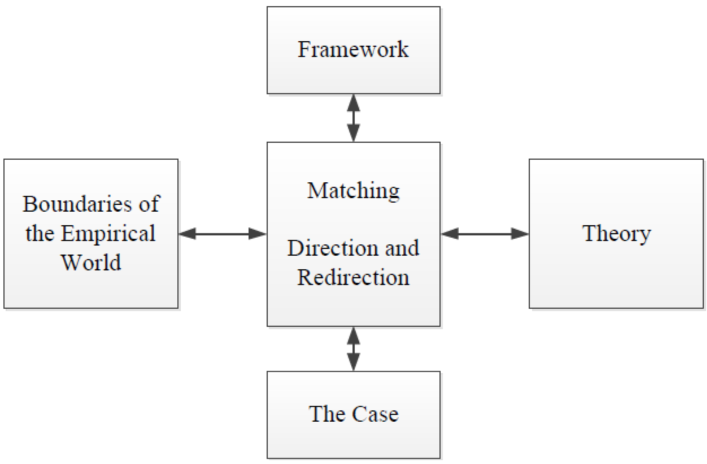

Figure 29: Systematic combining (adapted from Dubois and Gadde, 2002).

The Boundaries of the Empirical world

The interdependent variables in open case studies are numerous. This is why the boundaries of the empirical world have to be delimited, for example, to the case company and building projects (See section 1.5). The empirical boundaries have not been fixed throughout the research process; instead, they have changed as the research has evolved and redirected. The boundaries for each case study and other parts of the systematic combining process are explained after this general description.

The Role of the Framework

The framework in systematic combining describes the guidelines for the case study. Miles and Huberman (1994) suggested that two types of frameworks have emerged that fit with deductive and inductive research. One is tight and prestructured, while the other is loose and emergent (Dubois and Gadde, 2002). In contrast, the framework in systematic combining is tight and evolving. The tightness should reflect *the degree to which the researcher has articulated his "preconceptions"* (Dubois and Gadde, 2002). The framework should be evolving because empirical observations affect theory and theory affects empirical observations. The researcher is expected to learn from either theory or observations, which will initiate new observations or affect theory, respectively.

The Case in Systematic Combining

Apart from general theory on case studies, systematic combining emphasizes the evolution of cases; cases evolve until the final goal is clear and the case can be created as an end product. Therefore, the case is initially regarded as a tool, and forms the end product once the researcher has dissected the case and identified clear points of the case study. Rather than being a broad description of everything that has been observed, the case study represents the findings made clear by the framework. This research consists of four interrelated individual case projects. Some observations that have been made between actual case studies are explained further in section 3.4.

Theory in Systematic Combining

Dubois and Gadde (2002) referred to Strauss and Corbin (1990) when they described the role of theory in systematic combining. According to Strauss and Corbin (1990), the role of theory is either confirmatory or generating. A researcher adopting the confirmatory approach to theory can identify previous research within the relevant field of study and discover weaknesses in it. Theory can also provide a framework for new studies or explain phenomena. The aim of systematic combining is to generate theory more than to test it; that is, to add new aspects to theory or generate a completely new theory. It is the framework that guides the generation of theory. Theory in systematic combining is an ongoing development. The researcher's knowledge of literature must also develop. The researcher does not have to read all of the existing literature in order to initiate the research process; instead, the ongoing evolving research process involves the researcher learning what new theory is relevant as the process proceeds. This means that systematic combining is closer to inductive research than deductive research. However, some parts of the research process are likely to contain deductive work, which is also the case in this research process.

3.4 Systematic Combining in Practice

The present thesis is based on four main case studies, all of which have been documented in scientific articles. Each of the four studies has sub-processes that are united through an overall research process. Figure 30 summarizes this overall process and signifies the primary input and output of each case in relation to the five aspects of systematic combining. The case studies have provided input to subsequent case studies; however, new thoughts and observations have emerged between each case study, which has also provided input. The researcher has been situated within the case company in three years and has been involved with or investigated 44 construction projects. Figure 30 also illustrate deselected topics and problems. The following sections describe the purpose, research method, research process, and relation between each study through the five aspects of systematic combining. The description of each research process has been copied and only altered slightly from each of the scientific articles.

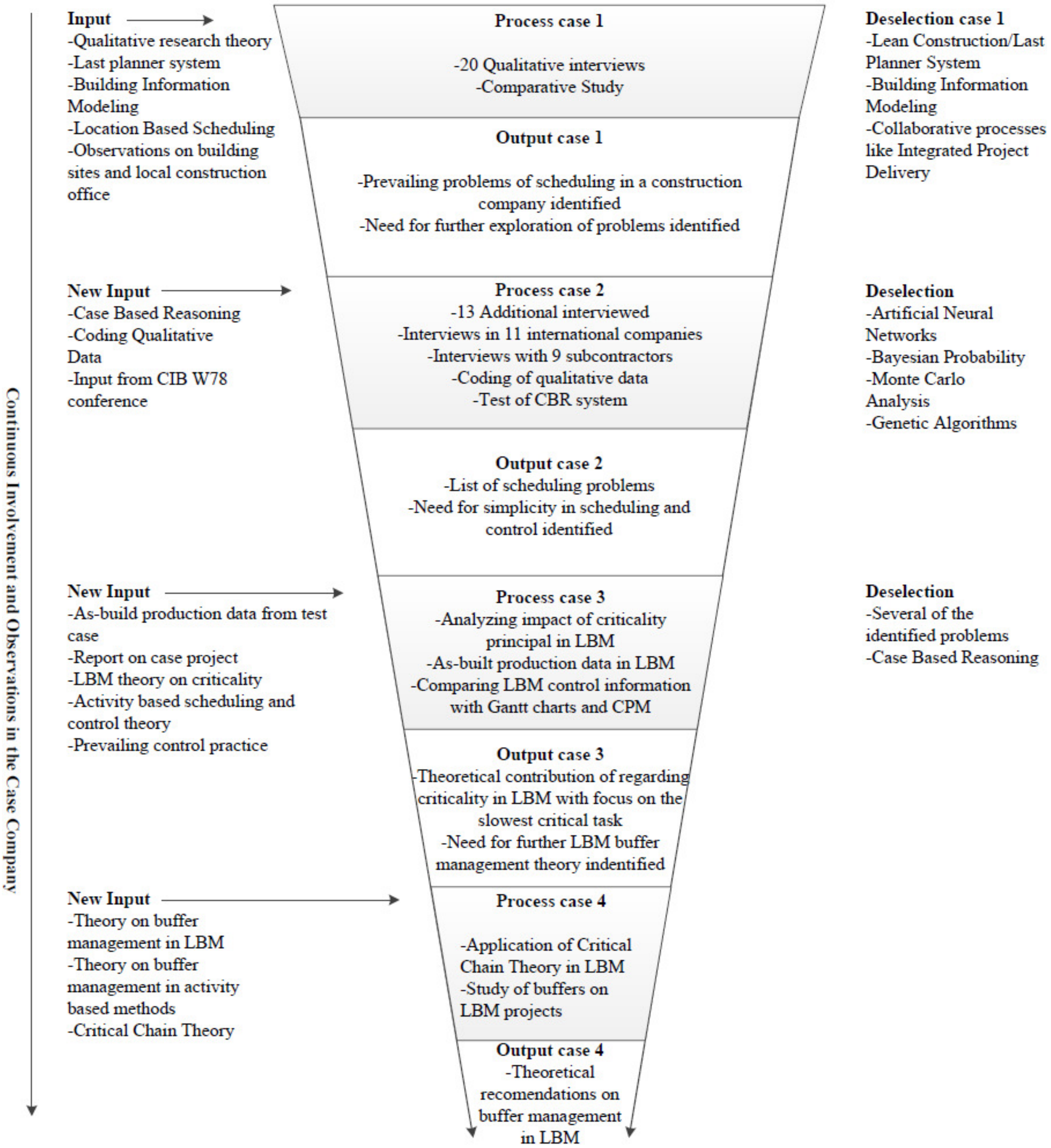

Figure 30: Overall research process.

First Case Study

Purpose

The first study aimed to uncover problems and best practice of scheduling in the case company and is documented in the first article. The initial intention of the study was to relate the identified problems to knowledge of existing technical solutions (such as BIM), scheduling and control techniques (such as LBM), and organizational and procedural solutions (for example, the Last Planner System), in order to identify the core problems that lacked attention. The purpose was to identify and analyze the problems.

Research method and process

The first study was purely explorative. The empirical foundation was based on qualitative interviews, including both individual interviews and focus group interviews. In total, 20 people from one major construction company participated in the interviews. All participants were selected based on their field of expertise, age, and knowledge of planning and scheduling.

Firstly, individual and focus group interviews were performed with a focus on the challenges and best practice involved when scheduling construction projects. These interviews included project managers, process managers, and contract managers who represented the operational and tactical level of the company. All interviews were exploratory and followed a guide with open-ended questions and discussion topics that covered the entire scheduling process, from input of information to schedule creation and schedule output. The input portion of the interviews included discussions on quality, availability, structure, sources, and the scope of the information needed for scheduling and progress control. The processing portion of the interview covered subjects such as responsibilities, work distribution, cooperation, and relationships with other management processes. Subjects concerning scheduling output focused on scheduling approaches, diagrams and reports, communication ability, manageability, distribution, and understanding the scheduling results.

The next step involved presenting the same subjects to the interviewees with strategic responsibilities. Participants in this focus group included representatives from top management and senior management, all of whom had comprehensive knowledge of scheduling. The interview guide from the first group of interviews was used. However, as these interviews had a strategic focus, this second round of interviews generated completely different outcomes. The purpose of the strategic interviews was to gather information on the long-term effects of the challenges and best practice of scheduling on the organization.

The interviews were coded through open coding (Corbin and Strauss, 1990) and sent to all interviewees to obtain confirmation of the correctness of the coding results.

Connection to the second case study

The study revealed numerous scheduling problems, including:

- Discrepancy in scheduling between the tender and construction phases.
- Schedules are based on personal experience and intuition. Few figures and data are applied.
- Knowledge from previous schedules is not reused. The case company does not continuously improve scheduling.
- Insufficient design coordination causes insufficient designs, which limits the ability to establish rigorous schedules.
- Creators of the schedules struggle to comprehend the amount of information that has to be incorporated into the schedules. The designs are difficult to assimilate and use as a basis for scheduling.

The study contributed to the overall research process by uncovering problems that needed attention, in order to justify further research. In particular, this included the ability to schedule quickly and rigorously in the early phases of construction projects. BIM and Lean Construction initiatives were not pursued further. It became obvious that BIM, in this research project, should be seen as a tool, albeit one that clarifies and uncovers challenges in the case company when implemented. BIM also provided the solution to some of the trivial problems in the case company, such as the communicative abilities of current schedule methods. The Lean Construction methodology and the Last Planner System (Ballard (2000); Ballard and Howell (2003)) were also abandoned, as these initiatives already provided answers to many of the identified problems and it was hard to identify a scientific contribution at the time. The focus shifted solely to improving the ability to schedule more quickly and rigorously.

The paper related to this aspect of the study was presented at the CIB W78 conference in 2010. Fellow researchers recommended that the underlying data from the interviews should be scrutinized again and that each problem should be presented individually. Consequently, the first article was used as a starting point for the second article, for which more interviews were completed and the scheduling problems were elaborated and presented individually.

Figure 31 provides an overview of the content in the systematic combining research process in the first study.

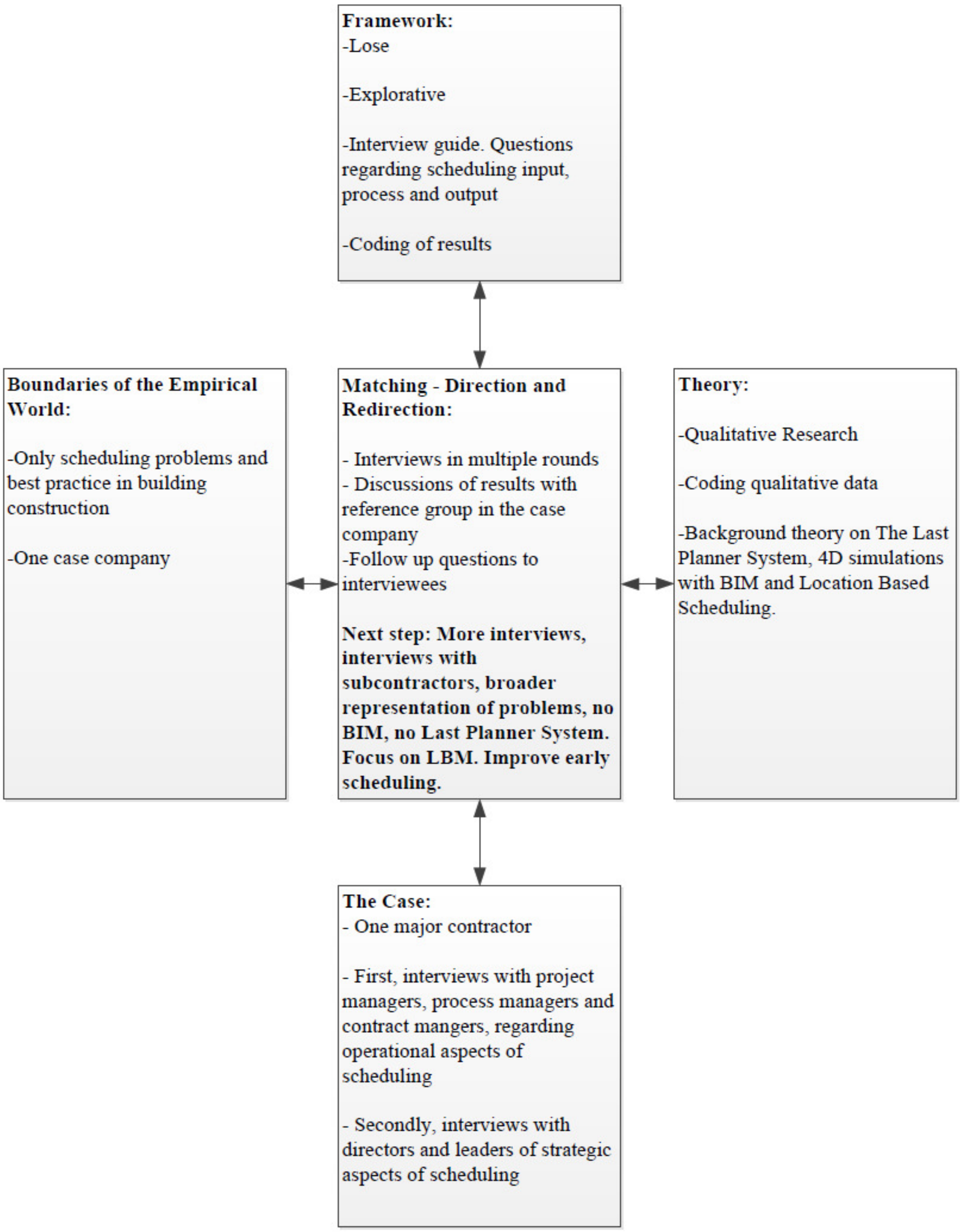

Figure 31: Systematic combining of the first study.

Second Case Study

Purpose

The purpose of the second article was to test CBR as a means of improving the scheduling technique and process in the pre-bid phase, which was identified as a core problem in the first article, as it was associated with great risk and lacked attention, despite its importance to the following phases in the projects. An elaborate description of CBR can be read in the second article. The second study had the following three main objectives: (1) to identify existing major problems related to scheduling at the case company; (2) to explore solutions to the problems at 11 international construction companies; and (3) to explore the CBR methodology to improve pre-bid scheduling. The research contributed to the body of knowledge by describing an example of gaps between current industry-applied technologies and work methods and existing scheduling problems. In addition, the research contributed by describing the experience with CBR to improve pre-bid scheduling, that is scarce in the current literature.

CBR was applied to help identify previous similar schedules that can be reapplied to new projects. The intention was to provide the tender department with a system and method for reusing relevant data, which should save time by more quickly generating schedules in greater detail. The ultimate aim was that the schedules would reduce risk associated with undefined processes. Other methods (namely, Tree Pattern Analysis (e.g., Wohed, 2000), Bayesian Probability (e.g., Kim and Reinschmidt, 2009), Monte Carlo Analysis (e.g., van Slyke, 1963), and Genetic Algorithms (e.g., Long and Ohsato, 2008)) were investigated with the aim of easing and supporting development of schedules from prior production data. These methods were deselected due to insufficient as-built production data and signified unsatisfactory significance levels.

Research method and process

Although the second study overlapped with the first in terms of its research process, it was treated as an independent study. The second study was divided into three sections. Firstly, current scheduling problems in the case company were identified. Secondly, the problems were presented to 11 reference companies to explore their potential solutions. Thirdly, the CBR system was developed and tested.

The first section of the research entailed in-depth qualitative interviews that were similar to those in the first study. The data included the interviews from the first study, while interviews with representatives from nine subcontractors were added. The interviewees were individuals and groups including project managers, process managers, contract managers, and employees from the operational and tactical levels in the company's tender department. Representatives from top and senior management, all with knowledge of scheduling, provided input on a strategic level. In total, 38 individuals participated in the interviews. Some of the research process was the same in the second article as in the first because some of the data overlapped. Data from the interviews was categorized through open coding (Corbin and Strauss, (1990)).

The coding process revealed 15 scheduling problems, which were subsequently presented to BIM experts and planning professionals from 11 reference companies that were identified due to their leading edge work with BIM. The reference companies were involved in order to obtain an indication of the current state of scheduling in the construction industry and to explore whether other construction companies experienced similar problems and how such problems were addressed. The participating companies, characterized by high investments in BIM and as front-runners in best practice work methods, recognized all 15 problems. Because only 11 companies participated, the intention was not to generalize the findings, but to discuss the problems in depth in order to establish a starting point for future research at the case company using scheduling problems that garnered minimal focus. The study selected pre-bid schedules as an area of focus because the reference companies indicated that, although they had ongoing attempts to solve 12 of the 15 problems, they paid little attention to this area. This does not mean that solutions do not exist for the three remaining problems, but instead indicates areas of interest for further study. Moreover, although the authors recognize the existence of many more detailed scheduling problems, the focus remained on providing a case study on the remaining identified scheduling problems at a single construction company. These problems were:

- Schedules are based on intuition and personal experience – no decision support systems exist
- Scheduling does not improve systematically at the company level
- No criteria or measure for quality of the schedules

The CBR methodology was tested as a possible solution for the first two of the three remaining identified problems. The CBR system was developed in cooperation with the tender department of the case company and was later tested by both estimators and project managers. The tender department, estimators, and project managers all saw the advantage of applying a CBR system combined with location-based scheduling. The system could point to similar cases by the use of basic project data. However, the test signified that the underlying design basis was insufficient for reapplying previous scheduling data. The design was generic and lacked project specific details, which prevented estimators and project managers from reapplying more detailed scheduling data from the previous cases. It was not clear whether the scheduling data was applicable to the new design, because the design was not finished. This was a significant finding for the overall research process of this thesis because it deterred further attempts to apply automated systems to improve scheduling. The result of the test clarified that the underlying assumption – that faster creation of schedules in the tender phase lead to improved schedules – was erroneous. Therefore, the test contributed to research process, as it stressed that any attempt to generate new useful schedules from prior data presupposes completed detailed design. While many other studies have relied on this assumption in the quest for automated generation of schedules, they have failed to stress the importance of it. The present research, therefore, pointed towards a more simple solution. The need for a simple and fast approach became clear during the test of the CBR system. Accordingly, the idea of a CBR system for pre-bid scheduling was abandoned and the pursuit for creating schedules and managing projects more simply was initiated.

Connection to the third case study

CBR proved ineffective in its given application, due to insufficient design information. The project information was generic and simply insufficient. Later discussions with the participants of the study from the tender department and from construction sites highlighted complexity as the main hindrance for fast and detailed creation of the schedules. The test indicated that simplicity in the scheduling process is decisive. Debates with other researchers led to a discussion about whether location-based schedules are simpler to create and manage than scheduling and control methods based on CPM and PERT. It was in part, the aligned flow lines of LBM that was the subject of discussion in terms of simplicity, which in turn led to the study of criticality.

Figure 32 summarizes the content of the systematic combining process of the second study.

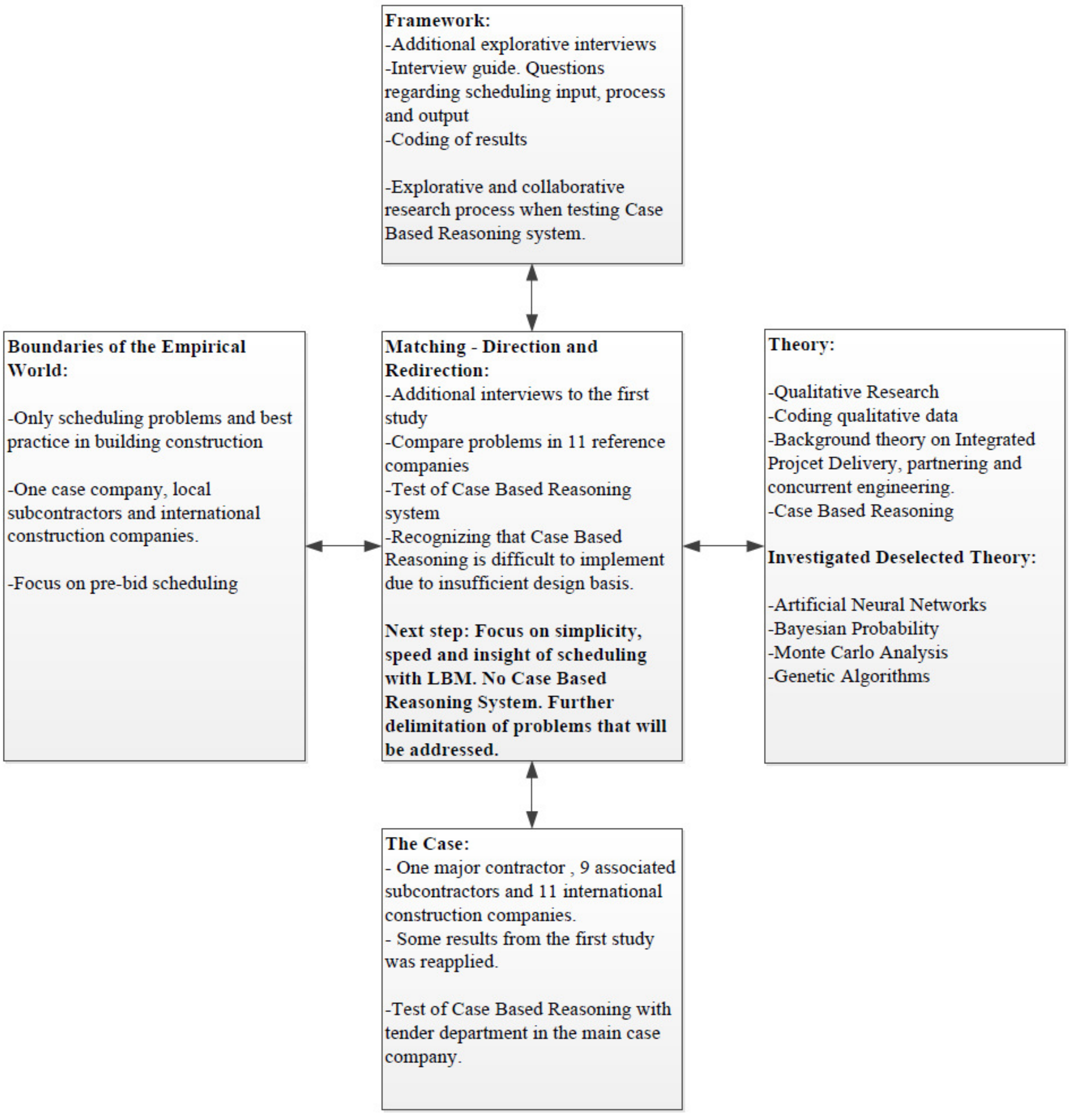

Figure 32: Systematic combining of the second study.

Third Case Study

Purpose

The purpose of the third article was to explore criticality in LBM. The first objective of the third study was to establish the criticality principle of LBM. That is the constraints that determine whether an activity should be considered critical. The second objective was to elaborate on the recommendations provided by Carr and Meyer (1974) and Peer (1974) regarding the importance of the slowest critical task, and provide data to justify them. The third objective was to exemplify practical differences in a case study if the criticality principle of activity-based management had been replaced by the criticality principle of LBM.

Research method and process

The LBM criticality principle was first studied through theoretical considerations of constraints in LBM theory and subsequently explored through a case study. The purpose of the case was to elaborate on the recommendations provided by Carr and Meyer (1974) and Peer (1974) regarding the importance of the slowest critical task, and investigate differences between the criticality principles of activity-based and location-based control methodologies. The case supports and elaborates on the suggestions made by Carr and Meyer (1974) and Peer (1974), and illustrates how LBM can uncover originating problems by identifying the slowest tasks. Both theoretical considerations of the inherent constraints in LBM and the case study provided input for the findings regarding the effects of the proposed criticality principle of LBM. Accordingly, the first and second research questions were answered based on the third article (See section 1.4).

The case project was a seven-story apartment building that was divided into two blocks, referred to in the case description as buildings A and B. The total size was 15,000m^2, consisting of 152 high-end apartments, each of which was between 80m^2 and 120m^2 in size. The entire project was documented during construction by other researchers who made five site visits, each of which lasted for 2–5 weeks. These results were reported in Joergensen (2008). The report describes the entirety of the project, identifies 52 problems and links them in cause-effect relationships. In addition to the report, all managing project participants, schedules, and progress data were available to this research. Both an overall master schedule and detailed schedules were utilized in the project, although the two types of schedules were controlled independently. Progress reporting was performed in an activity-based schedule that contained locations but not with location-based logic and the requirements of flow and continuous resource consumption. Accordingly, the project was planned as an LBM-based project, but controlled as a CPM project containing locations. The progress recording utilized the percentage complete and was recorded approximately 35 times (once a week), in 152 apartments and for 44 activities by a member of the project management team. Figure 33 shows an example of a production data sheet with the percentage completion of 12 apartments in one week. The overall production data was recorded 14 times for 81 activities in a Gantt chart (not shown). The production data taken from the excel spreadsheets and Gantt charts and entered manually in LBM software by the same control chart as described by (Kankainen and Seppänen, 2003).

These types of recordings are important to the perceived criticality of activities, which will be elaborated on in section 4.2.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1														
2	*Staircase 11A*													
3														
4	*Floor and side*	*1st left*	*1st right*	*2nd left*	*2 right*	*3rd left*	*3rd right*	*4th left*	*4th right*	*5th left*	*5th right*	*6th left*	*6th right*	*Total*
5	*Apartment No.*	*71*	*72*	*73*	*74*	*75*	*76*	*77*	*78*	*79*	*80*	*81*	*82*	
6														
7	**Activity**													
8	Wires in shafts	100	100	100	100	100	100	100	100	100	100	100	100	12
9	Water pipes in shafts	100	100	100	100	100	100	100	100	100	100	100	100	12
10	Ventilation in shafts	100	100	100	100	100	100	100	100	100	100	100	100	12
11	Fire protection electricals, shafts	100	100	100	100	100	100	100	100	100	100	100	100	12
12	Water pipe insulation, shafts	100	100	100	100	100	100	100	100	100	100	100	100	12
13	Insulation of ventilation pipes, shafts	-	-	100	100	100	100	100	100	100	100	100	100	10
14														
15	Concrete finish, walls	100	100	100	100	100	100	100	100	100	100	100	100	12
16	Concrete finish, ceilings	100	100	100	100	95	100	100	100	100	100	100	100	12
17	Precast concrete finish	100	100	100	100	100	100	100	100	100	100	100	100	12
18	Facades	100	100	100	100	100	100	100	100	100	100	80	100	11
19	Windows	100	100	100	100	100	100	100	100	100	100	80	100	11
20	Dry walls, steel fittings	0	100	100	100	100	100	100	100	100	100	100	100	11
21	Dry walls, plastering	0	0	0	0	70	100	70	100	100	100	100	100	6
22	Main electricals	30	40	30	40	20	40	20	30	10	10	10	10	0
23	Circuit breaker panels													
24	Pipes, radiators	100	100	100	50									3
25	Heat on	100	100	100										3
26	Closing shafts													
27	Filling and grinding, walls and ceilings													
28	Felt													
29	Spray painting, walls and ceilings													
30	Floors, joists													
31	Floors, floor boards													
32	Floors, covering													
33	Kitchens													
34	Doors and foot panels													
35	Final paint													
36	Final pipes													
37	Final electricals													
38	Final ventilation													
39	Cleaning													
40	Kitchen appliances													
41	Quality assurance													
42	Final corrections													
43	Final cleaning													
44														

Figure 33: Example of production data sheet from the case study in the third article.

Trends

The slowest controlling task of the case project was identified by plotting trend lines for all tasks in the dependency network in the same location-based view. The as-built data was transformed from an activity-based, percentage complete view to flow lines in a location-based view, and was then subject to trend analysis. The as-built progress data in respect to both the external and internal works was plotted into the location-based schedule. Trends can be seen when activity-based performance data is plotted in a location-based view (Figure 34), which shows how completion data for a single task has been plotted for each apartment in a location-based view. Each dotted horizontal line indicates an apartment and progress is shown by the slightly oblique lines for each apartment (Figure 34). The bold trend line indicates the completion of similar activities for each location. Singular extreme cases of slow or fast productivity within few locations were ignored. The trend lines simplify the data to make it manageable. This approach is visual and aims to communicate controlling trends.

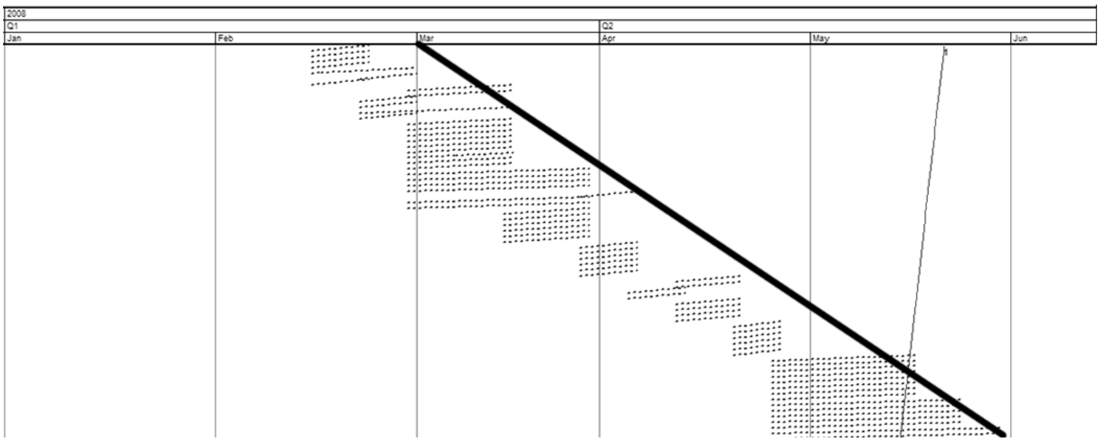

Figure 34: Trends of completion for a single task

All external and internal works data was plotted to form these trend lines. Figure 35 illustrates the overall development of completion for the external works and Figure 36 illustrates the trend lines for completion of internal tasks. Only critical tasks are shown and non-critical tasks are hidden. The results and implications of this data representation are presented in section 4.2. Simplified versions of Figure 35 and Figure 36 can be seen in the third article.

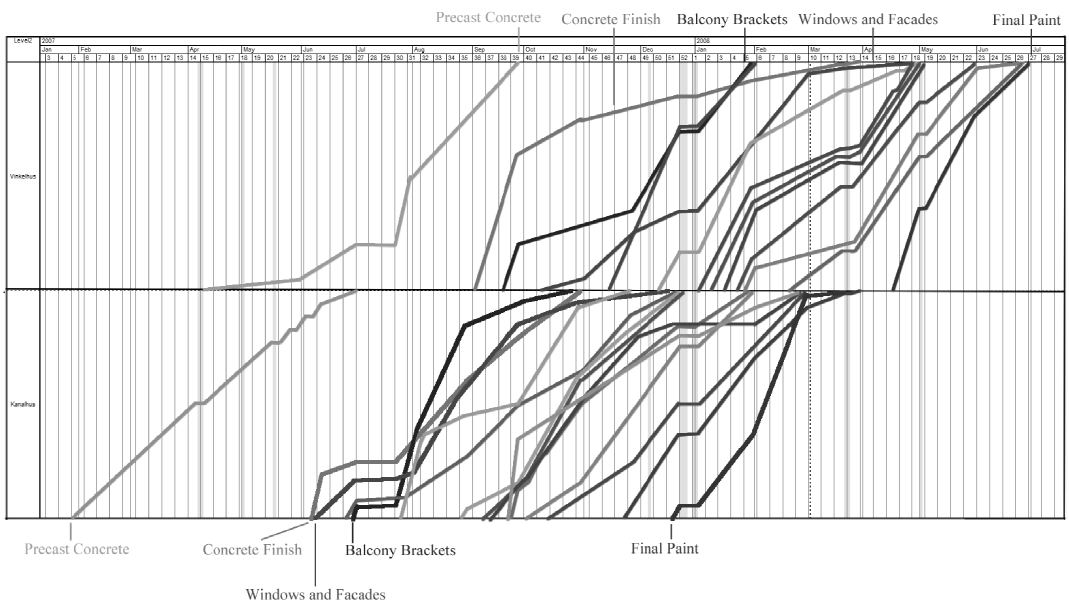

Figure 35: Trend lines of completions for similar activities in the external works.

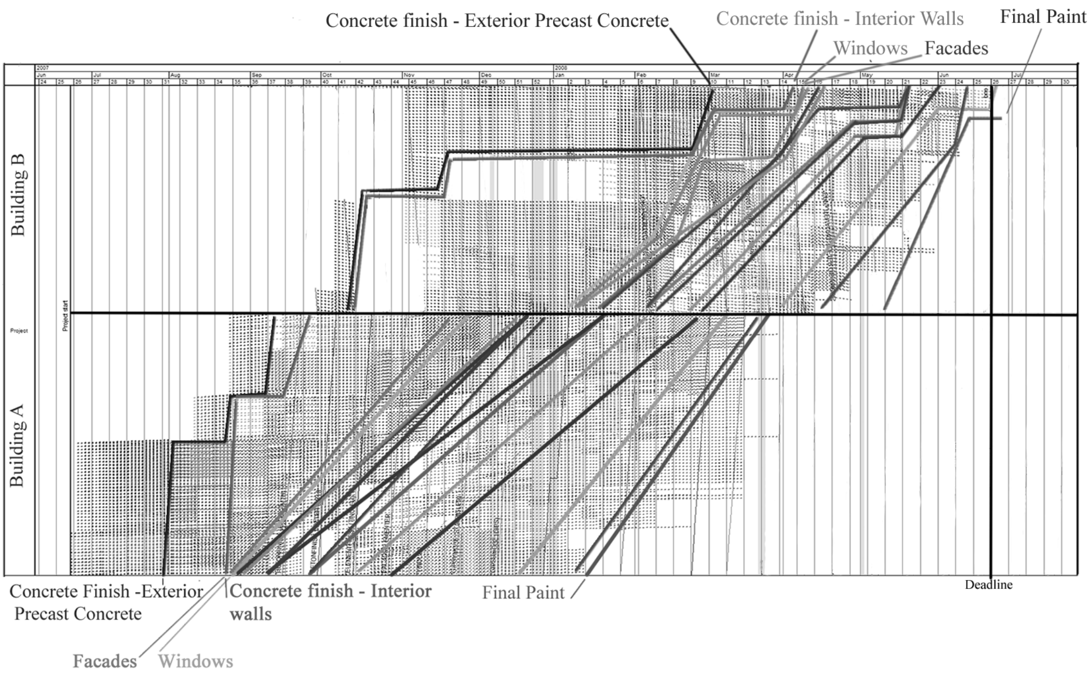

Figure 36: As-built control data in a location-based view with tendencies of task completion for the internal works

Connection to fourth case study

The case study exemplified how the criticality principle of LBM can allow project managers to focus on single slow critical tasks. The commonly applied control methods based on CPM using percentage complete and Gantt charts fail to inform project leaders if late critical activities can be accelerated. Gantt charts only show that an activity is late and by how much. The flow line view in LBM shows how location constraints and continuity constraints limit the progression of succeeding tasks to a critical slow task. The case study utilized actual control data to illustrate the impact of this difference. It is argued in the third article that project managers can use this principle to prioritize critical activities and avoid wasting additional resources on critical activities that cannot be accelerated. Another finding was that location based schedules become more sensitive when they are optimized because the LBM criticality principle imposes additional critical activities into the dependency network. Aligning all tasks by applying the same production rate will mean that any delay in any of the tasks will cascade through the critical tasks and delay the project (See section 2.8). Consequently, a fully optimized LBM schedule will be very sensitive to delay. The study on LBM buffer management in the fourth article became a natural extension to the subject of criticality, because little literature exist that explains how buffers should be prioritized and placed in order to best protect against this increase in sensitivity.

Figure 37 summarizes the systematic combining process of the third study. The results of this study are described in Part IV.

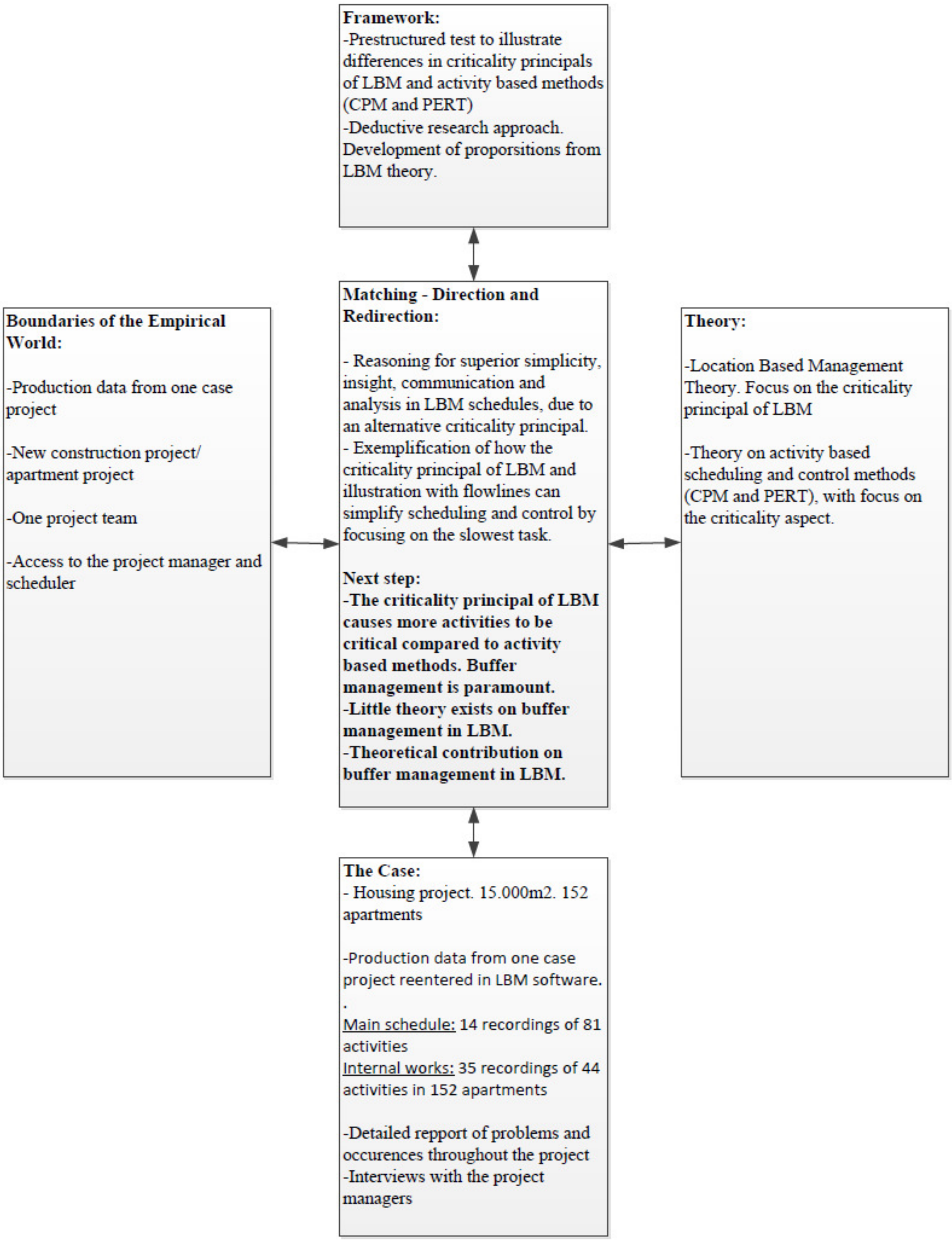

Figure 37: Systematic combining of the third study

Fourth Case Study

Purpose

The purpose of the fourth study was to provide theoretical additions to the buffer management theory of LBM. The first objective was to apply the critical chain theory (CCT) in a LBM setting. The CCT contains recommendations for managing and prioritizing buffers, but is created from CPM logic. Applying the CCT in LBM requires theoretical considerations due to the extended criticality principle of LBM; that is, the addition of continuity and location constraints to the critical path logic. The second objective was to explore the current use of buffers on LBM projects in a case company. The result provided the foundation for discussing the prioritization and placement of buffers on LBM projects, and therefore provided the basis for answering the third research question.

Research method and process

The theoretical framework for CCT was first presented in relation to LBM. The application of CCT in LBM is influenced by the additional constraints in LBM compared to CPM, which the CCT builds on. The theoretical considerations of buffer management principles of CCT cannot be applied directly due to these additional constraints. When applying CCT to LBM, the aim was to maintain the focus on continuous work and respect location constraints (that is, the focal point of LBM), while reducing and reallocating buffers according to the buffer management theory of CCT.

The empirical foundation for this research paper was based on two investigations. Firstly, all completed location base schedules in a case company were analyzed in order to gain insight into the current use of buffers on LBM. The analysis of buffers included tender schedules and construction schedules. Activity buffers, stage buffers, and project buffers were recorded for all critical tasks, and the size of the buffers were recorded and compared to the total number of work days in each case.

Secondly, the buffer management theory of CCT was introduced to the management of a LBM case project. Five hundred and forty-four similar apartments had to be refurbished within a three-year period. The project management created an optimistic location-based schedule with no activity buffers. Most critical and non-critical tasks were aligned to abide to the continuity and location constraints, which left the project schedule highly compact. The project management had three months of buffer to distribute over the project lead-time of three years, which meant there was a minimal buffer to protect the project. Accordingly, alternative ideas of buffer management were interesting to the project management, which is why the buffer management theory of CCT and LBM was discussed with the project management. The results of these discussions are used to comment on the use of the buffer management theory of LBM. The intention is not to generalize the results, but to investigate the use of buffers in depth in order to suggest potential improvements in the LBM buffer management theory. The applicability to other cases is assigned to future research.

This was the final contribution and did not provide input for subsequent research in this thesis. The results of this study are described in section 4.3 and can be read in the fourth article.

Figure 38 summarizes the content of the systematic combining process of the fourth study.

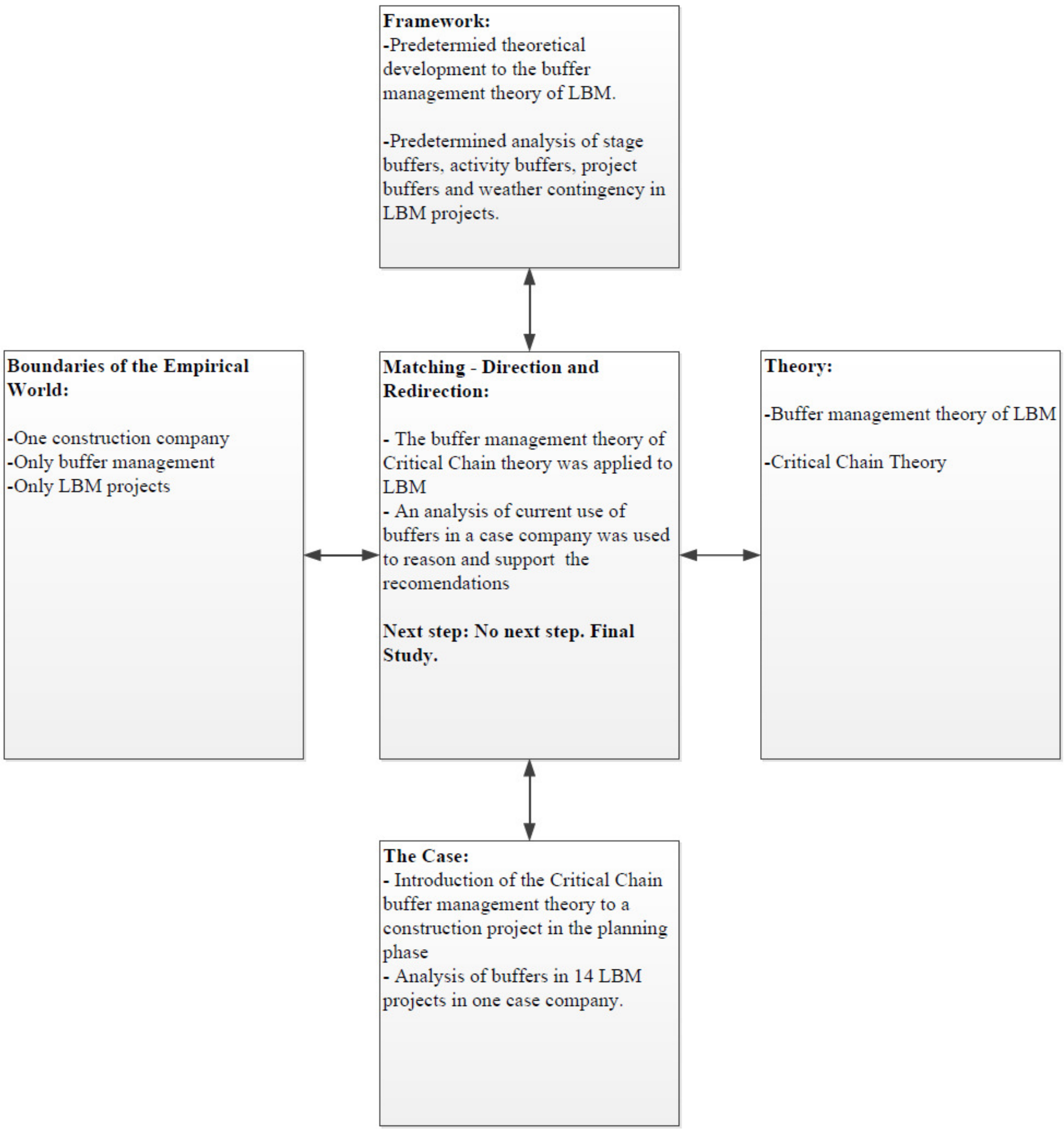

Figure 38: Systematic combining of the fourth study

3.5 Socio-Technical Research

The research includes both a social or behavioral aspect and a methodological or technical aspect, as the research centers on LBM as a scheduling and control technique.

People, institutions, and rules affect technology, and vice versa, in a relationship that is referred to as *socio-technical systems.* Social science is important in relation to research in technology, given that human interaction is hard to describe using the natural sciences (Vermaas et al., 2011). Coordination between physical objects or representations of proposed work task in schedules are affected by agreements, rules, laws, habits, and similar aspects that are studied in the social sciences (Vermaas et al., 2011). Therefore, the topic of socio-technical research is central to this research project, as the underlying rationale would suggest that scheduling and project control cannot be viewed in isolation, either from a social or technological perspective; it is a combination of the two. The combination of technology and social systems involves two different ontologies – one based on the natural sciences and one founded in social science – which complicate research within socio-technical research. Vermaas et al. (2011) stated that some components within these systems are researched according to the natural sciences, while others are researched according to the social sciences. This is complicated, because the socio-technical systems must be seen in the light of different individuals and settings; in other words, they are context-dependent. Although the physical artifacts of a system can be viewed from a natural science perspective, it can be difficult to fulfill validity requirements from the natural science in the social part of the system (Vermaas et al., 2011).

This thesis treats both the technologic and social realm with the same ontological, epistemological, and methodological principles. Viewing technology or systems of technology merely as physical objects would be a gross oversimplification. In order to be purposeful, the design of technological systems must be targeted for a specific use within a social setting (Vermaas et al., 2011). Therefore, social norms, human behavior and the like affect the way systems are designed (social determinism). However, systems or technology can also affect human behavior (technological determinism). Function and purpose is embedded in the technology, which entails human interaction with the technology. Accordingly, technological systems must be seen in a social context due to both purpose and function. Without a social setting, the technology would have no purpose, and without a social system, the technology would often not function (Vermaas et al., 2011).
Given that the social and technical side of the project cannot be divided, the scientific approach in this project is governed by the scientific principles within social science. Specifically, the project is performed under the principles of *constructivism*. Section 3.6 elaborates on the ontology and epistemology of constructivism.

3.6 Ontology and Epistemology in Constructivism

Although this study operates within the constructivist paradigm, positivism is briefly mentioned here in order to contrast the ontological, epistemological, and methodological views of constructivism. Despite many more research paradigms and sub-branches to constructivism and positivism exist, a broad presentation of these is beyond the scope of this research.

Selection of research paradigm depends on personal beliefs, the purpose of the research, and the background of the scientific field (Guba, 1981). *Just as it is proper to select that analytic statistic whose assumptions are best met by a set of data, so is it proper to select that paradigm whose assumptions are best met by the phenomenon being investigated* (Guba, 1981). There are no right or wrong answers, as all research paradigms are *human constructions, and hence subject to all the errors and foibles that inevitably accompany human endeavors* (Guba 1990).

Positivism

Positivism is driven by the belief that reality is a set entity. The purpose is to identify the *natural laws* that describe this reality; in other words, research results must be able to be reproduced and generalized. Positivist ontology has a *realist* view (Guba 1990), which is commonly accepted in natural science and assumable, not challenged as often as in social science. A choice of this ontology entails an *objectivistic* epistemology and the observer must not interact with the observed phenomenon. The "truth" must be uncovered by objective observations and any bias or influence of the researcher must be avoided. The methodology is experimental, with predetermined questions or hypotheses that are subsequently tested under controlled conditions (Guba, 1990).

Constructivism

Constructivists are different from positivists in two main ways. Constructivists dispute the principle of generalization (ontology) and the idea that knowledge can be free of human values (epistemology). The epistemology in constructivism suggests that knowledge is human constructs and there is no objective truth. A theory can never be "proven", as researchers cannot test indefinitely. The ontological principle is that generalization and laws of phenomena cannot, by definition, be proved. Guba (1990) illustrated this point by stating that *observing one million white swans does not provide indisputable evidence for the assertion, "all swans are white"*. Further, it is common for there to be more than one possible theory with which to explain a phenomenon. However, there is no practice to choose among these different theories. Unlike positivism, constructivism accepts the subjectivity of the researcher (Patton, 2002). Patton (2002) stated that subjectivity is an unavoidable part of research. In contrast to positivism, subjectivity is accepted as an unavoidable cornerstone of research and therefore embraced in the constructivist paradigm. The focus is on deep understanding of the observed rather than hypothesizing about generalizations and causes that seek a global truth. Constructivists even criticize the attempt to distance the observer from the observed. Patton (2002) stated that *distance does not* *guarantee objectivity; it merely guarantees distance.* Therefore, subjectivity should not be dismissed, but rather embraced, accepted, and reported. Regardless of what it is that drives the choice of research paradigm, it has consequences for the methodology of a research program. For example, it does not make sense to replicate results for validity purposes within a constructivist paradigm, as the underlying philosophy suggests that an indisputable truth can never be reached. Studying five cases instead of one does not make the results more valid; however, this does not imply that more cases should not be studied. Under the constructivist paradigm, additional cases can uncover additional aspects of a phenomenon, whereas the positivists use multiple cases to argue for the validity of observations.

Although objectivity was key in the exploratory interviews of the first and second article, involvement and subjectivity were unavoidable in the two last studies, which were both descriptive and explanatory and involved authoritative actions and personal involvement. This is acceptable under the constructivist paradigm, although it is important to note the researcher's own interest in the latter studies, as attempts to improve scheduling and control were central to the research. For example, the researcher described the implications and importance of a change in criticality on a construction project. Although the analysis was performed analytically and honestly, some bias may exist, as the advantages of LBM are promoted compared with the traditional activity-based approaches. Furthermore, the researcher made a suggestion regarding CCT in the fourth study. There has been interest in providing findings that advantages could be gained from combining the CCT with LBM. Although the researcher has attempted to be honest about any problems and weaknesses when attempting to find advantages in the approach, it is important to note this potential subjectivity and bias. One earlier attempt to improve construction scheduling proved inefficient and was therefore abandoned. A great deal of time was spent trying to create the CBR system in order to improve scheduling in the tender phase. However, the approach proved to be of little value to the participating practitioners due to fundamental problems of available design information in the early project phases. Reasoning and tests with the practitioners forced the researcher to abandon the idea and seek other ways of approaching the problems that had been identified in the first study.

3.7 Purpose and Research Typology's Influence on Research Methods

The purpose of each specific study determines the research typology and approach; that is, the methods (Patton, 2002). Patton (2002) described five alternative typologies and approaches to qualitative research, which essentially link purpose with methodic choices and ultimately specific research actions in what he calls the theory-to-action research continuum. The five categories and associated purposes are listed below.

1. Basic research:

   The purpose of this category is to contribute to fundamental knowledge and theory. Knowledge is created for the sake of knowledge, while the world is studied to enhance general understanding and to understand and explain certain phenomena. Basic research explores fundamental questions and seeks to uncover universal patterns, although these are difficult to establish in social research, as research in a social setting is, arguably, ever-changing and difficult to replicate due to constant change in people's learning patterns, moods, experiences, etc. The ever-changing world complicates repetition of the same experiments as the environment is hard to control. Judgment of quality within basic research depends on the discipline. Different traditions dictate how quality is defined and evaluated.

2. Applied research:

   The purpose of applied research is to contribute to knowledge that illuminates the nature of a problem, which subsequently enables positive change. Whereas basic research address fundamental questions within each discipline, applied research address problems that are articulated by people. Part of applied research involves identifying potential solutions to problems. Another difference between basic and applied research is the expectation of generalizability. It is accepted in applied research that a given problem is studied within a certain time and space. Results are dependent on the current setting, which means that they cannot necessarily be replicated.

3. Summative evaluation:

   Summative evaluation is applied to determine program effectiveness. The aim is to investigate the results of initiatives and programs designed to solve problems uncovered in applied research programs. The research design is created to intervene and create change in a specific setting. It is the effectiveness of the human intervention and proposed solutions that is of interest in summative evaluation. A common aim of summative evaluation is to determine whether investments in a given solution to a problem should continue. Results are not expected to be generalized, due to the focus on singular initiatives and programs.

4. Formative evaluation:

The aim of formative evaluation is to improve a program or product that has been deliberately altered. Evaluation research relies on process studies, implementation evaluations, and case studies, and does not attempt to generalize results.

5. Action research:

The final category in Patton's (2002) theory-to-action research continuum is action research, which aims to solve specific problems. Change, involvement, and influence of the research subject are all engaged actively and purposefully. Action research is furthest from the principles of basic science, and generalizability is completely beyond the scope of the research paradigm. Only the specific problem is of interest. The research process is commonly unstructured, open, and adapted to change. Action research differs from formative evaluation by the participatory role of the researcher and unstructured research methods.

Patton (2002) stated that understanding the purpose of each category is important, given that requirements and approaches to problems, research design, data gathering, publicizing, and disseminating findings vary between the categories. The different purposes and research traditions also influence how the audience perceives the quality of the research. The intended audience must be clear, as research is typically only able to target single purposes.

The present thesis targets practitioners and research in the construction industry. It is an example of applied research and seeks to shed light on the problems of scheduling and control in the first and second studies. These problems are used as the inspiration for the next two studies. In accordance with applied research, no attempt has been made to generalize the subject of inquiry in any of the articles. The results are not intended to be completely replicable in another time and space, due to the specific contextualization of each case study. However, this is not to say that results of this research cannot be applied in other contexts. Recipients of the research must simply be aware of the context in which the results are created in if they are to be able to judge whether the results are applicable in their own context.

3.8 Qualitative vs. Quantitative Research Methods

This thesis is based on qualitative research methods, partly because such methods support the generation of theory. Generally speaking, the purpose of quantitative research is to test theories (deductive approach), while qualitative research aims to generate theory (inductive approach) (Patton, 2002). Qualitative research is suitable when little is known about a phenomenon and it is difficult to establish standardized instrumentation (Patton, 2002). The knowledge base in qualitative research is built by exploring phenomena in depth, adding each piece of knowledge to a collected base that is then used to establish theoretical contributions.

In addition, the epistemological and ontological principles in the constructivist research paradigm match those of the qualitative research methods. The qualitative research methods support subjective interpretations of what has been observed and the results are not usually suited for generalization due to strong contextualization. In the first study, for example, the purpose was to uncover best practice and problems of scheduling and control. Scheduling and control is assumed to be dependent on the individual practitioners, organizational norms, choice of software, etc. Problems of scheduling and control are assumed to be different in other construction companies, although the problems were recognized in the 11 international reference companies. The point is that the research was not created with generalization in mind. It might have been difficult to replicate or generalize the results; in fact, the intention was never to generalize the results, but to create in-depth knowledge. The usefulness and applicability of this knowledge will have to be determined by each recipient outside the frame of research.

Qualitative research does not necessarily have a predetermined path, and research participants are typically approached with open-ended questions (Bryman 2012). The subject of study will often unfold naturally and be explorative. Therefore, the research design is only to be specified to a certain extent and the end result will not be clear when the research initiates the research process (Bryman 2012). Flexibility and openness are the keys in this process, as the research design should ideally allow for new knowledge to change the course of action. There are no guidelines regarding how much the research program must be defined. The degree to which research is specified depends on the given situation, purpose, and target group, etc. of the research (Bryman 2012). The open-mindedness in qualitative research has determined the course of action in this thesis, which is founded on the exploratory research of problems of scheduling and control. This was one point of departure, and the problems have established the foundation for the research, giving the general direction for following research. The subsequent case studies have been equally open, albeit with a narrower scope. For example, the fourth case study centered on buffer management in LBM by means of the CCT, which narrows the topic of research. However, the research process was open. It was initially unclear how the CCT should be applied in LBM.

Another elemental difference between qualitative and quantitative research is the sampling size and selection of samples. There is a difference because the purpose of the two groups of research methods. Probability sampling in quantitative research serves a specific purpose; namely, to generalize. Researchers in qualitative research engage in *purposeful sampling* of *information-rich cases,* which serves the goal of in-depth knowledge creation. Patton (2002) stated that *quantitative methods typically depend on larger samples selected randomly in order to generalize with confidence from the sample to the population that it represents.* Qualitative research, on the other hand, focuses on small sample sizes or just a single case. Patton (2002) wrote that *information-rich cases are those from which one can learn a great deal about issues of central importance to the purpose of the research.* Therefore, the two methodologies are not competing and can even supplement each other. The central point is that the purposes of this research are best supported by the qualitative research methods, as they are better at uncovering problems and exploring solutions in depth. Generalization of the results is reserved for future research.

3.9 Discussion of Primary Method – Case Studies

Case studies were the primary research method of this project. Case studies are suited for this research because they can provide in-depth knowledge and richness within the field of study. Using case studies is in line with the ontological principles of constructivism, as context-dependent knowledge is produced and no attempts to generalize the results are made. The purpose is to create insight of a specific part of the world in a certain context and time, which only can be reproduced to a limited extent. Yin (1981) stated that *the distinguishing characteristic of the case study is that it attempts to examine … a contemporary phenomenon in its real-life context… Experiments differ from this in that they deliberately divorce a phenomenon from its context.*

Criticism of Case Studies

The discussions of epistemology and ontology become highly important when case studies are utilized in research. The use of case studies has met criticism from the research community, as described by Flyvbjerg (2004), who not only listed some of these criticisms, but also countered them. Flyvbjerg (2004) refers to the criticism as five misunderstandings:

Misunderstanding no. 1: *General context independent knowledge is more valuable than concrete, practical context-dependent knowledge.*

Misunderstanding no. 2: *One cannot generalize on the basis of an individual case; therefore, the case study cannot contribute to scientific development.*

Misunderstanding no. 3: *The case study is most useful for generating hypotheses, that is, in the first stage of a total research process, while other methods are more suitable for hypotheses testing and theory-building.*

Misunderstanding no. 4: *The case study contains a bias towards verification; that is, a tendency to confirm the researcher's preconceived notions.*

Misunderstanding no. 5: *It is often difficult to summarize and develop general propositions and theories on the basis of specific case studies.*

The criticism highlights why it is important to debate choice of methodology and the understanding of epistemology and ontology. The criticisms that Flybjerg (2004) highlighted suggest that all three subjects have been misunderstood.

Flyvbjerg (2004) dismissed the first misunderstanding by arguing that decontextualized knowledge only can bring people up to a certain level of knowledge. Beyond that, contextualized knowledge is essential if one is to understand phenomena in depth. Further, Flyvbjerg (2004) claimed that generalized theories cannot be established in social science because they lack predictability, which ultimately diminish their worth. Flyvbjerg (2004) argued accordingly that in-depth contextualized knowledge is more valuable in social science, which forms the basis for the present thesis.

Regarding the misconception of generalization, Flyvbjerg (2004) argued that a single case can be generalized if it is conceptual. A single case can illustrate a point that, if selected purposefully, defies current knowledge. Flyvbjerg (2004) referred to Galileo's rejection of Aristotle's law of gravity, in which a single conceptual experiment could reject the claim that weight influences the velocity of a free-falling object. The principle is the same in social science. Well-selected cases can change the way phenomena are perceived without having to reproduce it hundreds of times. Equally, the third and fourth case studies attempt to show principle matters of project scheduling and control with LBM and buffer management. The results are expected to be applicable to other repetitive construction projects, although specific circumstances may prevent it from being true. The results cannot, by definition, be generalized. However, Flyvbjerg (2004) does not criticize formal generalization, as *such attempts are essential and effective means of scientific development.* His criticism only applies when *formal generalization becomes the only legitimate method of scientific inquiry.*

The third misunderstanding is that case studies are not suited for testing hypotheses or creating theory. Flyvbjerg contends this because falsifying cases can show something general about a phenomenon or hypothesis.

Flyvbjerg (2004) discussed the fourth misunderstanding concerning biased towards verification, stating that it is a general problem that is not only associated with case studies. However, case studies are more prone to subjectivity, which is seen as less rigorous than quantitative methods. Having said that, the rigor of case studies is different from that of quantitative methods. Flyvbjerg (2004) argued that case studies are rigorous because essential preconceived views, assumptions, concepts, and hypotheses change when the case unfolds in real circumstances. The uncontrolled environment of the case study challenges social science researchers, who are close and interact with the observed. Contrarily, Flyvbjerg (2004) argued that social research based on quantitative methods creates distance to the observed, which in turn limits the feedback from the environment that could signify wrong assumptions and preconceived views.

Flyvbjerg (2004) did somewhat accept the fifth and final misunderstanding, which concerns the inability *to summarize and develop general propositions and theories*. It is difficult to summarize and generalize case studies due to the vast amount of information and the fact that the important aspects often lie in the details. Flyvbjerg argued that the purpose of a case study is not to summarize and generalize, but to have narratives that explain meaningful observations in its entirety. It is then up to the reader of the narrative to evaluate its applicability in other settings.

Other criticisms include those made by Miles (1979), who criticized the data collection of qualitative methods in general. Miles (1979) stated that the amount of data can become overwhelming, causing the data analysis to lack important details, become oversimplified, or be reinterpreted in the light of more recent events. Miles also found that the overwhelming data can complicate the actual process of analysis during case-writing, rendering it intuitive, primitive, and unmanageable in any rational sense. Miles attempted to make order and sense of the data by applying a coding strategy, which is one way of approaching vast amounts of qualitative data. Statements and observations can be categorized and grouped in themes, which should make the analysis process more manageable. However, Miles (1979) found little use for the method as the data remained too extensive. Although the coding process did help reach a certain level of clarity, Miles (1979) asked: *Would someone else come to the same conclusion?* The results of the interviews in the first and second studies were coded according to Corbin and Strauss (1990). The method worked well, as it reduced and collected comprehensive statements to similar categories, which made the results manageable.

Yin (1981) reacted to these criticisms of overwhelming data and the use of case studies by stating that *the major pitfalls occur when investigators use categories that are too small and too numerous.* Yin (1981) also stated that *many case studies begin with the naive assumption that "anything might be relevant, so one ought to observe and code everything."* Therefore, the present study only describes significant findings in the case studies. All case studies are highly contextualized in real-life settings in the case company. The results are presented more parsimoniously and only with information that is believed to be relevant for the case. The aim was to avoid excessive descriptions and data that would be difficult to analyze and present, as argued by Miles (1979). The danger is that some details have been omitted and that the selection process caused researcher bias.

Yin offers no answer to the question raised by Miles (1979) regarding the conclusions of research performed through case studies. This must be seen as a weakness of the method. There is no clear way to ensure that different researchers would reach similar conclusions. So how do researchers ensure some kind of consensus of valid research processes and ensure rigorous conclusions? An attempt to answer this question is presented in section 3.10.

3.10 Trustworthiness of Constructivist Research

The epistemological, ontological, and methodological discussion is raised partly to comment on the truthfulness of the research project. Patton (2002) stated that: *it is important to acknowledge at the outset that particular philosophical underpinnings or theoretical orientations and special purposes for qualitative inquiry will generate different criteria for judging quality and credibility.* In order to argue whether this research has been produced with sufficient quality and credibility, one must explain the requirements within the epistemological, ontological, and methodological setting (Patton 2002), which constitute the research paradigm. Patton (2002) stated that: *As such, paradigms are important theoretical constructs for illuminating fundamental assumptions about the nature of reality.* Only by describing and contextualizing the thesis within these topics can the validity of the research be articulated. It is essential to discuss the placement of the research project within a certain paradigm (constructivism in this case) so that the research is evaluated on the same premise from which it was created. For example, it is meaningless to ask for external validity of research if it is not an inherent part of the research paradigm. In other words, it is neither relevant nor necessarily possible to replicate results if it is not believed to be generalizable. Generalization might not make a statement more true, as exceptions from this truth can always exist, in principle. This is a principle of constructivism and, therefore, of the findings in this research.

The quality criteria of the constructivist research paradigm are different, yet analogous to criteria in positivist research. Guba (1981) highlighted four aspects regarding trustworthiness in positivist research:

Truth value in positivism: How can confidence be established in the “Truth” of the findings, regarding the subjects and the context in which the subjects has been studied? The value of truth is determined by **internal validity** in positivist paradigm and natural science, which is determined by the links between causal relationships of the data.

Applicability in positivism: To what degree can the findings be applied in other contexts or with other people? Applicability refers to the **external validity** or generalization of the findings.

Consistency in positivism: To what degree would findings be similar if the same people and context were applied? This is referred to as **reliability** in positivism.

Neutrality in positivism: To what degree are the findings a function of the participating people (subjects) and the conditions of the research, and not of biases, motivations, interests, perspectives of the researcher? Neutrality is key to **objectivity** in positivism.

It is important to consider these terms differently in a constructivist setting due to the epistemological, methodological, and ontological differences (Guba, 1985). Guba (1981) suggested that credibility replaces internal validity, transferability replaces external validity, dependability replaces reliability, and confirmability replaces objectivity. All of these criteria indicate trustworthiness, whereas positivist research would use the term rigor. The differences are summarized in Table 5.

Aspect	Positivism	Constructivism
Truth	Internal Validity	Credibility
Applicability	External Validity - Generalizability	Transferability
Consistency	Reliability	Dependability
Neutrality	Objectivity	Confirmability

Table 5: Differences of rigor/truthfulness in positivism and constructivism (Guba 1981).

Guba (1985) described the definitions and causes for the emergence of the four aspects under the constructivist paradigm.

Credibility:

- Prolonged engagement – long and intensive interaction with the studied phenomena or subjects, seeking to eliminate distortion.
- Persistent observation – Search for in-depth knowledge through long periods of study.
- Triangulation – Use of multiple data sets, sources, and researchers that illuminate the same subjects.
- Peer debriefing – Communication of research processes and results to unbiased peers, to keep honesty as a central element.
- Negative case analysis – Supplements of negative cases, which highlight counter-perspectives and contrasting views on the subject of study.
- Member checks – Presentation of findings to program participants to ensure that the reconstructed results can be agreed upon.

Transferability:

- Thick descriptive data – The context, environment, special circumstances, etc. must be narrated so that other researchers can use the results and reapply them in a different setting.

Dependability and confirmability:

- Research results must be audited by unbiased peers. The audit must both address the process of how the results have been obtained (dependability) and the data (confirmability).

Guba (1985) was aware of the weaknesses of these suggestions. The criteria are probably not exhaustive as they have been adapted from the positivist paradigm. Other criteria might have emerged had the criteria been created without influence of the positivist paradigm. Consequently, the four criteria must be viewed as attempts to solve the problem of transferring the concept of rigor to the constructivist paradigm. Therefore, one could criticize this way of evaluating rigor of the research program, as no unity, standard, or convergence exists within the paradigm on these four criteria. However, these four points of trustworthiness are applied in the present project, which at least attempts to address the issue.

Trustworthiness of this research project

One advantage in the present project was the opportunity to retain an ongoing engagement with employees in the case company and have quick access to data. The researcher has been situated within the company for three years, and investigated scheduling and control on 44 construction projects in various degrees. Some projects were followed for minor specific purposes and provided background knowledge on scheduling and control, while other projects were investigated in-depth and applied explicitly in the research. This access to construction projects enabled persistent observation and extensive studies with the same employees and of the same subjects. Furthermore, the access to data has enabled triangulation. For example, external reports, internal performance data, and qualitative interviews were used in the third case study to triangulate the empirical data and observations. The triangulation highlighted incoherencies between reports and performance data, which underlined the usefulness of the triangulation. Also, all results within the project were presented to participants from the studies and to a control group to enhance the credibility of the findings and avoid misunderstandings from the interviews. Employees who participated in the research seemed open, honest and critical about their own work. Nearly all research participants consented to the criticisms that had been raised by themselves, their colleagues, and the researcher, in both the interview-based studies and the studies of project control. Only in a few instances were quotes changed in the coding processes because participants found their own quotes unfamiliar, despite them being recorded on tape.

The only aspect of trustworthiness that has not been addressed in this research project is the lack of negative cases. No specific negative case was performed within each study. The degree of transferability is hard to comment on, and must be evaluated by the recipients of this research. An attempt has been made to describe the cases within the confined space of journal articles. However, the journal articles have ensured the dependability and confirmability of the research. The studies have been submitted to peer-reviewed journal articles in order to ensure unbiased evaluation of the research. The results have also been presented at external scientific conferences, international researchers, and internal conferences for practitioners.

Part IV – Results and Discussion

Part IV presents the findings from the third and fourth article in relation to the research questions. Each research question is answered at the beginning of its assigned section and subsequently elaborated on. Because Part IV only provides a summary of the results, the more elaborate reasoning behind the results should be read in the appended articles. Part IV also includes a discussion of the results, recommendations for future research, and clarification of the contributions of this thesis to the body of knowledge.

4.1 Results – Conceptualizing criticality in location-based management

The LBM criticality principle is not defined and treated collectively in the current literature, as explained in section 2.7. There is some literature that describes aspects of criticality in LBM, but these aspects are fragmented and the relation between constraints and criticality has not been treated explicitly and collectively. This led to the first research question, which was presented in section 1.4.

RQ1 (Repeated): What aspects constitute the collected criticality principle of location based management?

The answer to this question was determined through analysis of how inherent constraints in LBM affect a project's lead time as described by Flood et al. (2006), and includes the fragmented aspects of criticality in LBM literature (Section 2.7).

The answer to RQ1 is that the collected criticality principle of LBM contains the following aspects.

- Activities or tasks on the longest path or paths through a project's dependency network with zero float are critical.
- Activities or tasks are critical if they are allocated to a location that imposes time delays on activities on the longest path or paths in a project's dependency network with zero float.
- Activities or tasks that cause discontinuity of activities and tasks on the longest path or paths through a project's dependency network with zero float are critical.
- The activity or task that has the lowest production rate on the longest path or paths through a project's dependency network with zero float is the most critical.

In short, the criticality principle of LBM consists of four fundamental constraints: technical, location, continuity, and productivity constraints. The remainder of this section elaborates on the reasoning behind the link between the constraints and the criticality principle.

Technical constraints

The LBM criticality principle is partly based on the same type of technical dependencies of which activity-based methods consist. Accordingly, activities on the longest path throughout a project's dependency network with zero float are considered critical. Although the time constraint represents effectively the same logic dependency as in CPM, they are interrelated through the first layer of logic, described by Kenley and Seppänen (2010) in section 2.6, and handled collectively, which affects the control capabilities and the concept of productivity float. Whereas technical constraints are treated discretely in activity-based methods, dependencies of similar activities are treated collectively in tasks across relevant locations in LBM (described in section 2.6 section). Compiling technical constraints for similar activities across locations affects the alleged simplicity of LBM, which will be discussed in section 4.4.

Location constraints

An activity is also critical if it is allocated to a location that imposes time delays on any activity on the longest path or paths in the technical dependency network with zero float. The location constraints were treated in section 2.6. Although technical constraints allow work to commence for an activity on the critical path, activities from another sub-network in the dependency network may block the location and require the given critical activity to start later. Accordingly, the critical activity on the critical path will contain float attributable to the location constraint, but will remain on the critical path. Consequently, activities not on the critical path must be considered critical if they extend the project's lead time as a result of location constraints.

Continuity constraints

As described in sections 2.4, 2.5 and 2.6 by for example Lumsden (1968) and Russell and Wong (1993), continuity is the cornerstone of LBM. However, continuity constraints are different from technical and location constraints in relation to the criticality principle. Discontinuous critical tasks do not necessarily have a negative effect on project lead time. A critical task may be discontinuous and still allow succeeding critical tasks to proceed at the fastest possible pace. However, continuous work is key in LBM because it ensures that work crews follow the same pattern of completion through the location breakdown structure. Time-critical activities that follow different completion sequences create waiting time in such locations, thus increasing a project's lead time. A continuity constraint imposes the same completion sequence throughout the location breakdown structure and, in turn, ensures that no waiting time arises because crews finish locations in different order, which in turn ensures that succeeding crews can initiate their work. Thus, activities or tasks that cause discontinuity of activities and tasks on the longest path or paths through a project's dependency network with zero float are critical.

The slowest critical task

Technical, location, and continuity constraints all add to the interrelatedness of activities and tasks in LBM. The production rate is also an important measure when establishing, controlling, and optimizing project location based schedules (Carr and Meyer (1974) and Peer (1974) in Sections 2.4 and 2.7). Technical, location, and continuity constraints require flow lines to align and become parallel whenever possible to obtain production flow and reduced waiting time. The combination of the three constraints and reliance on productivity factors opens up for a possibility in LBM. The critical task with the lowest production rate should be considered the *most* critical task of the entire project because it impedes progress on succeeding critical tasks. This was a key subject of the third article. Activity-based methods do not contain this distinction and treats all critical tasks equally. Figure 39 illustrates the principle that the slowest critical task ultimately determines the maximum production rate of all succeeding tasks because of residing technical, location, and continuity constraints.

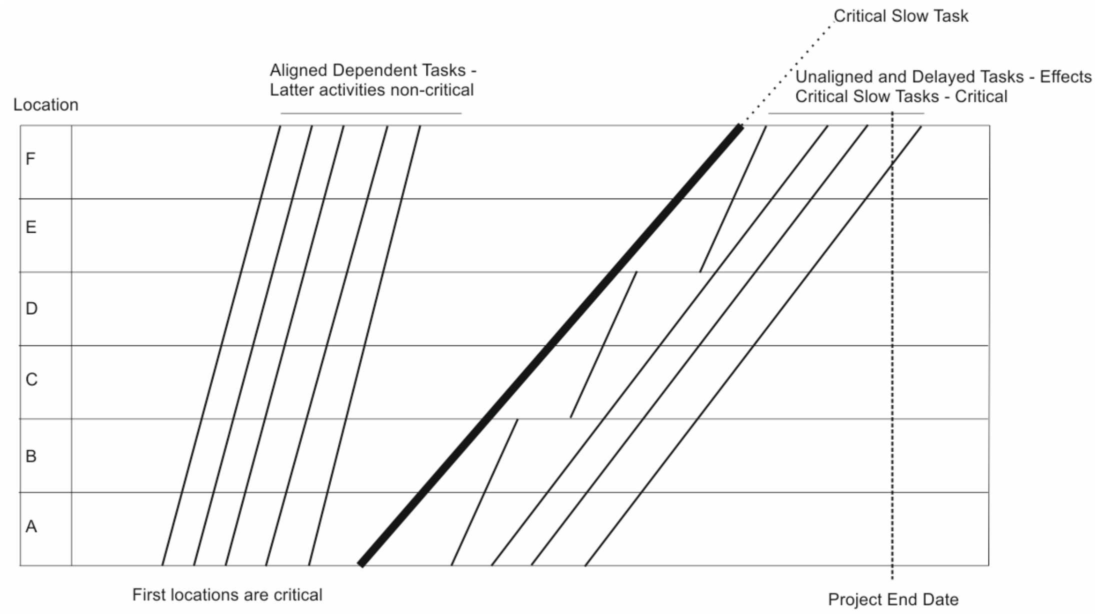

Figure 39: Criticality when controlling interdependent tasks in location-based management.

The slowest critical task will limit the production rate of its successors or cause them to be discontinuous from either technical constraint demands or other activities performed at the location. The second slowest task will determine the maximum potential production rate to the predecessors of the slowest task, etc. An activity for a specific location or an entire task becomes critical if it constrains the progress of its successors, which in turn delays the project's lead time. Thus, a task is critical if its low production rate has a negative effect on the project's overall delivery time. The principle builds on the recommendations provided by Carr and Meyer (1974) and Peer (1974) (see section 2.7). Carr and Meyer (1974) and Peer (1974) described the importance of the slowest task, but did not provide much reasoning behind their recommendations or relate it to the other constraints that make activities and tasks critical in LBM. The reasoning and supporting data for this assertion is further elaborated on in section 4.2 and in the third article.

The principle behind the controlling path (Harmelink and Rowings, 1998) or controlling sequence (Harris and Ioannou, 1998) and the concept of productivity float (described in section 2.7) become important in relation to the slowest critical task. Only the first locations in the location breakdown structure for predecessors to the slowest task contain critical activities because productivity float develops after activities in the latter locations given the difference in production rates (Figure 39:). Critical tasks that follow the slowest task are also important, but their progress is limited by the slowest task. Consequently, the focus should also be on enabling and impeding tasks of the slowest task, as described by Koo et al. (2007). A slow activity or task that does not affect other tasks and the project's lead time should not be considered critical. Therefore, an activity or a section of a task is not considered critical if it contains productivity float, as described by Harmelink and Rowings (1998). Some of the succeeding critical tasks may become the slowest tasks at a later point, but they cannot be rushed. This aspect will be described in further detail in section 4.2.

For example, economic constraints, technical aspects, and resource availability may decide the slowest activity or task. However, determining the causes of the slowest task is beyond the scope of this thesis.

Contribution to the body of knowledge

The described criticality principle is a conceptualization of constraints in relation to progression of work through a project that affects the lead time. The criticality principle was established and conceptualized by collecting the fundamental constraints of LBM and relating them to effects on project's lead time. Consequently, the contribution to the body of knowledge is not identification of the constraints, as they are described in current literature, but their relation to restrictions of effective completion of LBM projects. Therefore, formulation of the LBM criticality principle should be seen as an addition to current LBM theory as it fills a gap in the current literature.

4.2 Results – Implications of the LBM criticality principle on practice

Whereas section 4.1 collected the criticality principle of LBM, the present section presents the results from the third article regarding the effect of the criticality principle, thereby answering the second research question.

RQ2 (repeated): What are the practical implications when the criticality principle of location-based management is applied to schedule and control construction projects, instead of the activity-based criticality principle?

The summarized answer to RQ2 is:

- The number of activities that are critical, and appears to be critical, increases.
- Critical activities can be prioritized by means of the slowest critical task.
- Consequences from slower-than-planned production performance of critical tasks are forecasted more negatively.
- Work crews' flexibility of work sequence through a building is reduced.
- The sensitivity to disturbances and fluctuation in production rates increases.

The remainder of this section elaborates on these implications.

Increase of critical activities

An increased number of activities will be perceived as being critical, while additional activities also are likely to become critical when the criticality principle of LBM is applied rather than the criticality principle of the activity-based methods.

Activities that are restricted by a combination of technical and location constraints may be critical in activity-based projects, although their criticality is not made explicit in the activity-based methods. Therefore, practitioners may not be made aware of the criticality of activities, even though they will affect the project lead time. Because technical dependencies are not required to be treated explicitly in each location in the activity-based methods, restrictions on progress in each location are not explicitly illustrated. However, the progression of critical activities may be limited by otherwise non-critical activities in the given location. Therefore, activities that would not be on the critical path in CPM may extend the project's lead time, as they may incorporate float in the critical path in certain locations. Therefore, the location constraints are not restrictions that are imposed by LBM; instead, they are physical constraints and simply made explicit in LBM. In combination with the technical constraints, they are physical boundaries that cannot be broken. Accordingly, the introduction of location constraints will not increase the number of critical activities. The number of critical activities will appear to increase, and the physical limitations for progression will simply be made explicit when introducing the location constraints.

Contrarily, the continuity constraints imposed by LBM entail that additional activities become critical compared to the activity-based methods. LBM theory argues that discontinuous work may affect the progression of projects lead times, or at least entail disruptive unoptimized production that can extend a project's lead time. Also, as stated in section 4.1, a project's lead time will not by definition be prolonged if critical tasks are made discontinuous. However, the continuity constraints are seen as a necessity for optimized production, as explained throughout Part II. The continuity constraints not only ensure continuous production, but also production in the same sequence through the location break-down structure of a construction project (3-layerd logic described in Section 2.6). Consequently, the continuity constraints impose additional requirements in the dependency network of activities, which potentially removes float and forces otherwise non-critical activities to interfere with the critical path and become critical.

The additional constraints of the LBM criticality principle consequently both make additional activities critical and appear to be critical. Although it may seem unwanted that the number of critical activities increases, the additional critical activities can help practitioners to understand the restrictions of production performance and progress in their project, that would otherwise have been obscured if activity-based techniques were applied.

Prioritizing the slowest critical tasks

The third article showed how the additional constraints in the LBM criticality principle can help practitioners prioritize from amongst the critical activities and tasks, and therefore identify the maximum potential production rate of succeeding tasks. Therefore, the research exemplified how the slowest critical task in progress, rather than all critical tasks, governed the progress of the entire building project as initially suggested by Carr and Meyer (1974) and Peer (1974).

Similar to activity-based methods, the criticality principle of LBM can help managers focus their scheduling and control efforts. Practitioners may use the additional constraints to differ between the critical activities and focus their scheduling and control efforts even more, because the slowest critical task can be prioritized, as all succeeding time- and location-critical tasks cannot progress faster than this slow task. Therefore, whereas activity-based methods help practitioners to focus on the string of activities that comprise the critical path, LBM can help them focus even more on the activities that impact a project's lead time. Location-based schedules of activity based production data from the third article show that technical and location constraints force all critical tasks after the slowest task to slow down to the same rate of production regardless of the construction crew's reported excess production capacity and attempts to start early in multiple locations on all late critical activities. Only the completion of each individual location was important. However, this was not apparent from the applied activity based methods. As described in section 3.4, the case project was planned with LBM, but controlled with activity-based methods.

The activity-based methods did not illustrate the limitations imposed by slow production of certain critical tasks on remaining critical tasks because location constraints and production rates are not shown explicitly. The Gantt chart in Figure 40 indicated that several critical tasks were behind schedule in the case project. There was nothing to suggest that project management should refrain from accelerating all late critical activities, because the Gantt chart only illustrated that the critical tasks were behind schedule. However, some construction crews were prevented from making progress in certain locations, without this being visible in the control charts. Therefore, applying activity-based methodologies do not help in identifying core productivity problems because all delayed activities on the critical path may be considered "equally" critical. Ignoring location and continuity constraints can lead to the assumption that all late critical tasks should be prioritized and accelerated. However, the limitations made by location and productivity constraints become visible by illustrating production data in location-based schedules.

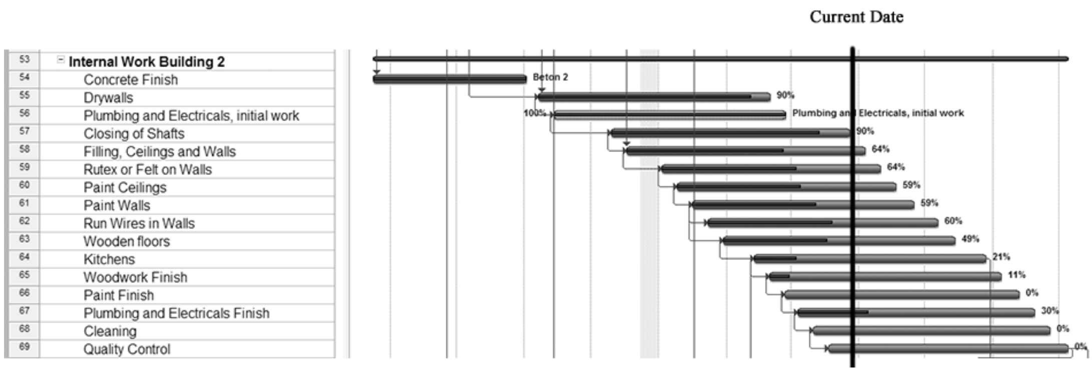

Figure 40: Progress control with percentage complete in the case project.

The as-built production data was taken from Excel spreadsheets and Gantt charts and entered into LBM software (Described in section 3.4). The data was recorded separately for the exterior works and the internal works. A more thorough analysis of the data should be read in the third article. Figure 41 illustrates the production data of critical tasks from the external works, and suggests that the *concrete finish, windows* and *facades* tasks limited the progression of the remaining work towards the final locations in the second building (top half of Figure 41). However, it was unclear from the overall production data how this affected the critical tasks in the internal work, which the project management attempted to accelerate by employing more work crews. The production data of the internal works was consequently explored in detail. The critical tasks of the internal work are illustrated in Figure 42. A simplified version of this figure can be seen in the third article.

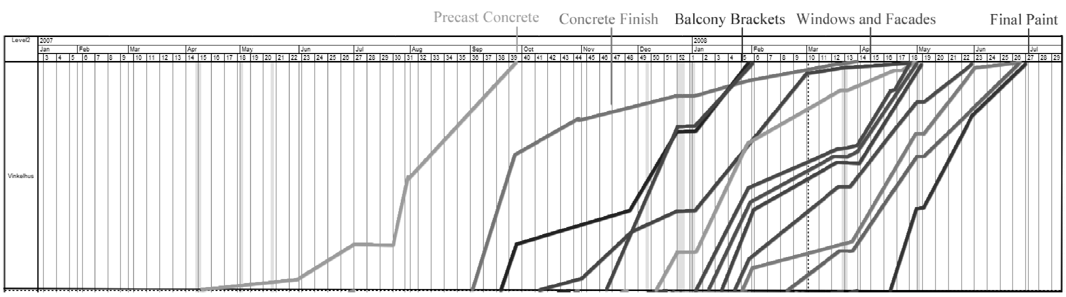

Figure 41: Productivity trend lines from production data of the external works.

Figure 42 shows how the *concrete finish* tasks initially have high production rates are therefore non-critical most of the time because of the time and space contingency that builds toward the succeeding tasks. However, the *concrete finish* task became critical as the last locations in the project approached. The *concrete finish* task limited the progression of the *windows* and *facades* tasks, which limited the progression of its successor, and so on, which ultimately caused the project to finish late. The close alignment of the tasks indicates that successors could not advance despite they were behind schedule. Accordingly, project management attempts to accelerate these late tasks were limited to the production rate of the *concrete finish* task. Any attempt to increase production rates for these eight critical tasks beyond that of the *concrete finish* task were wasted at the given point in time.

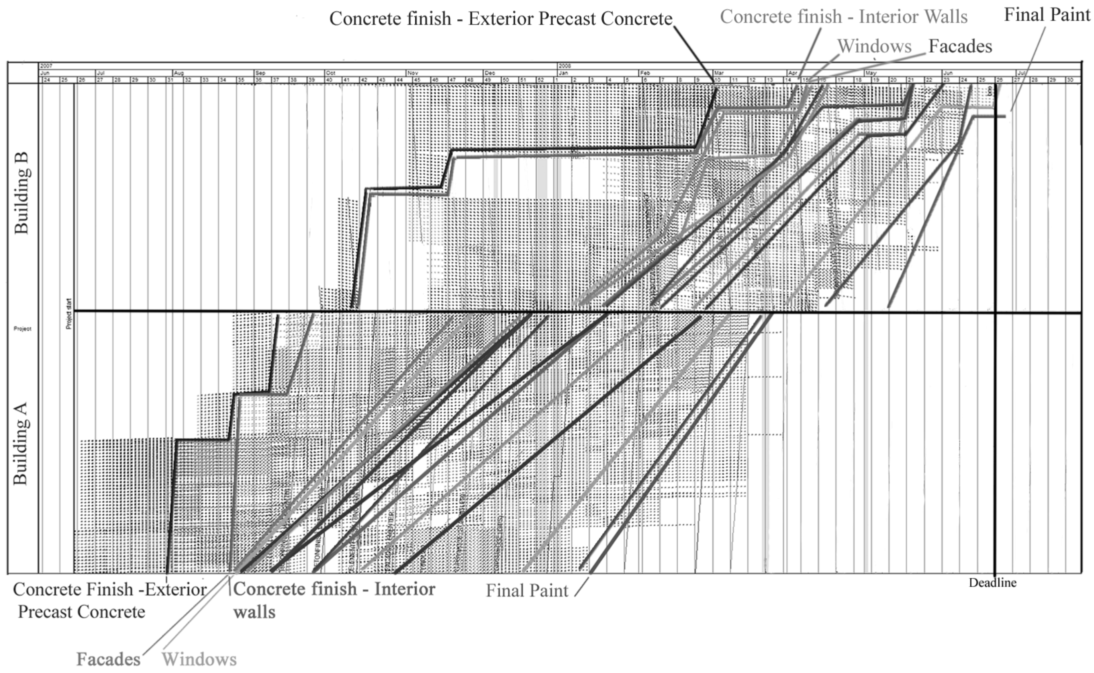

Figure 42: As-build construction data on internal works from the case project in the third article; only critical tasks.

The slowest task changed throughout the project. For example, in the middle of the completion of building B (Figure 42), the *facades* and *window* tasks, not the *concrete finish* task, were the slowest. A simplified version of Figure 42 can be seen in the third article. These tasks limited the progression of four succeeding critical tasks and seven critical tasks in building A at an earlier point in time. Therefore, the slowest task changes dynamically as the project evolves, just as the critical path does.

The criticality principle of LBM provides an opportunity to focus scheduling and control of construction projects more and minimize resource consumption without compromising a project's lead time. This opportunity results from realizing that the slowest critical tasks in LBM determine the completion of all succeeding tasks, which is attributable to the technical, location, and continuity constraints. However, project managers should be cognizant of the development of other tasks, because any task can become critical during a project's development. Nonetheless, focusing on the slowest critical task can provide a way to prioritize critical tasks in both the scheduling and the control effort, which reduces the perceived complexity of construction projects and help avoid ineffective use of resources.

Scheduling

In contrast to the control of projects in which various reasons can cause the slowest task to arise, the slowest task is chosen when projects are scheduled as described by Peer (1974) (Section 2.4). With the criticality principle of LBM, a project management can continue to optimize schedules by focusing on the slowest critical task until it is no longer the slowest. The only difference between scheduling and controlling from the slowest task is that the slowest critical task is selected during scheduling, whereas it is likely to occur more randomly during project control. This suggests that scheduling in LBM should focus on optimizing the slowest critical task until it is no longer theoretically the slowest. Following this logic, tasks preceding the slowest one should be aligned to the second slowest task, and so forth, in order to create a time contingency between the slowest task and its predecessors in all but the first locations, which will reduce the risk of disturbance to the slowest task.

Implications to current theory on project control

The case study from the third article exemplified how technical, location, and continuity constraints govern the slowest critical task, which in turn affects the progress of a project. The aspects related to the second research question should affect current theory on how projects are controlled. Peer (1974) included considerations of the task that should dictate the pace of the project in the construction planning steps of LBM (section 2.4). However, Peer (1974) only mentioned the slowest task and did not explain its importance in any great detail. The data from the case project in the third article exemplified why the slowest critical task is important and why it must be one of the planning steps of LBM. However, the slowest critical task should also be incorporated into the control process that was presented in section 2.9, because this makes it possible to further focus the control effort. The focus on the slowest critical task should be incorporated as illustrated in Figure 43, where the slowest critical task is determined when scheduling projects and identified and prioritized when projects are controlled.

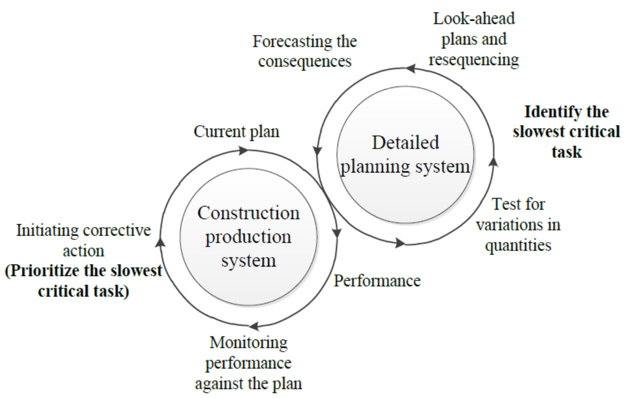

Figure 43: Recommended addition of the slowest critical task to the control process of Kenley and Seppänen (2010).

Slower-than-planned production performance is forecasted more negatively

As described in section 2.9, activity-based methodologies produce forecasts based on planned durations. Therefore, previous performance data from similar activities does not influence the expectations for future production rates. Activity-based methods ignore the fact that the same construction crews perform the work for similar repeating activities.

The layer 1 logic dependencies that were described in section 2.6 are important to the forecasts, and therefore the understanding of consequences from critical slow tasks. The LBM requires projects to be controlled using continuous activities and, therefore, repetitive application of work crews. Because similar activities are grouped in summary tasks, the productivity performance factors affect the forecast for each future activity in the summary task. Accepting that the same construction crews perform similar activities arguably provides a more realistic estimate of future productivity compared with the original estimates. The difference becomes apparent when the activity-based principle is depicted in a location-based view, as illustrated in Figure 44, which shows a forecast assuming planned durations for remaining work, and Figure 45, which illustrates a forecast based on actual performance. These forecasts show the contrast between how the application of discrete activities can fail to warn project managers of the full consequences of slow tasks. Tasks are allowed to be discontinuous in activity-based methodologies because the logic treats them as discrete, even though the tasks are repeated for each location. Therefore, forecasts are not inclined to change to correspond to actual performance in previous locations. This is because the continuity constraint is not part of the activity-based methods and activities are treated discretely. This means that using the original planned estimates for future production can be misleading and may portray an overly optimistic forecast for projects, given actual performance. Optimistic forecasts can be harmful as they affect how practitioners perceive the consequences of slow productivity and, in turn, how they implement control actions. An optimistic forecast may cause crews to plan or attempt to start earlier than what is actually possible given the rate of production of their predecessors.

With discrete treatment of activities project managers will see the consequences to the project if the planned production rate is reached for the remaining activities (Figure 44). If activities are considered continuous and previous performance data affects the forecast, project managers are presented with an outlook that illustrates the consequences if productivity factors remain the same (Figure 45). This will accordingly be a more negative forecast. Thus, the discrete activity concept can potentially obscure the effects of slow productivity when projects are controlled in activity-based techniques. Thus, the continuity constraints in LBM entail extrapolation of a more negative forecast, which provides a more realistic view of the consequences of slower-than-planned production performance.

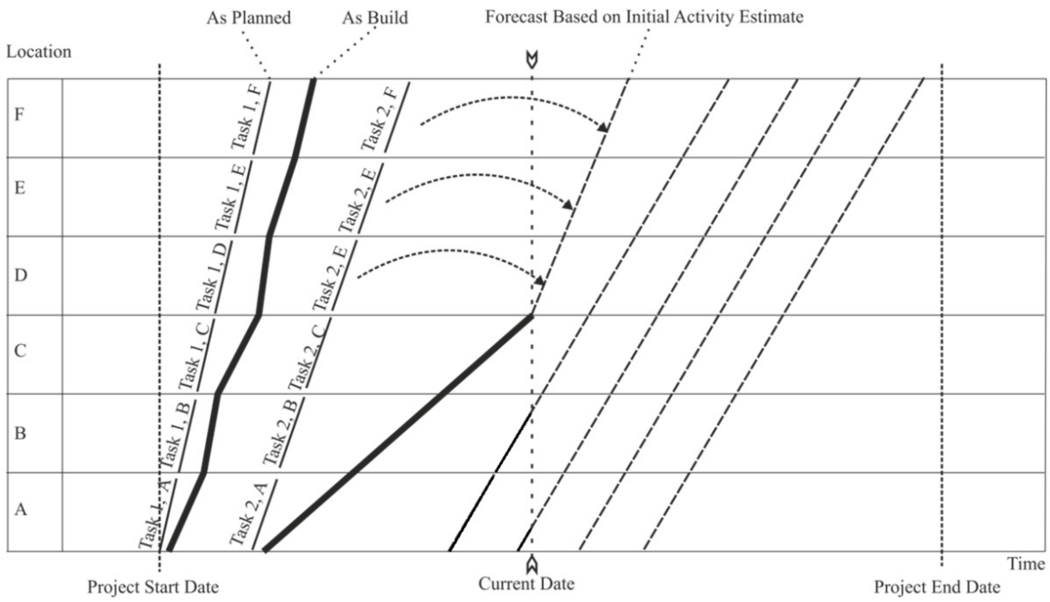

Figure 44: Discrete activity and resource usage, depicted in location-based view – as planned-based forecast.

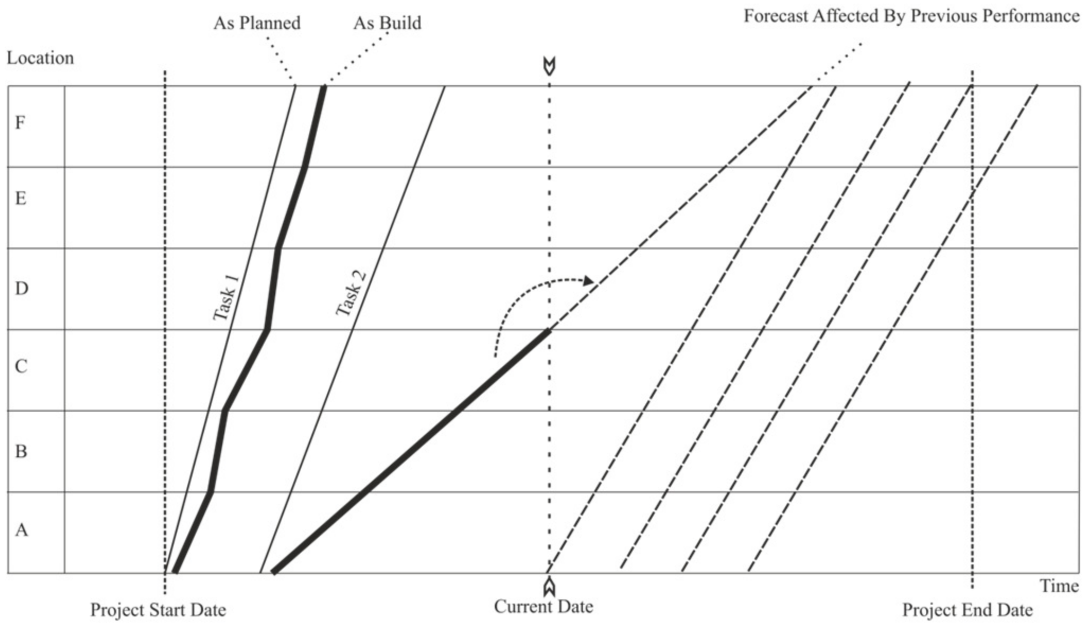

Figure 45: Continuous activity and resource usage – performance-based forecast.

Reduced flexibility in the completion sequence

Another significant difference between the criticality principles of LBM and the activity-based methods is that activity-based controlling rewards commencement in multiple locations.

Combined continuity and location constraints are important to a project's monitoring process. Late critical activities in activity-based methods are considered to be equally important because progress is tracked and visualized using percentage completion measurements. Activity-based methods do not illustrate the limitations imposed by slow production of certain tasks on remaining tasks because production rates are not explicitly shown. Project managers must compare all changes in progress in order to indicate the underlying productivity for each task. Once several activities on the critical path have been delayed, the project manager's view may be restricted to the effects of a fundamental productivity problem, rather than the fundamental productivity problem itself.

CPM controllers will commence multiple locations because they believe that this is faster and will lead to a reward from an indicated early commencement. For example, the Gantt chart from the case study in the third article (Figure 40) will communicate progress in terms of percentage of planned completion if several work faces are started, because location constraints are not shown explicitly. However, initiating work in multiple locations is not beneficial for the project lead time because it will take longer for a single crew to complete the first location, thereby blocking the progress of succeeding crews. This incorporates float between the flowlines and prolong the project lead time. This practice becomes apparent when the activities "flatline" in location-based schedules (a colloquialism meaning that the activity extends its duration greatly in excess of the planned duration because of an apparent difficulty in completing each location). Figure 42 illustrates this principle. The control data showed that such behavior of a few critical tasks in certain locations causes succeeding critical tasks to finish equally late in the same locations, as was the case for the *concrete finish-interior wall* task (Figure 42). The *concrete finish* tasks have many open work faces, which remain open and limit the progression of succeeding critical tasks.

To avoid multiple open work faces and flatlining activities, the constraints of the LBM criticality principle restricts work crews' flexibility in terms of work sequence. Despite the reduced flexibility, the rigid completion sequence entail that crews finish work in locations as fast as possible, thereby opening it up to succeeding crews, which ensures work continuity and minimization of float between tasks, and in turn reduces the project lead time.

Increased sensitivity

Aligning all tasks to the slowest task provides the most compressed schedule and the shortest project lead time, as described in section 2.7. More activities become critical in LBM compared to the activity-based methods due to the location constraints and continuity constraints as described previously in this section (4.2). The additional critical activities will make schedules more sensitive to fluctuations in productivity and delays because any delay will immediately cascade through the schedule (See section 2.8). Some of the additional sensitivity is a consequence of the optimization that arises when float is removed by exploiting vacant locations, grouping similar activities into continuous tasks, and aligning the production rates of critical tasks. However, some of the sensitivity is inherent in a project, although it is not shown explicitly in activity-based schedules because restrictions imposed by the location constraints are excluded, as described at the start of this section. Regardless of how the sensitivity arises, it must be mitigated to ensure effective completion of the construction projects. The activities and tasks must be protected, and LBM uses time buffers for that purpose. However, the placement and prioritization of time buffers on LBM projects have not been treated in current theory, as described in section 2.8. Accordingly, this subject has become a natural extension of the research on criticality. The results on buffer management in LBM are presented in section 4.3.

Contribution to the body of knowledge

The extant literature has not compared practical implications to scheduling and control of construction projects entailed by the criticality principle of LBM and the activity-based method's criticality principle. The present study contributes to the body of knowledge by relating technical, location, continuity and productivity constraints to the criticality of activities and explaining how schedules and the control effort is affect by them. The analysis builds on the conceptualized guidelines of the collected criticality principle of LBM that were established in section 4.1 and by means of as-built production data from a case study in the third article.

4.3 Results – Buffer management in location-based scheduling

More activities will be perceived to be, and be, critical when projects are scheduled and controlled with LBM compared to the activity based methods, as explained in section 4.2. Activity-based methods only rely on the technical constraints that form the logic dependencies. The addition of location constraints in LBM entails that multiple tasks are not scheduled simultaneously in the same location, while the continuity constraint ensures that all activities in a task are completed in succession. Further, technical, location, and continuity constraints mean that production rates for all critical tasks are aligned in fully optimized location-based schedules. Fully optimized LBM schedules seem like a rarity. However, regardless of the extent of optimization, a larger number of tasks are critical in LBM projects, compared to activity-based methods. The problem is that fully optimized LBM schedules are highly sensitive to fluctuations and delays in production because every task is critical. Current LBM theory recommends the application of stage, activity, location, and project buffers to mitigate schedule sensitivity and risks, as described in section 2.8. However, current LBM literature does not describe how these buffers should be prioritized and placed. Consequently, the fourth study adds to the body of knowledge by providing new theoretical guidelines for the placement of buffers in LBM. The guidelines are based on the buffer management paradigm of critical chain theory, empirical data on buffer placement and sizing along with tests in the case company.

A study of 14 LBM projects at the case company showed that buffers added up to 47 percent of an entire project's duration (Table 6), whereas other cases had schedules with no buffers. This implied that the lead time of some projects could be significantly shortened by reducing the buffers, whereas other projects were highly sensitive and vulnerable to disturbances. The application of different buffers and their sizes was also arbitrary; that is, the emphasis on activity, stage, and project buffers varied from project to project.

Project	Activity Buffer (Days)	Stage buffers (Days)	Weather Contingency (Days)	Project Buffers (Days)	Total buffer (Days)	Work Days	Buffer % of Workdays	Schedule type
1	5	148	25	60	238	510	47%	Tender
2	0	0	0	0	0	438	0%	Tender
3	9	76	0	0	85	328	26%	Tender
4	0	60	0	29	89	378	24%	Tender
5	60	0	0	0	60	648	9%	Construction
6	14	6	0	33	53	418	13%	Construction
7	25	105	0	101	231	630	37%	Construction
8	84	30	0	0	114	454	25%	Construction
9	94	0	0	50	144	714	13%	Tender
10	0	4	0	2	6	175	3%	Construction
11	0	16	0	0	16	152	7%	Construction
12	22	89	0	13	124	482	26%	Construction
13	0	0	0	19	19	381	5%	Construction
14	9	0	0	47	56	251	22%	Construction

Table 6: Analysis of the use of buffers on 14 projects.

Critical chain theory (CCT) was applied in the fourth article to provide the reasoning for the theoretical recommendations of an extended buffer management theory in LBM. However, the CCT had to be accommodated to the criticality principle of LBM, as it originally was based on the activity based methods. The CCT was accordingly applied to provide an answer to the third research question.

RQ3 (Repeated): How should time buffers be prioritized in projects that are scheduled and controlled with location-based management theory?

The recommendation from this research, and the answer to RQ3, is that stage buffers and weather contingency buffers should be avoided. Moreover, activity buffers should only be applied to the most sensitive critical tasks otherwise reallocated, and productivity feeding buffers should be incorporated in front of the slowest tasks, leaving the project buffer to predominate.

Figure 46 shows the generic types of buffers from LBM theory and Figure 47 shows the recommended placement from this research. The proposed addition to the LBM buffer management theory is summarized in the text below. Details on the reasoning behind the recommendations should be read in the fourth article.

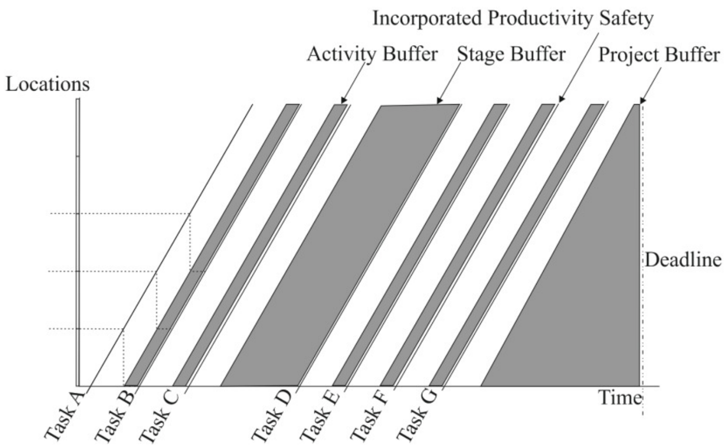

Figure 46: Generic placement of buffers in LBM.

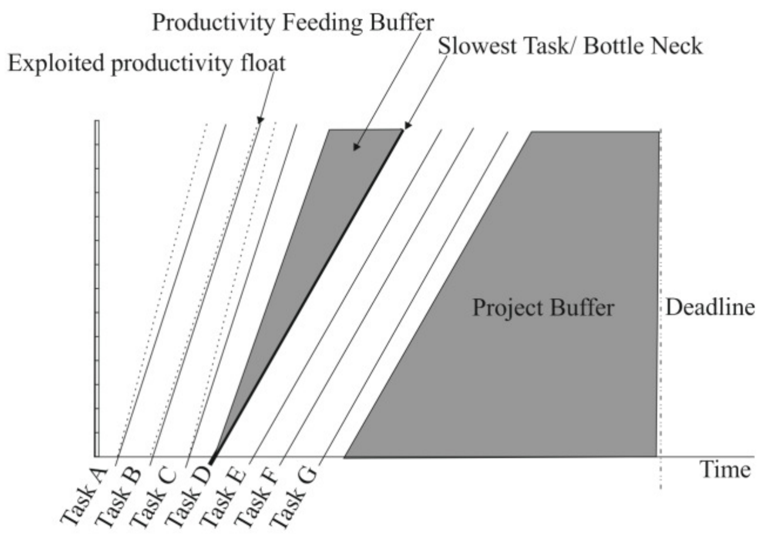

Figure 47: Recommended placement of buffers.

Productivity feeding buffers

Productivity feeding buffers should be established by exploiting excess production capacity before the slowest task. This is a feature that was inspired by the CCT, which recommends that the bottleneck task should protected at all cost, as it governs the progress of the project. The bottleneck task is similar to the slowest critical task which was described in sections 4.1 and 4.2. Doing so will provide a time contingency between the slowest critical task and its predecessors on all but the first location. Thus, the productivity feeding buffers is useful because it protects the slowest task without extending a project's lead time.

Activity buffers

CCT recommends the removal of all activity buffers. However, doing so can compromise the very essence of LBM; that is, the continuous work flow. Consequently, the activity buffers should encompass only the most sensitive activities and tasks as described by Kankainen and Seppänen (2003) (See section 2.8). Project no. 8 in the analysis of the current application of buffers indicated that 19 percent of total workdays were activity buffers (Table 6). Therefore, some projects incorporate vast amounts of activity buffers that may be wasted due to procrastination or if the project management fail to exploit early completions. In LBM, task sensitivity can be defined through Monte Carlo simulations. Optimistic, expected, and pessimistic duration estimates provide input for the simulation, which is performed approximately 10,000 times. The sensitivity of a task is determined from the number of times that a previous task affected it during the simulations. Allocating activity buffers should follow this type of sensitivity analysis to be justified and to avoid ineffective use of time contingencies. Task sensitivity is discussed further in section 4.4.

Project buffers

The project buffer should predominate, for the following four reasons: (1) to prevent unnecessary consumption of activity buffers, stage buffers, and weather contingencies; (2) to ensure that all of the buffer protects every task; (3) to ensure truthful communication of a project's progression in the control charts; and (4) to ensure that the risk of late completion is detected as early as possible. According to the CCT, placing buffers after each task or after stages can cause them to be consumed unnecessarily from procrastination because they can appear to be a part of the plan. The assumption is that construction crews will use all available time, which is why stage and activity buffers should be reduced to a minimum.

Further, project buffers protect all tasks, whereas activity buffers, location buffers, and stage buffers protect only the tasks that precede them. Buffers placed early cannot protect latter activities or tasks unless early completions are ensured and remaining tasks are moved forward.

Placing buffers in the early parts of schedules as activity, location, or stage buffers also affects how a project's progress can be communicated to clients or the head office of the general contractor, or even understood by project management themselves.

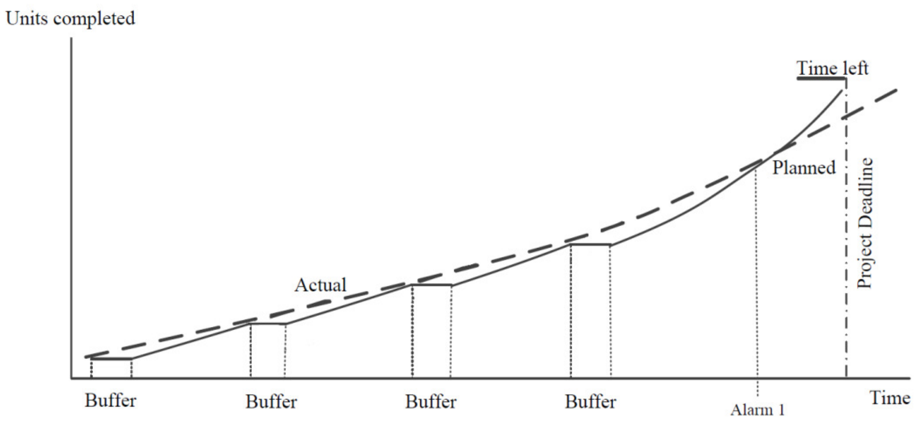

Figure 48: Early placement of buffers.

Early placement of buffers enables project managers to communicate that the project is progressing according to plan, even though each buffer is consumed and the time contingency diminishes toward the final stages of the project (Figure 48). Such practice is dangerous because project managers can deceive themselves and fail to acknowledge that a project's progress is worse than planned. Placing buffers early displaces the first point at which the project appears to be behind schedule because the buffer appears to be part of the plan. Figure 49 illustrates the same line of completion as in Figure 48. Instead of distributing the buffers across the project, they are placed collectively as a project buffer and divided into three sections. In the first section, the management should continue as planned, until the first third of the buffer is consumed according to the CCT. The second section of the buffer allows correction of the slow progress and time for creating contingency plans. The contingency plans should be implemented if the second section of the buffer is consumed, leaving the third section to protect the project from delays. The project buffer can then be used to control from and provide earlier warnings. Reliance on project buffers will consequently ensure that buffers are used for unforeseen events rather than to conveniently add time to reduce the need for corrective actions in the control process and, simultaneously, ensure a realistic portrayal of a project's state of completion.

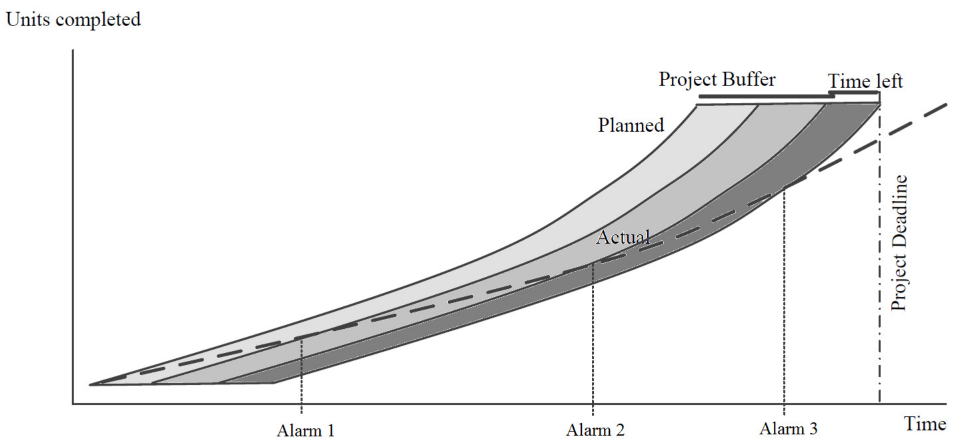

Figure 49: Late placement of buffers provides earlier warnings.

To summarize, stage buffers and weather contingency buffers should be avoided, activity buffers should only be applied to the most sensitive critical tasks otherwise reallocated, and productivity feeding buffers should be incorporated in front of the slowest tasks, leaving the project buffer to predominate. Allocating buffers to the end of schedules as project buffers reduces the temptation to procrastinate and consume buffers unnecessarily, protects all tasks, and ensures correct communication of a project's progress. It also provides a clearer picture of the remaining time contingency, and ultimately encourages a project's earlier delivery.

Contribution to the body of knowledge

The buffer management recommendations are a matter of prioritization. It is not recommended that all stage buffers and weather contingency be removed at all causes. Stage buffers might still be relevant if the cost of the buffer is lower than the cost resulting from a possible likely delay. Therefore, the basic buffer types that were presented in section 2.8 should persist. The theoretical guidelines suggest how the different types of buffers should be prioritized and should be seen as an addition to current theory. Thus, it is the prioritization and placement of buffers that constitutes the recommendations and the contribution to the body of knowledge.

Three issues in particular relate to these recommendations. The recommendations rely on the correctness of the assumption of procrastination, the size of buffers, and that the increased sensitivity that arise due to reduction in activity buffers is mitigated to conform with the requirements of continuous work flow in LBM. These issues will be discussed in section 4.4.

4.4 Discussion of the findings

This section discusses the identified scheduling and control problems, the criticality principle of LBM, and the recommended buffer management theory of LBM. This is accompanied by discussions of the delimitations of the research project and the effect of the constructivist research paradigm.

Discussion of the identified prevailing scheduling and control problems

This thesis does not address the majority of the identified prevailing scheduling and control problems at the case company. Understanding and applying the theoretical contributions of this research will depend of the extent to which construction companies succeed in addressing some of the identified problems from the case company. The use of LBM is subject to several prerequisites that its effectiveness depends upon that are not addressed in this thesis. Although organizational aspects are vital to the success of the method, such as for countering problem J (Section 1.2), they have not been included.

J. Input from subcontractors is **not incorporated in the earliest schedules** – Contracts are signed with little indication or analysis of **timely risk**, and construction process is sub-optimized.

Lean construction methods and LBM are likely to be applied symbiotically. This combination was discussed and researched previously by, for example, Kenley (2004) and Seppänen et al. (2010). Both methodologies commend production flow as a cornerstone for success in construction projects. LBM can provide the scheduling and control method to support the organizational and procedural aspects of the last planner system (see Ballard, 2000) that ensures close cooperation among building product manufactures, engineers, architects, and, most importantly, subcontractors. Although the organizational aspects are important for LBM, some of the other identified problems are direct prerequisites for the success of the technique, such as problems H, O, P, and R (See section 1.2):

> **Problem H. Necessary information is not available** for scheduling purposes early in the project. Design and construction processes overlap but are not coordinated, so inputs to schedules are often missing.
>
> **Problem O.** Detailed and **systemic recordings of performance data** on a weekly basis are **rarely done**.
>
> **Problem P. Base-line schedules are not used**. **Schedules** are **adapted to match current state**.
>
> **Problem R.** There is **little active use and understanding of dependencies**, **buffers, lags and float**

These fundamental problems must be addressed in practice to benefit from LBM in general and the theoretical contributions of this thesis. Missing necessary information is one of the most pressing problems because it is deeply rooted in the frequent failures in coordination and execution of the design process. Proper schedules cannot be created if the design and descriptions of building projects are not performed thoroughly, as it was described in the second article.

Problems with recording of performance data, baseline schedules, and a basic understanding of the technical aspects in scheduling and control indicate ineffective scheduling and control processes. The value and applicability of the schedules to the control process are diminished if task duration estimates and progress data are based on instincts and logic dependencies are not constructed properly. These behavioral and procedural problems must be addressed in order to harvest the benefits of LBM in general and the recommendations of this thesis.

Discussion of the criticality principle

Changing from activity-based control methods to location-based methods is expected to require more centralized coordination of construction crews. One challenge is to persuade all construction crews to follow the same production rate and sequence throughout the project. In this regard, observations of multiple LBM projects at the case company showed that construction crews have different preferences. Some construction crews prefer to work horizontally through the location breakdown structure (for example, foundations), whereas others prefer to work vertically (for example, plumbing). Many construction crews find following the same production rate controversial when first presented with the notion. Some construction crews are forced to work slower than their maximum production rate, which is unattractive for them if they are engaged through lump-sum contracts. However, location-based schedules and an understanding of the principles of the slowest critical task provide an explanation as to why they cannot complete their work faster, regardless of their efforts, given slower predecessors. Construction crews must reduce their pace or choose to work discontinuously; nevertheless, they must respect location constraints and not open up work faces unless their predecessor has finished. Observations of construction projects and discussions with LBM schedulers at the company revealed that construction crews tend to understand this aspect very quickly; therefore, the issue is considered a minor pitfall.

Fully aligned tasks

It is noted in the results that alignment of all critical tasks to the slowest task provides a fully optimized location-based schedule. Obtaining full alignment of all tasks seems rare. Several tender schedules at the case company were found to be fully aligned, but no fully aligned construction schedules were observed. Therefore, fully aligned schedules are not expected when the slowest task criticality principle is applied in practice. Nor are the overall flow lines of actual production expected to be neatly parallel, as experienced by Russell and Wong (1993):

We were quickly disabused of the notion that real-life projects followed the nice, neat parallel lines of a pure flow model (or for that matter, the precision portrayed by the traditional network diagram).

However, the principle of scheduling and controlling from the slowest critical task is the same. The production data from the third article showed that one slow critical task in some locations limits the progression of its successors. However, the slowest task would only be critical in certain sections, and then change to a different task.

Consequently, the slowest critical task should be analyzed at a detailed hierarchical level in the location breakdown structure, to ensure a more precise level of control.

Discussion of buffer management in LBM

Three issues are particularly important in relation to the recommended placement of buffers: the size of buffers in general, the sensitivity to production flow that arises if activity buffers are allocated only to the most sensitive activities, and correctness of the assumption regarding procrastination of the CCT.

Sizing of buffers in LBM is a topic for future research because few recommendations exist in current literature that is specified for LBM. Some research does exist from which this future research can be initiated. This literature was presented in section 2.8 and suggests that the sizing of buffers should be linked with an analysis of cash flow and impacts on a project profit.

A procedure for analyzing activities' sensitivity is also described in section 2.8. The sensitivity of activities in LBM is determined by Monte Carlo analysis, and should be used to prioritize available buffer amongst critical activities. Some critical activities will be more sensitive than others in a Monte Carlo analysis because it is based on the variability of each activity. Activities that have the least float in many of the simulations in the Monte Carlo analysis, will be the most sensitive and should be prioritized.

Neither Goldratt's (1997) research nor the present thesis prove the assumption of procrastination. Although the assumption is expected to hold frequently, no indisputable proof for the correctness of the assumption has been obtained. Project managers and contract managers who were interviewed recognized a tendency for procrastination, stating that available time is usually consumed and activities are rarely completed early. Even if activities finish early, the project does not benefit because succeeding tasks are not moved forward. Consequently, the statements supported the underlying assumption of procrastination, although the assumption remains an assumption until further research indicates its correctness.

Discussion of perceived complexity

The practical inspiration and point of departure for the research on criticality was the identified complexity of prevailing activity-based methods. Although perceived complexity is not the direct subject of research, the topic of criticality could provide the basic understanding that is needed for mitigating the seemingly complex environment of a construction project by imposing the additional constraints of the LBM criticality principle. Respecting and understanding the four constraints in the LBM criticality principle can provide a simplified way of scheduling and controlling projects as they follow a linear flow that is easily overview in the location-based schedules. The alleged simplicity arises out of the additional constraints that force tasks to align, and focusing on the slowest critical task should help practitioners in prioritizing the critical tasks as described in section 4.2, thus reducing the control effort.

The additional constraints exist in LBM because of the practical implications that follow if they are ignored. Ignoring location and continuity constraints and allowing crews to work simultaneously in the same locations or in random order can be hard to overview, manage, and control. Thus, illustrating location constraints explicitly may contribute to the alleged simplicity of LBM. Location constraints are difficult to identify in activity-based scheduling and control methods. Locations are incorporated into activity-based schedules by copying similar tasks and naming them according to their location. As similar activities are treated discretely, each activity, despite its similarity, must be altered individually when changes occur during project control. Although it is possible to abide by location constraints in activity-based methods, doing so is a complex and exhaustive task in practice, given the number of dependencies that must be defined for each activity. Accordingly, activities are commonly defined as generic summary tasks without specification of the intended location for the work. Failing to define the locations, and thereby avoiding multiple construction crews working in the same location, can cause rework and halts in production due to some crews not being able to complete their work at the given location. The location conflicts can mean that construction crews initiate work in other locations, which limits other construction crews' accessibility, potentially leading to discontinuous work and ultimately chaotic construction sites.

The continuity constraint is the focal point of LBM, but is not inherent in activity-based methods. The continuity constraint in LBM is a practical measure rather than a strict necessity. Building projects can be finished without respecting continuity constraints, but they will be completed ineffectively and be complicated to schedule and control. Accordingly, the continuity constraint is a "weak" constraint and can be broken if necessary. However, the constraint is important in LBM to ensure orderly completion of all critical tasks. Single critical tasks can delay all succeeding critical tasks if they break the working order and work in random locations because it incorporates float in the schedule. It is important to prevent construction crews from "jumping" from one location to another. Productivity will decrease if construction crews work in random locations because technical constraints make the crews depend on one another, which again can be a significant contributor to the experienced complexity of the activity based methods.

In short, although it may seem counter-intuitive, the additional constraints in LBM are the enabler for a more simple yet effective scheduling and control technique compared to the prevailing activity-based methods.

Discussion of the constructivist research paradigm

A principle conflict exists between the effort to contribute to LBM theory and the creation of knowledge through the constructivist paradigm. Project management theory, including LBM theory, is a generalization that is expected to be applicable in all or most circumstances within its scope; however, the creation of theory in this project is not generalized. It is emphasized that the results and theoretical contributions in this thesis must be viewed as theory development. The present research project must consequently be seen as the initial steps in a longer research process. Generalization of the recommended additions to LBM theory regarding the criticality principle and buffer management theory of LBM should accordingly be a subject for future research. Research within a positivist paradigm and using quantitative research methods could establish whether the theoretical contributions of this research are generally applicable, or to uncover special circumstances that would make it inapplicable.

Discussion of the delimitations

Section 1.5 presented the delimitations of the research project which included, amongst other, a focus on time management and focus on a selection of the identified problems. The delimitations on the problems were discussed previously in the present section. The delimitations on time management especially concern the disregard for cost and the isolated view of a contractor's perspective. These aspects are discussed below.

Cost is excluded

This thesis does not treat cost considerations as integrated part of the time dimension. Nor are mathematical aspects included. In particular, cost is essential to the slowest task and buffers. This thesis treats cost as a black box, but such treatment is not expected to directly influence the suggested theoretical guidelines. Cost can be a determining factor for the slowest critical task and the buffer sizing, but it does not change the principles of the recommended theoretical guidelines. The economic aspect is also interesting in relation to cost savings that result from exploiting the slowest critical task. The construction project that was applied as a case study in the third article had been subject to a large increase in resources because of timely delays. Calculating cost savings that result from reduced resource consumption on critical tasks that cannot be accelerated because of the slowest critical task, would be an interesting assignment for future research, because it would exemplify and indicate the monetary value of the enhanced focus LBM provides in this aspect.

The existing mathematics supports the suggested contribution because the constraints are described in current literature. Further, the slowest critical task and recommended buffer management theory are simply ways to focus the attention that can be operationalized using current mathematical theory in LBM.

Contractor's perspective

The research was performed from a general contractor's point of view. Views from and the expected effects on clients, sub-contractors, engineers, architects, and building product manufactures were not addressed.

Clients are expected to obtain more objective insights into the progress of their projects if buffers are placed according to the recommendations of this thesis. Enabling project buffers to predominate limits the ability to communicate an optimistic view of a project's progress to the client because buffers cannot be considered part of the duration estimates of activities.

Controlling from the slowest critical task requires that construction crews accept strict control by following a common predetermined sequence through the location breakdown structure and by respecting the continuity constraints as described in section 4.2. Breaking the location and continuity constraints can cause multiple activities in different critical tasks to become the slowest, which compromises the simple overview of controlling from the slowest critical task. However, construction crews should benefit from understanding the slowest critical task because it will illustrate whether they can progress at a given rate of production. Nevertheless, one construction crew will be the slowest, which could be portrayed and understood negatively if not handled correctly. Consequently, construction crews must understand the importance of the slowest critical task and be made aware of its effect on succeeding tasks, thereby promoting collaborating work processes such as integrated project delivery (IPD) (see, for example, Matthews and Howell, 2005) and Lean Construction initiatives (Ballard and Howell, 2003).

The combination of controlling from the slowest critical task and the application of buffers according to the CCT requires control and adaptability, particularly by construction crews, but also by engineers, architects, and building product manufactures. Removing the buffers and placing them last requires just-in-time deliveries from manufacturers and also requires that engineers and architects complete the design for upcoming tasks and locations if the design and construction phases overlap. Several interviewed project managers at the case company did not find these requirements problematic because current project control also requires construction crews, material deliveries, and other aspects of a project to accommodate timing that differs from what is specified in the original schedule.

Designers are also expected to benefit from the principle of the criticality of the slowest task. One recurring problem (Problem H) (Section 1.2) is the insufficient design basis that contractors experience during construction. Some tasks are slow because the design is not completed by the time it is needed. Importantly, the cause of slow progress must be considered and countered. One way to highlight the fundamental problems that restrict the progress of a task could be to include prerequisites from the seven streams in the last planner system (Ballard, 2000), such as the readiness of the design and the materials. This inclusion may assist in communicating and prioritizing the design effort, subsequently supporting flow on the construction site when construction and design processes overlap.

Future research

In summary from the above discussion, the following aspects are recommended for future research on LBM:

- Theoretical recommendations for quantification of buffer sizes in LBM should be carried out and elaborate on current literature. The research should incorporate the aspects of criticality from this thesis in order to prioritize allocation of available buffer.
- Micro management of LBM projects should be explored in greater depth, with focus on reducing activity buffers and closing the gap between critical flowlines. It is experienced through analysis of location based schedules that much spare time is incorporated into the schedules because locations are defined at too high a level in the location hierarchy. Future research should provide recomendations on the balance between the protective requirements of this spare time and the reduction in project lead time by means of micromanagement.
- LBM in relation to initiatives such as Lean Construction and concurrent engineering should be studied in further depth. It has been evident throughout this research project that the applied scheduling techniques must be implemented with organizational or procedural initiatives, which support the seemingly complex task of controlling construction projects. Much current literature targets these initiatives,

however little research includes LBM as a supporting scheduling and control technique.

- Economic aspects should be studied in relation to the results in this thesis regarding criticality, for example to establish the monetary value of focusing on the slowest critical task or the potential cost savings related to the recommended placement of buffers.
- Generalization of the results should also be a subject for future research. This research did not aim to generalize the results. Future research should apply the findings in additional settings and contexts and indicate the generalizability of the findings.

4.5 Concluding Remarks

The findings in this research project have the potential to affect current practice of scheduling and control of building projects. The case company developed immensely from undertaking the research project. Presentations on the slowest task criticality aspect had a major effect on top management, who flowingly initiated significant investments in LBM.

The results have been presented to all layers of the case company, from top management to contract managers, on both on-going construction projects, projects in the planning phase and internal conferences, to receive feedback and criticism. These presentations ensured the practical relevance of the research and initiated a companywide debate regarding current scheduling and control processes, methods, and tools. LBM is now one of the highest prioritized *technical* initiatives in most business areas at the case company. Obviously, the investments and interest in LBM are not attributed to this research project alone because LBM has many more advantages and several other people have promoted and worked with it. However, the research project was a determining factor because it clarified the limitations of prevailing scheduling and control methods and contributed by moving location-based scheduling from the purely technical aspect of flow-line schedules to more advanced LBM. Several project managers, schedulers, and contract managers expressed their interest in the slowest task criticality principle and buffer management theory and intend to apply it on future projects. The hope is that the contributions from this thesis can inspire other construction companies equally.

In conclusion, this research project provides the following three main theoretical contributions to the body of knowledge:

1. A theoretical conceptualization of the criticality principle of LBM by linking inherent constraints in LBM to how activities and tasks affect a project's lead time. The collected criticality principle of LBM is suggested to contain the following aspects:
    - Activities or tasks on the longest path or paths through a project's dependency network with zero float are critical.
    - Activities or tasks are critical if they are allocated to a location that imposes time delays on activities on the longest path or paths in a project's dependency network with zero float.
    - Activities or tasks that cause discontinuity of activities and tasks on the longest path or paths through a project's dependency network with zero float are critical.
    - The most critical activity or task is that which has the lowest production rate on the longest path or paths through a project's dependency network with zero float.

2. A contribution to location-based management theory and practice by combining LBM theory and actual production data to illustrate the effects, of the established LBM criticality principle on scheduling and control of

construction projects compared to the criticality principle of the prevailing techniques. The findings suggest that the combined criticality principle of LBM entails five major effects:

- The number of activities that are critical, and appear to be critical, increases.
- Critical activities can be prioritized by means of the slowest critical task.
- Consequences from slower-than-planned production performance of critical tasks are forecasted more negatively.
- Work crews' flexibility of work sequence through a building is reduced.
- The sensitivity to disturbances and fluctuation in production rates increases.

3. A contribution to the buffer management theory of location-based management through the application of critical chain theory, and a case study on the current use of buffers in LBM projects. The recommendations suggest how buffers should be placed and prioritized, which closes a gap in current LBM literature. These recommendations are that stage buffers and weather contingency buffers should be avoided. Moreover, activity buffers should only be applied to the most sensitive critical tasks, and should otherwise be reallocated; and productivity feeding buffers should be incorporated ahead of the slowest tasks, leaving the project buffer to predominate.

Stating these contributions concludes this thesis.

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Appendix – Articles

Article 1 - BIM-based scheduling of construction

BIM-based scheduling of construction
– A comparative analysis of prevailing and bim-based scheduling processes

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ABSTRACT

The potential of BIM is generally recognized in the construction industry, but the practical application of BIM for management purposes is, however, still limited among contractors. The objective of this study is to review the current scheduling process of construction in light of BIM-based scheduling, and to identify how it should be incorporated into current practice. The analysis of the current scheduling processes identifies significant discrepancies between the overall and the detailed levels of scheduling. The overall scheduling process is described as an individual endeavor with limited and unsystematic sharing of knowledge within and between projects. Thus, the reuse of scheduling data and experiences are inadequate, preventing continuous improvements of the overall schedules. Besides, the overall scheduling process suffers from lack of information, caused by uncoordinated and unsynchronized overlap of the design and construction processes. Consequently, the overall scheduling is primarily based on intuition and personal experiences, rather than well founded figures of the specific project. Finally, the overall schedule is comprehensive and complex, and consequently, difficult to overview and communicate. Scheduling on the detailed level, on the other hand, follows a stipulated approach to scheduling, i.e. the Last Planner System (LPS), which is characterized by involvement of all actors in the construction phase. Thus, the major challenge when implementing BIM-based scheduling is to improve overall scheduling, which in turn, can secure a better starting point of the LPS. The study points to the necessity of involving subcontractors and manufactures in the earliest phases of the project in order to create project specific information for the overall schedule. In addition, the design process should be prioritized and coordinated with each craft, a process library should be introduced to promote transfer of knowledge and continuous improvements, and information flow between design and scheduling processes must change from push to pull.

Keywords: BIM, planning and scheduling, gap analysis, 4D-modeling, implementation

Introduction

The Critical Path Method (CPM) constitutes the prevailing technique for planning and scheduling of construction projects, since it was introduced in the late 1950s. CPM has proven to be a very powerful technique for planning, scheduling and controlling projects, especially for complex and non-repetitive work (Kenley 2006). However, despite the dominance of the CPM-method there is criticism raised on the method for the management of construction work. The criticism of CPM primarily refers to the inability to manage and monitor resource limitations in a way that corresponds to the reality of construction, i.e. work that to a large extent is characterised by repetition (Kenley 2006). Consequently, resources such as labour, building materials and equipment are seldom allocated to the scheduled activities despite the obvious requirement of work and resource coordination in construction works (Andersson and Johansson 1996). Thus, the activities, and their logical connections, are the principle focus of the CPM-method, whereas it is often assumed that there are unlimited resources available for executing the work. CPM-based schedules that are graphically represented by Gantt charts, the universal graphical representation of schedules that was introduced by Gantt and Taylor in the early 1900, may result in discontinuous resource usage that in turn will lead to interruptions in the production where each trade suffers from recurrent starts and stops during the project process (Andersson and Christensen 2007). Together with the Gantt chart, CPM provides the common corner stone in the vast number of scheduling software tools available on the market (Kenley 2004).

The implementation of building information modelling, BIM, currently being adopted by many actors in the construction industry, will substantially change the way construction work is organized, performed and documented (Eastman et. al. 2008) and will allow for considerable improvements to the construction delivery process (Goedert and Meadati, 2008). The employment of BIM enhances trade coordination as it turns architectural and engineering design and management disciplines of cost estimating, time scheduling, constructability analysis, risk management, procurement, etc. into parallel and integrated processes (Kousheshi and Westergren, 2008). Though the benefits of the BIM are well documented and implemented among many architects and consultants working in the early stage of construction, the utilization of BIM for the management of construction work, e.g. scheduling, is, however, still about to emerge in industry (Goedert and Meadati, 2008).

BIM-based scheduling, also referred to as 4D-modeling or 4D CAD, in which the time schedule is linked to and visually presented by a 3D-model, is however widely recognised in research studies and literature (e.g. McKinney and Fischer 1998, Koo and Fischer 2000, Kamat and Martinez 2002, Kähkönen and Leinonen 2003, Heesom and Mahdjoubi 2004 and Chau et.al. 2005 among others). 4D-modeling bridges the gap between the 3D-modeling in the design phase and the planning and scheduling of the construction phase. 4D-modeling provides increased possibilities of identifying unanticipated problems and inconsistencies beforehand by viewing the graphical presentation, it facilitates the understanding of the scheduling results and supports the identification of potential time-space conflicts (Koo and Fischer 2000). The possibilities of evaluating and optimizing design and scheduling alternatives in the context of space and time is also brought out by Webb et.al. (2004) as a significant benefit of 4D-modeling, besides that it promotes improved integration and communication between the various participants in the construction process.

Besides the benefits of 4D-modeling identified, there are also obstacles reported on the path towards model-based scheduling for construction management purposes. Porkka and Kähkönen (2007) points out the lack of standardization as one major obstacle, addressing the need for software interoperability and information exchange. Another issue of 4D-modeling that concerns the software systems is the biased focus on aesthetic visualization of spatial-time process, with less developed options for analyses of the scheduling scenarios (Heesom and Mahdjoubi 2004). However, a 4D-representation can contribute greatly to the understanding of a complex schedule. Visual communication tends to increase the involvement of workers, since it allows rapid comprehension of and response to problems (Formoso, et.al. 2002). Consequently, BIM-based scheduling can contribute by illustrating the entire project to project participants, making it easier to envision potential issues, as activities are integrated with building components, time and cost. Thus, BIM-based scheduling can help to reduce risk by enabling project managers to collect, structure, and communicate vast amount of information. The superior communication abilities of BIM-based scheduling can be applied on a detailed as well as an overall comprehensive schedule level.

Problem Statement

Currently there is a major focus on the use of BIM. As companies start to implement BIM, it seems like a natural step to focus on 3D-design initially and exploit straightforward advantages like design coordination and clash detection. One opportunity to derive further advantages from BIM is to use it for scheduling purposes. But, what challenges are companies facing when implementing BIM-based scheduling? Moving towards BIM-based scheduling of construction implies a significant process of change that will include a number of technological, organizational as well as other challenges for all parties of concern. A change process of this magnitude requires a clearly formulated vision, strategy and communicated goal (Kotter 1999), besides an understanding and awareness of the need for change. Awareness of the need for change has its starting point in the current situation. Thus, a solid understanding of the current situation of scheduling in construction, its pros and cons, is necessary to analyze expected effects on the organization with the introduction of BIM-based scheduling.

Purpose and Objectives

The purpose of this study is to analyze current scheduling practice in construction and put forward arguments on how BIM-based scheduling can and should effect the organization. Consequently, there are three objectives in the study. One objective is to describe the current situation of scheduling in a case company. The second objective is to analyze the current situation in the light of BIM-based scheduling, and argue how BIM can be integrated to counter the challenges and support best practice work methods. The third objective is to analyze major necessary expected changes to the case company, if the transition to BIM-based scheduling were to be realized.

Definitions and Delimitations

There are numerous explanations and definitions of Building Information Modeling, BIM, available in literature, e.g. BIM constitutes "a conceptual approach ... that encompasses three-dimensional (3D) parametric modeling of buildings ... and computer-intelligible exchange of building information..." (Sacks et.al. 2010), "… a set of interacting policies, processes and technologies…"(Succar 2009), "a methodology to manage the essential building design and project data in digital format throughout the building's life-cycle" (Penttilä 2006). (C. Eastman, 2009) refers to a building model "as the basis for BIM" and implies that "BIM is a process."

Thus, BIM is described in terms of an integrated process or as technology, and accordingly, the BIM-abbreviation refers to both Building Information Modelling as well as Building Information Model. The modelling understanding of BIM refers to the process of generating and managing (building) information in an integrated and collaborative way. It is the BIM process that generates the Building Information Model, which typically includes a 3D representation of the building with information about the building geometry and spatial relationship and quantities and properties of the building components etc. Thus, the Building Information Model constitutes a virtual mock-up that visualizes the building in 3D and enables the various actors of the project to add and retrieve information from the model through the lifecycle of a building. This study connects to the understanding of BIM as the collaborative process that involves and integrates the input from the various actors of the project.

The scope of the study is delimited to BIM-based scheduling. BIM-based scheduling of construction work is, in this context, described as the management processes that make use of, and add to, the Building Information Model of the project. The scope of the study is additionally delimited to the planning and scheduling process of construction, i.e. the coordination of the work activities that take place on the construction site and the processes in the tender and planning phase. Accordingly, the scheduling process is reviewed in light of the construction management team of the main contractor.

Method

The empirical foundation for the study is based on qualitative interviews, including both individual interviews and focus group interviews. All interviews were conducted within one Danish contracting company with 5.500 employees - MT Hojgaard a/s. MT Hojgaard has its own department for Design and Engineering, which masters 3D-design, but is only beginning to exploit the digital models for other purposes. 20 people participated in the interviews in total. All participants was explicitly selected from their field of expertise, age and knowledge regarding planning and scheduling.

First, individual and focus group interviews were performed with focus on challenges and best practice in scheduling on construction projects. These interviews included project managers, process managers and contract managers representing the operational and tactical level of the company. All interviews followed an interview guide which was sectioned by a holistic transformation process model covering input, process, and output. The model was used to keep focus on the entire scheduling process in the interview guide. The input part included topics like, but was not restricted to, quality, availability, type and integration of information in scheduling. The process part included subjects like interconnections, managing the schedules, responsibilities and automation. Topics concerning the output included use of the output, standards, communication and revisions of the schedules. The same structure was used at all the interviews. As the objective was to explore the current state of scheduling, the interviews was explorative and with open-ended questions.

Secondly, the same subjects were put forward to the interviewees with strategic responsibilities. Participants in this focus group included representatives from top management and senior management all with comprehensive knowledge of scheduling. The interview guide from the first group of interviews was used. However, as these interviews had a strategic focus, this second round of interviews generated completely different outcomes. The purpose of the strategic interviews was to gather information on long term effects of the challenges and best practice of scheduling on the organization. The study is carried out with the purpose of describing one case in depth. Thus, in this study there has been no attempt to generalize the results. The end result is summarized and represented in the following section.

The Current Scheduling process

The account of the current approach to scheduling is divided into two sections. The first section describes the overall scheduling level that comprises the whole project and the second reports on the detailed level that covers a period of one to five weeks. The choice of this outline rests upon the fundamentally different approaches to scheduling identified at the overall and the detailed level.

The overall level of planning and scheduling

The overall planning and scheduling level refers to the so called production schedule, which is established by the main contractor in the planning stage when the contract has been signed and the onsite activities are to be prepared. The master schedule, which is the most comprehensive schedule, typically established by the client, provides an overall framework for the production schedule. However, the master schedule is primarily considered a legal document, enclosed the contract, and has limited impact on the planning and scheduling of the production. Thus, the overall planning and scheduling in this context refers to the production schedule established by the general contractor.

The overall planning and scheduling process is to a large extent characterised as being an individual endeavor, closely related to the knowledge, professional skills, role and identity of the project manager who establishes the schedule. Managing the scheduling process implies a significant amount of control, power and influence on the production process, and thus, being individually responsible for the scheduling contributes to the role and impact of the project manager. - “Scheduling does not follow an outlined and predefined process ... different schedulers have their own personal planning and scheduling process.” Scheduling, at the overall level, relies to a significant extend on intuition and the personal experiences of the project manager, rather than on complete well known figures about the construction project and its context. Another example of the individual dimension that characterises the scheduling process at the overall level is stated as - “Scheduling is an inspirational and intuitive endeavor. The principle scheduling input is not provided by explicit figures and facts about the project, instead the choice of relevant production methods, the establishment of activities and their interconnections, assessment of durations etc. rely on personal experience and intuition of the construction manager.”

The strong support on intuition and personal experience is, as explained by the project managers, partly a consequence of the overlap between the design and the production phases which delimits the available amount of information in the early planning phase. The building design stretches into the construction phase, although the design is expected to be complete when construction starts. As the design is not complete when needed, necessary information for the overall scheduling is often unavailable. Thus, insufficient communication and scarce coordination of work between the design and the production teams render difficulties for the planning and preparation of the onsite production. However, when the information is available, the project managers often find it difficult to assess and take in the information that is of relevance for scheduling purposes. The overload of information in this context refers to the vast number of drawings, project specifications, contracts, etc. that constitute the extensive project documentation, which is difficult to assimilate and to use as a basis for understanding the project and its characteristics. One problem highlighted in connection to the drawings was that there are too many of them, and the content is not for scheduling purposes but for construction purposes. -“The amount information in the drawings is difficult to grasp. The vast number of different drawings (A and E) made it difficult to get an overview of the project. Rather than going through the set of drawings, the scheduler gets introduced orally to the project by the appointed project manager and the management team.” It is the pronounced generic characteristics of the overall scheduling that enables and allows intuition and experience, with only limited consideration of project specific figures, to be the prominent scheduling characteristics at the overall level. - “The fundamental structure and sequence is basically the same in every building project, which means that part of schedules can be stored and reused in a subsequent project, e.g. the assembly sequence of an elevator, an interior wall, etc., after adjusting the durations of the respective activities.”

Another of the interviewed project managers had, however, a different view on this subject. -“The projects are unique, so it is not possible to reuse parts of other schedules. It is easier to create a new schedule for every project.” The conflicting opinions can both be considered valid depending on the level of detail by which the project is observed. If the construction project is considered on an overall level, very few buildings are identical. However, different construction projects can easily comprise of parts, subsystems or technical solutions which is similar from project to project. Thus some employees find that data of scheduling can be reused and some do not. Regardless of how a project is perceived by the individual employee, the fact is that there is no systematic storage and reuse of scheduling data presently in the case company. Consequently the transfer of knowledge between employees is mostly through personal relations. The case company has launched an initiative, teaching all project managers a standard for scheduling, in order to support knowledge sharing. Despite this effort, the use of the same scheduling standard does not promote knowledge transfer. The individual character of the current scheduling procedure impedes the sharing of scheduling knowledge and skills between colleagues in the projects and in the company. Thus, the approach to scheduling, i.e. how the scheduling process is designed, the information content etc., is again an example of an individual choice by the respective project manager. -"There are no company processes securing the quality of the schedules, but some best cases are made available on the intranet." - "... the company does not express any explicit rules and requirements regarding the schedules developed in a project."

The traditional scheduling method of CPM and Gantt charts, supported by MS Project, constitute the prevailing approach to scheduling. A Gantt-schedule of a general building project includes about 2 000 – 3 000 interlinked activities. The vast number of activities and links make it difficult to get an overview of the work processes of the project, besides it is difficult to communicate the schedule to subcontractors, suppliers and other actors involved in the project.- "It does not make sense to make a printout of the schedule or to send it to the subcontractors. It is simply too extensive and I guess I am the only one who can fully understand and read it."

Further, the comprehensive and complex structure of the overall schedule makes it difficult to use as a tool in the daily management and control of the project, i.e. the progress control. -"… the plans are typically not updated because changes keep coming in and the focus is elsewhere."- "If a master plan is too detailed, it will not be used because the craftsmen and other users loose the overview of the plan." - "The schedule for the KPMG-project consists of 5000 separated activities, which is of course difficult to use as a basis for progress control."

The detailed level of planning and scheduling

The most significant and important improvement of the scheduling process through recent years is represented by the implementation of the Lean Construction philosophy and the Last Planner System, LPS in the construction phase. The interviewees emphasised, in concordance, the importance of the so called process planning and the LPS, in which all actors of concern, meet, discuss and add their professional knowledge and skills as input to the coordination of work. The involvement and commitment of the various actors of the project creates a strong sense of ownership for the plans and schedules that are established. - "Acceptance and ownership of the schedule is a key issue in scheduling. Scheduling is about communication – input as well as output." - "Dialogue, involvement, a sense of ownership and commitment to the schedule among all suppliers to the project is fundamentally crucial to the acceptance and successful implementation of all of the scheduling in the project."

LPS puts focus on the day-by-day management of the onsite activities, with a narrow scheduling range of one and five weeks. Despite the short time scope, LPS is dependent on the overall project conditions, e.g. if the overall schedule includes fragmented and overlapping activities then the beneficial contribution of the detailed scheduling is reduced. Thus, the quality of the overall level of scheduling sets the conditions for the detailed level, but the interconnection between the scheduling levels is currently insufficient. One project manager describes this issue according to the following quote:- "The interconnection between the top down and the bottom up scheduling is critical. [...] Early decisions are based on the top down schedule, but this provides an insufficient information basis at the time. The problems that follow will show up in the detailed bottom-up scheduling. The two scheduling approaches should eventually meet, and hopefully correspond. However ... the overall schedule provides an insufficient information basis for the detailed weekly scheduling process."

The disconnection between the overall and the detailed scheduling, referred to as top-down and bottom up planning in the quote above, must be considered a major challenge and drawback in the current scheduling process as it impairs the power of the LPS on the detailed level.

Moving towards BIM-based scheduling

The current state analysis of the planning and scheduling process reveals significant discrepancies in the approach to scheduling at the overall and the detailed levels. The overall scheduling process is described as an individual endeavour carried out by the project manager or the management team of the main contractor. As the overall scheduling is performed individually, sharing of knowledge is restricted to unsystematic personal initiatives. Thus the reuse of data in scheduling is limited in the case company which, further, creates a challenge of continuous improvements regarding the overall schedule. In addition, the design and construction processes overlap, are separate and unsynchronized, resulting in absence of necessary information to the overall schedule. This leaves the overall scheduling to be based on intuition and personal experiences, rather than extensive and explicit figures of the specific project. Finally, the overall schedule is deemed comprehensive and complex, and consequently, difficult to overview and communicate to other project participants. Scheduling on the detailed level, on the other hand, follows a stipulated approach to scheduling, i.e. the LPS, which is characterized by participation and involvement of all actors on a project in the construction phase.

Thus, the main goal with the introduction of BIM-based scheduling in this context must be to ensure a better match between the top-down overall scheduling and the bottom-up scheduling approach of LPS. As the interviewees express great satisfaction towards the LPS, focus for further improvement of scheduling should be directed towards the overall top-down scheduling. By ensuring improved overall schedules, the project team will have a better starting point for the LPS and in turn more precise control of the project and finally improved risk management of time.

Personal experience and intuition, design coordination

Although the potential and importance of early involvement of subcontractors is clear, it is limited to the construction phase. By including the subcontractors in the early tender and planning phase, qualified and project specific information can be include in the schedule – similar to LPS. However, the manufactures also have a lot of knowledge regarding time consumption and processes, related to their products. E.g. several lift manufactures supply both the physical product and mange the installation process. Thus both subcontractors and manufactures should be included in the initial planning phase of a construction project to provide scheduling input. Incorporating direct input from subcontractors and manufactures in the overall schedule can potentially enhance the precision and create a closer connection to the bottom-up planning of LPS. However, there will still be a problem of missing information due to late design decisions.

The design continues into the construction phase

One option is to design the building completely before construction starts as it is expected to currently. However, this is, as described, difficult to obtain currently and it is uncertain whether the introduction BIM can counter this issue. Another option is to allow for design alterations in the construction phase and promote coordination of the design effort. By incorporating subcontractors and manufactures early in the design phase, the project team could decide on the macro design and prioritize solutions fundamental to the progress of the project. Thus, in a collaborative effort the project team could decide on which areas, elements or systems that must be readily designed before construction can start. Only when the macro design has finished, and agreed upon by the engineer, architect, contractor, and client, construction can commence. During construction, the coordination process between design and construction can continue, but with focus on the earlier de-prioritized areas of the building. By introducing this form of concurrent engineering to overall scheduling, the construction team can obtain the right information, at the right time in the right level of detail. Thus, involvement of subcontractors and manufactures can address both the issue of schedules being created from personal intuition and experience as well as the issue of absent information due to the uncoordinated design process. However, the use of subcontractors and manufactures does not secure knowledge sharing and continuous improvements of the overall scheduling internally in the company.

Knowledge sharing and continuous improvements

The case company will need to secure information obtained on each project with the goal of reusing it. However, as stated earlier, many participants in the interviews supports the view of construction projects being unique, while others find the final product unique, but with several sub-systems and the associated processes are repeated in most cases. If it is assumed that objects and consequently processes can be reused, it would be obvious to create an object library. The concept of an object library is well known. E.g. Autodesk Seek. Each BIM-object is stored in a database containing relevant information or links to information for the specific object. Likewise, a library for processes could be created containing historic data of how systems, subsystems or objects from the object library were processed. However, it is unlikely that each object, subsystem and system in the object library, can be linked to standard processes and reused directly on new projects. E.g. the same window installed on the 20th floor in an apartment building and in a single story house, would require different processes. Thus it is unlikely that the schedule can be created directly by use of object from prior projects. Despite this challenge, a process library could supply historic data in areas of the master schedule where information from subcontractors and suppliers is not obtained, due to the time pressure in the tender, design and construction phase. Thus, with the use of BIM-based scheduling, the master schedule can be created from explicit knowledge from subcontractors and suppliers on highly prioritized areas of the project, while the remaining parts can be created from the library until there is time to detail it. Consequently, the purpose of the library will be to create a foundation from which the schedule can be created.

Expectedly it will always require a critical approach from individuals with explicit knowledge. However, a process library can support systematic use of data, knowledge sharing and function as a starting point on each new project. Further, the introduction of the library is obviously a long term investment, and it will probably take a few years to become effective. However, it also has the potential of countering the challenge of continuous improvements of overall scheduling in the case company. As there undoubtedly are numerous challenges combined with the creation and implementation of a process library, it is an apparent subject for future research.

Information overload

As stated in the previous section there is currently an issue of information overload from drawings and specifications of the design. Thus, the introduction of BIM-based scheduling should ensure that only relevant information is processed. Consequently, when transitioning into BIM-based scheduling, the flow of information from the design to the scheduling processes must change from the current push approach to pull. Instead of basing the overall scheduling on technical drawings and specifications, the person accountable for the schedule should be able to pull necessary information from the design, at the relevant level of detail. However, with the use of BIM, both options are possible. Potentially, the case company can continue to produce and use technical drawings and specifications as basis for the overall scheduling even if BIM is introduced. Consequently, in order to counter the current problems of improper information for scheduling purposes, the case company must transform the tendency of pushing out information in terms of drawings and specifications and allow employees to pull information from a model or other information source.

The overall schedule is comprehensive and complex

BIM-based scheduling is an obvious solution to the issue of comprehensive and complex schedules. Communicating the overall schedule, regardless of the complexity of the schedule, has proved to be very effective with BIM-based scheduling and it is well documented, as stated in the introduction. However, there is a difference between communicating the end result of a schedule in a 4D-animaiton and working with the underlying schedule. If the schedule contains several thousand activities, it will still be difficult to overview work in progress despite introduction of BIM-based scheduling and 4D-animations. Thus, although BIM-based scheduling has potential of enhancing communication of the schedule, another tool or approach is needed to promote the usability and comprehension of the schedules under development. One option is to introduce Location Based Scheduling (LBS). Jongeling and Olofsson (2007) claim that Location-based scheduling (LBS), which combines the dimensions of time and location of the activities of the project, can enhance the usability of 4D-modeling for improved work-flow analyses of production via the Line of Balance method. As Line of Balance summarizes similar activities and illustrates them by location and time with lines, an overview of the entire schedule can be shown in one single diagram. As commercial software which integrates LBS with BIM is readily available, and the advantages of LBS and BIM are well covered in the literature, this issue will not be subject of further analysis in this paper.

Conclusion

Overall the study finds that most challenges with scheduling in the case company originate from the early stages of the construction project. The case company has great success with the LPS in the construction phase, scheduling and controlling the project from the bottom up. The major challenge is to create trustworthy overall schedules. The issue is that, the detailed bottom up scheduling of the project builds on assumptions created in the early phases from the top down approach of the overall scheduling. Accordingly, there is a clash between the two scheduling approaches, with most issues originating from the overall schedule. One challenge is that the overall schedule is created from personal experience and intuition. This limits accuracy of the schedule and in turn the trustworthiness. In addition, as the overall schedules are created from personal experience and intuition, it is difficult to share knowledge systematically and thus secure continuous improvements. Moreover, necessary information to the overall schedule is often limited, as the design and construction processes overlap, are separate and unsynchronized. This again, leaves the overall scheduling to be based on intuition and personal experiences, rather well defined figures of the specific project. Finally, employees accountable for the overall schedule have difficulties processing the vast amount of information stored in the building design, as schedules are created from technical drawings and specifications not suited for scheduling purposes.

As BIM-based scheduling is an ambiguous concept and has no bounded goals, configuring and implementing the technology is very much a matter of adapting it to the needs and current state of the organization. In this case it is evident that BIM-based scheduling cannot solve the current challenges without a restructuring of processes, work methods and norms. Involvement of subcontractors and manufactures in the very beginning of a project is vital for the success of BIM-based schedule in this case. If scheduling is not based on project specific figures, little is gained with BIM-based scheduling. There might be an advantage of visualizing the schedule in a 4D-animation, but if the schedule is not based on input derived directly from the design and realistic solutions, the full potential of BIM-based scheduling is not exploited, and the current issues are not addressed. However, if subcontractors and manufactures are involved, BIM-based scheduling can constitute a centralized platform for coordination and communication between the design team, subcontractors, manufactures and the person accountable for the overall schedule. Involvement of subcontractors and manufactures can also play an important role in coordinating and prioritizing the design effort, effectively securing a trustworthy project specific estimate of time consumption at the right level of detail and at the right time. Securing transfer of knowledge between knowledge and employees and reusing it for continuous improvements purposes is also a challenge which is dependent new work methods if BIM-based scheduling is implemented. Although not unproblematic, a process library, linked to an object library can potentially form the foundation for the overall schedules and fill out gaps where project specific knowledge has not yet been obtained from the subcontractors and manufactures. Applying a library of processes enables experience from prior projects to be transferred and reused on new projects. The historic data can obviously not be applied uncritically. Human judgment will still be of essence. However, a process library can potentially increase effectiveness and promote knowledge transfer as data can be shared systematically. Solving the current challenge of information overload with BIM-based scheduling also requires renewed work methodologies. When introducing BIM-based scheduling, the system must allow that information is pulled from the design, contrary to the push of information which occurs presently. By pulling the information from the design, the person accountable for the overall schedule, subcontractor or manufacturer can sort out unnecessary details, ending up with more comprehensible data for use in the overall schedule.

Conclusively, introducing BIM-based scheduling is not a question of simply applying a new tool to the current organization. Without a thorough change of current practices, norms and processes BIM-based scheduling can only improve some of the challenges faced by the case company. In fact, several of the challenges could be countered without the use of BIM-based scheduling. However, the challenges have not been resolved so far. Thus, BIM-based scheduling can solve some challenges directly and concurrently be the mean to initiate and facilitate new processes, work methods and norms which counter the remaining challenges of scheduling in the case company.

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Article 2 - Exploring Scheduling Problems in the Construction Industry

Exploring Scheduling Problems in the Construction Industry – A Case Study

By Rolf Büchmann-Slorup

Abstract

This article presents a case study on existing major problems in construction scheduling and compares them with available technical solutions and work methods to identify areas lacking attention from the industry and research. The study began with an investigation of whether current technological and methodological practices provide solutions to existing scheduling problems in construction, and found that solutions exist for most of the identified problems. However, three problems have received little attention from the companies involved in this case study: (1) schedules created during the tender phase are based on the personal intuition and experience of project managers, as time is scarce and no decision support system or process is available; (2) project duration estimates and timely risk analysis processes fail to improve continuously at the company level; and, (3) the concept of quality in construction schedules does not exist. Other studies suggested case-based reasoning (CBR) to address the first two problems, yet little practical experience exists. This study adopted CBR to analyze the case company, and explore the potential of the methodology. The goal was to improve pre-bid scheduling by accelerating schedule creation and reusing prior relevant scheduling knowledge, which are expected to ultimately result in continuous improvements. However, the test results indicated that pre-bid schedules do not improve significantly simply by generating schedules faster and making prior relevant scheduling knowledge available to estimators and project managers. Early project design specifications currently consist of generic information. Thus, schedules are equally generic, which means that timely risk analysis and project duration estimates remain uncertain and CBR can contribute little to improving the situation. Subsequent testing of CBR clarified that improvements in pre-bid schedules depend on a shift from generic, early project design specifications to more detailed, product-specific content. Thus, before the advantages of initiatives such as CBR can be effective, early project design specifications must be changed to include more detailed, project-specific design information.

Keywords: Scheduling, Building Information Modeling, BIM, Construction, Current State Analysis, Best Practice, Case-Based Reasoning.

Introduction

The success of construction projects is typically evaluated using three measures: economy, quality, and completion time. Even though the three measures are strongly interrelated, this article focuses on the time dimension of construction scheduling from a contractor's perspective. Delays in construction projects result from numerous causes, including slow decision making by clients, change orders, weather complications, design errors, long material delivery time, insufficient resource availability, and insufficient project scheduling and control (Faridi and El-Sayegh, 2006). This research presents a case study that focuses on scheduling problems at a major contracting company. The identified problems from the contracting company were presented in 11 other contracting companies to explore whether and how others solve them. Three out of 15 problems were isolated for further study, as the 11 reference companies had explored solutions to only the remaining 12 problems. The research continued by testing a case-based reasoning (CBR) system to address two of the three remaining problems, which both concerned the tender phase of projects. The outcome of the test resulted in a general finding relevant to both researchers and the construction industry. Thus, the aim was not to present CBR in detail, but to describe the outcome of the effort to improve pre-bid scheduling.

The objectives of this case study are to: (1) identify existing major problems related to scheduling at the case company; (2) explore solutions to the problems at 11 international construction companies; and (3) explore the case-based reasoning methodology to improve pre-bid scheduling. The research contributes to the body of knowledge by describing an example of gaps between current industry-applied technologies and work methods and existing scheduling problems. In addition, the research contributes by describing the experience with CBR to improve pre-bid scheduling, which is scarce in the current literature.

Literature Review

The consequences and risks resulting from insufficient scheduling in construction have been studied for many years. Laufer and Tucker (1989) divided the risks associated with scheduling into three categories: conceptual risk, administrative risk, and environmental risk. Schedules are established using incorrect assumptions and inaccurate data and data models (conceptual risk). Further, even well-conceived schedules may be executed incorrectly (administrative risk), and are subject to environmental changes (environmental risk). Thus, attempts to improve construction scheduling address the technical, methodological, organizational, and procedural aspects of scheduling. Consequently, various technical and non-technical means to solve current problems in scheduling are explored through both technical and non-technical means.

Methodical and Organizational Changes in Recent Scheduling Initiatives

In recent years, scheduling has been subject to improvements through initiatives such as Lean Construction (Sacks, R. et al., 2010-a), which includes the Last Planner

System®, Seven Stream pull scheduling, and interactive process planning through 3D visualization (Gil, N. et al. (2000)). The aim of these initiatives was to counter the irregularities and uncertainties in initial schedules (Sacks, R. et al., 2010-b). The methodologies were applied to identify and remove constraints from every scheduled activity within a predefined time window once construction starts (Ballard and Howell, 2003).

Integrated Project Delivery (IPD), partnering, concurrent engineering, and early involvement of subcontractors in the planning and design phase were utilized to improve collaboration during project tender and design phases (Parrot & Bomba, 2010; Eriksson, 2009). The goal was to coordinate the design effort and subsequently optimize the process plan and construction schedules. The 4D-scheduling tools supported this effort by integrating the functions, roles, responsibilities, and relationships of all project participants (Webb et al., 2004).

Improvements in Current Scheduling Tools

Numerous research projects seek to improve scheduling by automating certain aspects of the process (e.g., Huhnt and Enge, 2006), optimizing resource allocation (e.g., Hegazy & Kassab, 2003), reducing the makespan between activities (e.g., Zhu, J. et al., 2011) and determining and allocating time contingencies (e.g., Barraza, G., 2011). For example, Al-Tabtabai (1997) used artificial neural network models to define scheduling variances, allowing project managers to automatically generate revised schedules. In particular, the Critical Path Method (CPM) and the Project Evaluation and Review Technique (PERT) have been used for many years to improve the scheduling process. As another example, Christodoulou (2005) applied ant colony algorithms to identify the longest path in an activity network. Kim and Reinschmidt (2009 and 2010) used the Kalman filter forecasting method (KFFM), the earned value method (EVM), and Bayesian inference and beta-distributions to provide probabilistic predictions of possible project durations and expected success. These examples are a small selection of the attempts made to improve scheduling using better procedures and tools to address conceptual and administrative scheduling risk. Many more examples exist.

Scheduling using Building Information Modeling

In recent years, improvements in scheduling efforts resulting from the use of building information modeling (BIM) have gained much focus among contracting companies and researchers. The literature reported that the technology and associated work methods, i.e., LPS, IPD, and Seven Stream pull scheduling, enhanced communication of construction schedules by illustrating when, where, and how building products are installed and who installs them (Kamat and Martinez, 2002). BIM-based scheduling, also referred to as 4D-modeling or 4D-CAD (McKinney and Fischer, 1998), involves the graphical presentation of construction schedules in 3D geometrical models. The 3D-visualization of the production process supports the identification of constructability issues and schedule inconsistencies by facilitating communication and an understanding of the scheduling results (Koo and Fischer, 2000). Visual communication enhances worker comprehension and response to construction problems and increases the involvement and commitment of the project team (Formoso et al., 2002). Thus, the technology has been reported to enable planners to predict problems before they arise, resulting in considerable cost and time savings (Heesom and Mahdjoubi, 2004). Further, BIM-based scheduling assists in identifying location clashes between trades (Chau et al., 2005) and eases the evaluation of work process alternatives (Webb et al., 2004).

Case-Based Reasoning

The case-based reasoning (CBR) methodology was introduced in the case company to improve pre-bid scheduling. CBR was explored as a potential method for countering some of the isolated problems in this case study that the 11 reference companies did not address. Statistical and probabilistic methodologies were also investigated, aiming to establish correlations between basic project data (e.g., number of floors, apartments, and gross area) and project duration outcome for apartment building construction projects. However, the data set was insufficient to produce significant results. The scarcity of CBR cases only results in dissimilarity and the notion that no cases are available for reuse.

CBR is a branch of artificial intelligence and mimic the thought patterns of human reuse of knowledge or problem solving. CBR compares and adapts new problem cases (i.e., development of new design-build construction projects) with previous problems (i.e., prior construction projects). The CBR process follows four main steps (Aamont and Plaza, 1994): (1) retrieve the most similar cases; (2) reuse relevant information from the retrieved case; (3) revise the result after it has been used in the new case; and (4) retain the new solution if useful. The purpose of CBR is to provide and reuse relevant information to enable decisions to be made in less time or at lower cost (Bergmann et al., 2003).

CBR has been studied for multiple purposes in the construction domain, including construction scheduling. However, minimal research exists with a particular focus on pre-bid scheduling. However, Mikulakova et al. (2010), Ryu et al. (2007), and Dzeng and Tommelein (2004) created methodologies to support pre-bid scheduling. Dzeng and Tommelein (2004) stated that some contractors reuse parts of prior schedules to construct new early schedules, although traditional scheduling software provides little support for such reuse. Subsequently, Dzeng and Tommelein (2004) proposed a CBR methodology in which new schedules are created by determining activity networks from each component and collecting them into larger networks for entire products (i.e., projects). However, although Dzeng and Tommelein (2004) aimed to improve scheduling during the tender phase, their methodology was highly specialized as they focused on generic product models for power plant boiler erections.

Mikulakova et al. (2010) presented a methodology to reuse prior construction process knowledge to create new project schedules. The construction knowledge is contained in product models (i.e., building information models) and each component is associated with work tasks (i.e., construction processes). By specifying product models based on problem subsets and solution subsets, new schedules—with unknown solution subsets—are created from similar retrieved cases with similar problem subsets. This process allows the user to quickly create new schedules at the time that the product model for the new project is created.

Ryu et al. (2007) first used basic project figures such as, for example, number of floors, site area, and total build area, to identify prior cases with macro-level characteristics similar to that of the new project. More detailed information on structural type, finish, and other features is incorporated into the similarity analysis as it becomes available. The underlying assumption is that prior schedules can be reapplied and adapted under new, similar circumstances, thus ensuring continuous improvements. Reusing prior schedules is assumed to save time and produce more realistic estimates when creating new schedules. The system follows the basic process of Aamodt and Plaza (1994), and is partly a manual process. Cases are retrieved through matching and ranking, and parts of schedules are reused and then revised to fit the actual schedule. The completed schedule is retained for the next iteration.

These CBR systems were used as a basis for the test system, as described later in this article.

Research Method

The underlying research for this article was divided into three sections. Firstly, current scheduling problems in the case company were identified. Secondly, the problems were presented to 11 reference companies to explore their potential solutions. Thirdly, the CBR system was developed and tested.

The first section of the research entailed in-depth qualitative interviews. The case company is a major contracting company that started to invest in BIM and made changes to the organization accordingly. In addition to the contracting function, the company controls a design and engineering department and several associated subcontracting companies. The interviews involved representatives from the main contractor and nine associated subcontractors. Individuals and groups comprised of project managers, process managers, contract managers, and employees from the operational and tactical levels in the company's tender department were interviewed. Representatives from top and senior management, all with knowledge of scheduling, represented the strategic level of the company. In total, 38 individuals participated in the interviews. All interviews were exploratory and followed a guide with open-ended questions and discussion topics that covered the entire scheduling process, from input of information to schedule creation and schedule output. The input portion of the interview included discussions on quality, availability, structure, sources, and scope of the information needed for scheduling and progress control. The processing portion of the interview covered subjects such as responsibilities, work distribution, cooperation, and relationships with other management processes. Subjects concerning scheduling output focused on scheduling approaches, diagrams and reports, communication ability, manageability, distribution, and understanding the scheduling results. Data from the interviews were categorized through open coding (Corbin and Strauss, (1990)) and a review of the interviews was published in Büchmann and Andersson (2010).

The coding process revealed 15 scheduling problems, which were subsequently presented to BIM experts and planning professionals from the 11 reference companies. The reference companies were involved to obtain an indication of the current state of scheduling in the construction industry and to explore whether other construction companies experienced similar problems and how such problems were addressed. The participating companies, characterized by high investments in BIM and as front-runners in best practice work methods, recognized all 15 problems. Because only 11 companies participated, the intention was not to generalize the findings but to discuss the problems in depth to establish a starting point for future research at the case company using scheduling problems that garnered minimal current focus. This study selected pre-bid schedules as an area of focus because the reference companies indicated that, although they had ongoing attempts to solve 12 of the 15 problems, they paid little attention to this area. This does not mean that solutions do not exist for the three remaining problems, but instead indicates areas of interest for further study. Moreover, although the authors recognize that many more detailed scheduling problems exist, we maintained our focus on providing a case study on of a major scheduling problem at a single construction company.

The CBR methodology was tested because other research suggested it as a possible solution for two of the three remaining identified problems. The CBR system was developed in cooperation with the tender department of the case company and was later tested by both estimators and project managers. The outcome of the test provided general points for addressing pre-bid scheduling problems. The outcome must be explained in conjunction with the results from the interviews, as it emphasizes an incorrect assumption that both this CBR test and other research projects build on when seeking to improve scheduling for construction projects. While attempting to solve two of the three remaining problems, the test clarified that for the solution to be beneficial, it requires certain prerequisites.

Results - Describing the 15 Identified Problems of the Case Company

Creating schedules requires vast and extensive project documentation, including drawings, project specifications, and contracts (Problem 1). Extracting quantities of information is time consuming as little coordination exists between design, planning, and construction processes and necessary drawings may not be available, although drawings and specifications are plentiful (Problem 7). When information is available, project managers often find assessing and comprehending the relevant data a difficult task. The overload of information makes data difficult to assimilate and use as a basis for creating schedules. As a project manager explained, *"The amount information in the drawings is difficult to grasp. The vast number of different drawings makes it difficult to get an overview of the project. So rather than going through sets of drawings, the scheduler gets introduced orally to the project by the appointed project manager and the management team."*

In addition, time is scarce (Problem 5), especially during the tender phase. The scarcity of time during the tender phase and the challenges in easily obtaining necessary information force project managers to put a low priority on scheduling and they create schedules from personal experience and intuition (Problem 11). Only limited consideration of the project-specific data occurs when creating schedules. A contract manager states, "Scheduling is an inspirational and intuitive endeavor. The principle scheduling input is not provided by explicit figures and facts about the project, instead the choice of relevant production methods, the establishment of activities and their interconnections, assessment of durations, etc., rely on personal experience and intuition of the project manager." During the tender and design phase, scheduling relies on project managers' conception of a generic production sequence for the construction work, together with an intuitive understanding of the specific characteristics and scope of the specific project. Moreover, project managers do not have access to detailed information on time and resource consumption for the project's subcontracted work, which generally represents a significant part of the total workload (Problems 2 and 9). Several subcontractors interviewed for this study emphasized the general importance of having reliable and realistic time schedules early in a project and manifested a genuinely positive attitude about their own involvement and contribution to the overall scheduling process. An argument put forth by subcontractors was the need for sufficient schedules as a basis for more reliable assessments of risk, resource usage, and general cost estimates to ensure more competitive bids during the tendering phase. *"If we have reliable time schedules we can better control our expenses and estimate a more accurate price."* Reduced risk during the planning and coordination of the onsite activities was also highlighted as a key reason for the generally positive attitude toward committing to the overall scheduling process. However, despite the recognized importance of early overall scheduling and a willingness to contribute, subcontractors made a very sharp distinction between the pre- and the post-contract phases. During the pre-contract phase of tendering, considerations over scheduling and work coordination are largely omitted, as subcontractors are unwilling to invest time in the project before securing a contract. *"If we put a lot of our knowledge into a bid, e.g., scheduling alternatives, logistic considerations, risk reductions, etc., there is a risk that all of our efforts end up in our competitors' hands if they get the contract,"* said a representative from a roof manufacturer. Since subcontractors are not involved, schedules become generic, meaning that project-specific time risk and possible scenarios remain unexplored (Problem 8). Although cost estimation is considered paramount (Problem 5), the effects of time and resource consumption on cost estimates are neglected in the early phases of projects (Problem 6).

The individualized scheduling procedures (Problem 11) also entail different perceptions of scheduling quality. The company does not express any explicit rules and requirements regarding the schedules developed for a project. Thus, a common definition of what a schedule should contain or quality measures does not exist (Problem 13). Further, the lack of standards, guidelines, and support systems provided by the company impedes sharing of scheduling knowledge at the company level (Problem 12).

A clear division between early overall planning and later detailed planning exists. Although the consequences of insufficient scheduling become apparent during the construction phase, most problems originate from the tender and design phases. Although the quality of the overall level of scheduling sets the conditions for the detailed level, the interconnection between scheduling levels is currently insufficient (Problem 4), and current overall schedules provide an insufficient information basis for the detailed scheduling process. Overall scheduling created from project managers' personal experience and intuition and with little use of project-specific data determines the outline of the construction process. To adapt to the project outline determined during the tender phase, the case company utilized the Last Planner System (LPS). The LPS contributes to imminent production preparation and commits the involved parties to the plan. However, despite the power and benefits of the LPS, the need for sufficient production coordination and resource planning at an overall level is still present as subcontractors are not involved during the tender phase. Consequently, the disconnect between overall and detailed scheduling is considered a major challenge in current scheduling processes. This disconnect impairs the impact of the LPS at the detailed level, as coordination of activities with subcontractors begins too late in the construction process (Problem 9).

The comprehensive and complex structure of detailed CPM schedules make managing and controlling the progress of a project difficult (Problems 3 and 14). As a contract manager explained, "If a master plan is too detailed, it will not be utilized as subcontractors loose overview of the plan, as schedules for large projects consists of about 5,000 separated activities." The vast number of activities also makes communicating the schedule to subcontractors, suppliers, and other actors involved in the project difficult (Problem 15).

In addition to the identified problems presented above, the interviews reported on the consequences of these scheduling problems. When describing the consequences of insufficient scheduling practices, project managers and others interviewed referred to disruptions in workflow, uneven resource usage, quick fixes, rework of completed work, and location conflicts during the final phase of construction.

Table 1 summarizes the current scheduling problems in building construction identified in this case study.

Table 1. Identified construction scheduling problems **in the case company**

Problem No.	Problem description
1.	It is difficult to create schedules from available drawings, descriptions, and system requirements - **Input is inconsistent** and unsuited for scheduling purposes, resulting in **information overload**.
2.	**Input** from subcontractors is **not incorporated in the earliest schedules** - Contracts are signed with little indication or analysis of **timely risk**.
3.	Traditional CPM scheduling tools and procedures do not easily manage changes - It is **difficult to evaluate the consequences of changes** as reviewing schedules is not easy.
4.	**Interconnections between schedules** from different project phases are bad or **non-existent** - Time restrictions and schedules from the tender and design phases are difficult to accommodate during the construction phase.
5.	Scheduling is **prioritized low** - Cost is a focus - **There is not enough time** for scheduling during the tender phase.
6.	The relationship between time consumption, **resource consumption**, and **cost** is **ignored**.
7.	**Necessary information is not available** for scheduling purposes early in the project. Design and construction processes overlap but are not coordinated, so inputs to schedules are often missing.
8.	**Risk analysis** and scenario analysis are **not performed** systematically. Implications of alternative scenarios are not considered.
9.	Early overall schedules are **not coordinated with and among subcontractors**, leading to sub-optimization of the construction process.
10.	Little optimization of activities regarding sequence, resource consumption, and locations. Too high a **focus on milestones**.
11.	Schedules are based on **intuition and personal experience** - **No decision support systems** exist for scheduling.
12.	Scheduling does **not improve systematically** at the company level.
13.	**No criteria** or measure **of quality** for the schedules - schedules vary in quality.
14.	The **level of detail** in the schedules is often **too high or too low** - Schedules become unmanageable and incomprehensible, or carry to little information.
15.	The output of current schedules is too **complex to communicate**.

Comparing the Problems with the 11 Reference Companies

Most of the identified problems are being addressed by the companies involved in this study, and are described in the literature. However, three of the problems (11, 12, and 13) are not being addressed by the participating companies and garner little attention in the current literature. Consequently, this study gives special attention to these three problems after a brief description of how the participating companies are addressing the other identified problems.

The problem of inconsistent and unsuitable input for schedules (Problem 1) is currently managed by BIM-based quantity takeoff. Because BIM software extracts quantities efficiently, quantities can be utilized for scheduling purposes. However, in addition to quantities, project managers need information on expected resource consumption and productivity rates to make timely estimates. Some companies currently focus on early subcontractor participation to provide this information. Early subcontractor participation also addresses Problems 2, 4, and 10, as subcontractors provide project-specific knowledge, enable project-wide resource optimization, and secure interconnections between the design and construction phases. Current commercial BIM-software, which utilizes the line of balance methodology, simplifies comprehensive schedules by collecting and displaying similar tasks as a single activity distributed over multiple locations, thus countering Problem 14. Current BIM-based scheduling software also enables easy overviews of the consequences to cost and time from design changes (Problem 3) once a link has been made. BIM software also provides software communicative abilities, i.e., flow charts and 4D-simulations, superior to conventional Gantt chart methods (Problem 15) and that support Monte Carlo risk analysis (Problem 8). However, several identified problems cannot be addressed using software alone. Some problems are currently being addressed by organizational and contractual initiatives. IPD is applied to counter the fragmentation of the construction industry by enabling contractors, engineers, and architects to collectively solve design and constructability issues before construction begins (Problems 6, 7 and 9).

None of the companies included in this research addressed Problems 11, 12, and 13, although each of these problems was considered important. None of the participating companies have decision support systems for scheduling and they have no means to systematically improve scheduling at the company level (Problems 11 and 12). New schedules are mostly created during the tender phase from personal knowledge, rules of thumb, and some knowledge of productivity in certain areas of the project (e.g., concrete works). In addition, no company had a standard for or measure of schedule quality (Problem 13). Consequently, there was no way to compare schedules from project to project and there was no basis for improving schedules. Schedule outcomes basically depend on the individual efforts of the project managers.

Analysis of Problems 11, 12, and 13

Problem 11 - Schedules are based on intuition and personal experience - No decision support systems exist

Prior research has commonly found that scheduling in construction is based on the knowledge of individuals rather than company-specific methods or processes (e.g., Mikulakova et al. (2010), Firat et. al (2008), Thomas et al. (2004)). It is often the starting point for methodologies and frameworks seeking to automate or support the individual scheduling efforts in projects. This case study found that collaborative work processes are replacing individual scheduling efforts once a contract is won. However, the individual scheduling procedure persists during the tender phase. Subcontractors are not involved and do not provide input to the schedule, time is insufficient, and project managers receive no systems support when establishing schedules. Although 4D simulations are often used during the tender phase and enhance communication of the schedule (Webb et al., 2004; Manning and Messner, 2008), such simulations do not provide support for creating a schedule, and the project manager has to rely on personal knowledge and experience. Little research focuses exclusively on this issue. Abdul-Malak and Hassanein (2002) address this exact problem, and found that minimum effort to create schedules occurs during the tendering phase because time is scarce, the probability of winning the contract is small, and relevant information is not available. Abdul-Malak and Hassanein (2002) provide a detailed description of how planning and scheduling are coupled with cost estimations and formalize how scheduling should evolve from the tender phase to the construction phase through continuous detailing of work items, but do not include how this should be achieved. Kataoka (2008) also addressed pre-contract scheduling, stating that 4D-scheduling works well for the latter parts of pre-construction phases. However, during the early project phases, 3D-models are incomplete, and creating schedules and linking them to the 3D-models is time consuming. Consequently, Kataoka (2008) proposed a system that targets the tender phase by processing simple 3D geometries to generate construction components for automatic takeoff and scheduling using existing construction planning knowledge. The methodology builds on the reverse approach of current 4D-simulation tools. Instead of using schedules as input for a 4D simulation, predefined construction method templates and simple geometry are used to produce schedules. Although the system targets pre-contract scheduling, users need to provide information on resource consumption that, as stated previously, is unavailable in the very beginning of the tender phase because subcontractors are not yet involved. Although some research was performed in this area, the problem of schedules created during the tender phase based on the knowledge of individuals does not receive much attention from researchers or the industry, despite its implications on later phases of the construction process.

Problem 12 - Scheduling does not improve systematically at the company level

Relying on the knowledge of individuals to create pre-bid schedules is highly related to the problem of systematically improving schedules at the company level. As there is no way to store, transfer, or reuse prior schedule knowledge, project managers have to rely on their own experiences and the knowledge of close colleagues. Little current research focuses on the potential for systematic and continuous improvements and for reusing schedule knowledge during the first phases of construction projects. Many methodologies reuse, for example, activity networks or productivity data, but little research exists to describe an entire process for reusing knowledge for scheduling purposes. CBR is one methodology that has been explored for this purpose, and was consequently included in this study.

Problem 13 - No criteria or measure for quality of the schedules

Research focusing on what constitutes high quality schedules is very limited, although the term is often mentioned in the literature. Snoo et al. (2011) studied the scheduling process at 43 companies in multiple industries and defined scheduling performance criteria into 21 different categories, i.e., they viewed schedules as products and as processes, and identified indirect criteria and influencing factors. Scheduling quality criteria identified by Snoo et al. (2011) included the number of schedule errors, costs to execute the schedule, fulfillment of constraints and commitments made to "external" parties, fulfillment of resource utilization constraints, fulfillment of preferences and wishes of employees using the schedules, schedule robustness/information completeness, and information presentation and clarity. Snoo et al. (2011) also found that scheduling output and process are equally important to incorporate when addressing scheduling quality. However, all participating companies in the study by Snoo et al. (2011) were in the manufacturing, transportation, or service industry. Similar research could be performed for the construction industry. Russell and Udaipurwala (2000) explored the criteria for a complete, accurate, and workable schedule, and identified various measures of schedule quality and different methods of visualizing the results. The criteria include accuracy and completeness, consistency with other planning documents, good practice/workability, benchmarks for control, compliance with contract requirements, and abstraction, yet their study was unclear on how these categories emerged. The topic of quality measures in construction scheduling is not treated further in this case study, and is a subject for future studies.

Testing Case-Based Reasoning for Pre-Bid Scheduling

System description

To explore a potential solution for Problems 11 and 12, a CBR system for the rapid creation of pre-contract schedules from actual performance data was created for the case company. The purpose of this activity was to explore the potential of the CBR methodology in supporting the individualized scheduling process during the tender phase and enabling continuous scheduling improvements at the company level. The system was developed using regular feedback from the tender department and project managers. All 21 cases used were residential construction projects and contained basic project attributes, as shown in Table 2.

Table 2. Selected Output from Case-Based Reasoning Similarity Analysis

	Weight	Rmax	Cmax	Cmin	Problem case	Case 10	Simi. 10	Case 11	Simi. 11	Case 12	Simi. 12
Site area (m2)	0.05	23,600	25,000	1,400	10,000	4,964	0.79	2,250	0.67	25,000	0.36
Building base area (m2)	0.05	12,586	13,346	760	1,700	1,519	0.99	1,200	0.96	4,500	0.78
Gross area (m2)	0.20	55,496	57,824	2,328	7,654	6,073	0.97	4,223	0.94	20,600	0.77
Net. area (m2)	0.05	43,155	45,299	2,144	6,900	4,983	0.96	4,068	0.93	20,400	0.69
Basement area (m2)	0.15	12,370	12,525	155	1,105	1,090	1.00	155	0.92	200	0.93
Number of buildings (pcs.)	0.15	6	7	1	5	3	0.67	1	0.33	5	1.00
Max. Number of storries (pcs.)	0.20	10	12	2	6	4	0.80	4	0.80	5	0.90
Number of lifts (pcs.)	0.05	33	35	2	7	8	0.97	2	0.85	15	0.76
Number of appartments (pcs).	0.10	442	456	14	80	48	0.93	50	0.93	225	0.67
Total similarity							0.88		0.80		0.82
Rank							**3**		**11**		**7**

As in Ryu (2007), the underlying assumption made was that construction schedules from previous projects can be identified, adapted, and reused in new cases if the base attributes (e.g., number of apartments, area, number of floors) are satisfyingly similar. The goal is to present estimators and project managers with previous relevant and successful as-build scheduling information for new bids. As the most similar cases are identified (see the example of ranked cases in Table 3), estimators and project managers can retrieve and reuse parts of detailed as-build schedules to create new schedules. This process is assumed to enable faster schedule generation, increase the level of detail, and ensure realistic activity durations. As successful and unsuccessful duration estimates, methods, and sequencing are recorded, the CBR system is assumed to enable continuous improvements to pre-bid schedules across projects. However, as such data on prior as-built schedules do not currently exist at the company, the test focused on case retrieval and reuse of previous scheduling data. Testing of prior, as-built schedules in this manner may be a focus of future research as such data become available.

Table 3. Case Ranking Example: Comparison of 21 Existing Cases to New Bid Case

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10	Case 11	Case 12	Case 13	Case 14	Case 15	Case 16	Case 17	Case 18	Case 19	Case 20	Case 21
Site area	0,81	0,58	0,73	0,72	0,92	0,58	0,64	0,58	0,77	0,79	0,67	0,36	0,70	0,99	0,58	0,58	0,95	0,82	0,94	1,00	0,83
Building base area	0,98	0,86	0,93	0,86	0,99	0,86	0,97	0,93	0,90	0,99	0,96	0,78	0,95	0,68	0,86	0,86	0,95	0,98	0,86	0,98	0,07
Gross floor area	0,78	0,93	0,90	1,00	0,98	0,94	0,90	0,98	0,92	0,97	0,94	0,77	0,92	0,79	0,99	0,90	0,95	0,96	0,91	0,81	0,10
Net. floor area	0,75	0,90	0,89	0,95	0,99	0,94	0,88	0,98	0,95	0,96	0,93	0,69	0,91	0,82	1,00	0,88	0,94	0,94	0,87	0,81	0,11
Basement area	0,93	0,98	0,93	0,85	0,99	0,91	0,98	0,98	0,85	1,00	0,92	0,93	0,93	0,73	0,96	0,99	0,93	0,97	0,91	0,81	0,08
Number of buildings	0,33	0,33	0,50	0,33	0,83	0,67	0,33	0,33	0,33	0,67	0,33	1,00	0,33	0,83	0,17	0,17	0,33	0,83	0,67	0,50	0,83
Max. Number of storries	0,40	0,90	0,70	0,80	0,90	0,60	0,40	0,90	0,80	0,80	0,80	0,90	0,70	0,90	0,80	0,40	0,70	0,80	0,90	0,90	0,80
Number of lifts	0,94	0,85	0,85	0,97	0,97	0,79	1,00	0,94	0,94	0,97	0,85	0,76	0,94	0,88	0,94	1,00	0,85	0,97	0,88	0,85	0,15
Number of appartments	0,76	0,85	0,87	0,94	1,00	0,94	0,90	0,96	0,98	0,93	0,93	0,67	0,89	0,85	0,98	0,89	0,95	0,91	0,88	0,84	0,15
Total similarity	0,68	0,81	0,79	0,81	0,94	0,80	0,72	0,84	0,80	0,88	0,80	0,82	0,78	0,83	0,79	0,69	0,80	0,90	0,86	0,80	0,39
Rank	20	8	16	9	1	13	18	5	14	3	11	7	17	6	15	19	12	2	4	10	21

As in Mikulakova, (2010) some processes in the system are manual. Referring to the cyclic CBR-process of Aamodt and Plaza (1994), the test system was only automated in regard to retrieving cases. *Reusing, revising*, and retaining cases were manual processes. The system used in this study followed the structural principles described by Ryu (2007) and the similarity algorithms described by Serpell (2011). Serpell (2011) used similarity algorithms that contain the weighted sum of local similarities for all descriptive attributes involved in the project. The similarity between the problem case, *P*, and the stored case, *C*, is given by equation (1).

$$Sim(P,C) = \frac{\sum_{i=1}^{n} W_i \times sim_i(P_i, C_i)}{\sum_{i=1}^{n} W_i} \qquad (1)$$

Sim(P,C) is a normalized function with values between 0 and 1, where 0 describes a total mismatch and 1 describes a perfect mach. *n* is the number of attributes of each case and *i* is an individual attribute. W_i is the feature weight of attribute *i*. $Sim_i(P_i,C_i)$ is the local similarity function of attribute *i* and is described by equation (2).

$$Sim(p_i, c_i) = 1 - \frac{dist(p_i, c_i)}{R_{max}} \qquad (2)$$

$Dist(p_i,\ c_i)$ in equation 3 represents the absolute value of the difference between attribute *i* of the problem case and the stored case.

$$dist(p_i, c_i) = Abs(p_i - c_i) \qquad (3)$$

R_{max} in equation 4 describes the difference between the maximum and minimum values of attribute *i*, which is stored in the case database.

$$R_{max} = c_{max} - c_{min} \qquad (4)$$

The tender department selected the input attributes, and the authors selected the attribute weights. The attributes were selected because they are commonly used for cost estimations. Optimizing attribute weights is part of the retaining procedures of CBR (Aamodt and Plaza, 1994). Any CBR system is provided with initial weights, which are continuously adjusted to improve identification of the most similar cases. Both optimization of attribute weights and selection of other suitable input attributes may be topics for future research.

CBR Test Results

The estimators saw the potential of the CBR methodology for pre-bid scheduling. As estimators currently focus exclusively on cost estimates without integration of time estimates, the methodology can provide insight into the time dimension using previous similar cases. However, as the retrieved schedules are currently separated from the cost estimate, they only provide a general understanding of the previous projects. The estimators need integrated information on the effects of time and resource consumption on cost to gain advantages from the methodology. Further, project managers saw how the CBR methodology could provide support for faster schedule creation and reuse of prior experience, although they believed that it would not significantly improve schedules developed during the tender phase given the current design basis. The problem is that project managers cannot reuse, for example, productivity rates, task durations, and work sequences, as it is unclear whether these factors would be applicable to a new project. The early project design specification is generic in most tenders; therefore, information used to create schedules is bound to be generic. Further, as the schedule content is generic, planned activities cannot represent the actual construction processes that will occur on the project. Such generic content represents a significant risk, as the scheduling procedure fails to support identification of potential problems during the actual construction process, which is currently defined after the contract has been won. Many productivity issues occur because real production processes are first determined during the production phase. Testing the CBR system showed to project participants that the issue identified in the interviews - insufficient time for scheduling during the tender phase -cannot be solved simply by providing support for the schedule creation task. Generally, a weak link exists between estimated processes, which are superficial and generic, and actual processes. Scheduled activities, which are very generic, do not necessarily represent the actual production process. This gap between generic, overall estimates and actual, project-specific construction processes represents a major risk for each project. As the construction processes are undefined, the overall estimate of completion time contains the inherent risk of timely overshoots. This study assumed that supporting the schedule generation process can improve schedules because, if schedules can be produced faster, more time would be available to include additional details, which would subsequently allow project participants to better evaluate procedural and time-based risks. The test indicated that decision support for the creation of schedules could be beneficial, but this presupposes that the initial design specification is defined in detail. Because several sections of any project are not defined in detail, project managers are prevented from creating a construction schedule that addresses project-specific terms. This is an important point, as much research seeks to improve scheduling by automatically creating schedules, as mentioned in the literature review. The interviewees claimed that project managers and estimators have insufficient time for creating schedules during the tender phase. Although possibly true, the assumption that faster generation of schedules could counter this problem is inaccurate because the fundamental problem is rooted in generic design specification. Defining early project design specifications is time consuming and difficult because the information needed to choose the optimal solutions for subsections of the project are scattered throughout contractors' organizations and the supply chain. Knowledge of applicability, cost, time consumption, quality, among other important items of information, resides with various resources, including subcontractors, project managers, designers, engineers, and product manufactures, and this information is typically not retained and is not reused, and is collected for each project. Since gathering this information from the various resources is time consuming, little time remains to evaluate alternative solutions, work with details, consider scenarios, or analyze timely risks. Consequently, project managers found that pre-bid schedules only improve if the early project design specification can be established faster and using less generic, more specific information. Thus, although CBR was believed to aid in retrieving relevant previous schedule knowledge during the tender phase, the first step is to improve decision support for early project design specification, i.e., selection of specific components and systems that allow estimators and project managers to evaluate alternative design solutions on the basis of, for example, design, cost, time, and quality attributes.

Conclusion

By presenting the 15 identified scheduling problems faced by the case company to the reference companies, three problems were highlighted as lacking attention. Schedule quality was not treated further in this case study, and is a topic for future research.

This case study found that many construction problems arose from insufficient coordination and scheduling during the tender phase, as time is limited and project information is generic because subcontractors are not yet participating in the project. Pre-bid schedules are created from the intuition and experience of individual project managers, are superficial and generic, and contain little project-specific knowledge. Therefore, pre-bid schedules fail to enable analysis of timely risks, cannot accurately estimate project duration, often have an adverse impact on cost estimates, and fail to improve over time. The CBR methodology was tested in an attempt to assist project managers in establishing schedules faster and with greater detail and in reusing prior relevant schedules to promote continuous improvements. The overarching goal was to reduce the risk associated with undefined construction processes and estimations of necessary time consumption given by the client. Timely risk was assumed to decrease if schedules that are more detailed could be produced faster, subsequently freeing up time to obtain input from subcontractors that could evaluate the risks and determine the accuracy of the estimates. The test clarified that current attempts to reduce timely risk during the tender phase are limited by generic design specifications. The test also countered the belief that schedules receive insufficient attention because of a lack of time during the tender phase. Although participating estimators and project managers found support for schedule creation to be highly relevant, more detailed design specification is a prerequisite for any improvements in pre-bid schedules. Because early design specifications are typically generic and poorly defined for several project areas, future research could explore CBR or other methodologies to improve early project design specifications. Future research could also investigate whether improved design specifications during the tender phase enable the creation of more detailed and project-specific schedules, which in turn could lead to reduced timely risk and better planning of construction projects.

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Article 3 - Slowest Task Criticality in Construction Control

Slowest Task Criticality in Construction Control

Abstract

It is essential to understand the underlying rationale for the perception of critical activities because it affects how construction projects are scheduled and controlled. However, there is no collected description of what constitutes critical activities in the location-based management (LBM) technique. In this study, therefore, the constraints that affect progression of activities on the critical path and determine a project's lead time on LBM projects are analyzed and described collectively. For example, the findings explains how location constraints can cause otherwise non-critical activities to prolong a project's lead time, and why they accordingly should be considered when determining the criticality of activities. Secondly, a case study is presented that elaborates on the reasoning behind recommendations from the LBM literature about prioritizing the critical task with the lowest production rate. The slowest critical task is essential to the criticality principle of LBM, but is described sparingly in current literature. Thirdly, the effects of extending the criticality principle of the prevailing techniques with the proposed criticality principle of LBM are analyzed. For example, the findings suggest that critical activities increase in number which subsequently increases the sensitivity to disturbances and fluctuation in production rates, when LBM projects are optimized.

By Rolf Büchmann-Slorup and Prof. Russell Kenley

Key Words: Criticality, LBM, CPM, Management, Scheduling, Control, Construction

Introduction

Ever since the critical path method (CPM) was introduced by Kelly and Walker (1959), the method has helped project managers to plan and control projects more effectively and deliver projects on time. CPM can help project managers prioritize activities on complex projects by analyzing the time float that appears between activities by means of technical constraints and duration estimates (Ferdinand et al., 1963). In other words, CPM can help project managers to identify critical activities. This means that information about technical constraints are vital for a project manager's perception of which activities are critical, and subsequently determine which control actions are implemented on construction projects. Location-based management (LBM) is an alternative to CPM that been used since the 1930s, most famously in the construction of the Empire State Building (Kenley and Seppänen 2010), and has been found beneficial for scheduling and controlling building projects (e.g., Russell and Wong, 1993; Soini et al., 2004). The perception of criticality is ambiguous and depends on the applied management method. However, as is the case with CPM, a collected description of what constitutes critical activities in LBM has not been described explicitly in current literature; it needs to be defined because the perceived criticality of activities affects how projects are managed. Harmelink and Rowings (1998) argued that the absence of a criticality principle is one reason why the location-based methods have gained little influence in the construction industry.

CPM originated from the aerospace and military industries (Cooke-Yarborough, 1964), but has long been applied to construction projects (Kelley, 1964; Starnes, 1969) and is currently utilized for numerous purposes, including periodic control of work after the start of construction; developing look-ahead schedules; coordination of subcontractors; detailed planning of work prior to construction; schedule impact, claims analysis and tracking of changes; coordination of own trades; estimating and bidding; tracking shop drawings and submittals; calculating payment requests for work performed; design development; operation and maintenance of projects; tracking costs; and materials planning (Galloway, 2006). CPM has accordingly been utilized for many aspects of scheduling and control of building projects.

Despite its advantages, the use of CPM for building construction has been criticized for scheduling and controlling building projects, because it simply is ill-suited for that purpose. For example, Peer (1974) stated: It cannot be expected that the use of a technique for purposes for which it has not been developed originally could produce a practical solution to a real situation, which requires a completely different approach. Peer (1974) found that CPM did not support site management needs due to its disregard for flow and resource optimization. Given the origins of CPM, particularly in the aerospace and military industries, CPM was seen as a useful method for complex one-of-a-kind projects because it focuses on the earliest possible completion. However, Birrell (1980) also found that CPM does not cover all necessary aspects of the building control process because it does not account for resource utilization. Therefore, the criticisms of CPM are especially directed towards CPM's disregard for resource constraints. Other criticisms of applying CPM for construction management include its disregard for continuous work flow, communicative abilities, and lack of spatial context (Stradal and Cacha, 1982; Laufer and Tucker, 1987; Koo and Fischer, 2000; Andersson and Christensen, 2007). The shortcomings of CPM, and especially its resource leveling problem, have been subject to a great deal of research (e.g., Galbreath, 1964; Lu and Li, 2003; Kim and de la Garza, 2005). LBM is another management technique that reportedly provides solutions to these shortcomings because it explicitly treats constraints of the construction process that are omitted in CPM (e.g., Russell and Wong, 1993; Soini et al. 2004).

LBM promotes task continuity, synchronized tasks, and productivity optimization through resource allocation and breakdown of the project in locations so that repetitive effects are exploited. Location-based control has been applied to many projects, both repetitive and non-repetitive, for several decades (Johnston 1981, Stradal and Cacha 1982, Hegazy 2001), including high-rise buildings, bridges, pipelines, tunnels, stadia, highways, and housing projects (Russell and Wong, 1993). The term location-based management was coined by Kenley (2004) and has its roots in the line-of-balance methodology that was originally introduced by the Goodyear company and the US navy in the 1940s and 1950, respectively (Kenley and Seppänen, 2010). The methodology has developed from multiple techniques, with the common feature that project locations are information carriers. These include line-of-balance scheduling, the linear scheduling method, the vertical production method, the repetitive project model, velocity diagrams, the time space scheduling method, the construction planning technique, the time location matrix model, disturbance scheduling, and horizontal and vertical logic scheduling (Lutz and Hijazi, 1993; Harris and Ioannou, 1998). Even though each location-based method has a particular approach to scheduling and control, the common goal is to minimize production time by depicting continuous construction of repeated activities across locations through time (Harris and Ioannou, 1998). LBM is a modern location-based method that is founded on the family of abovementioned methods. Like CPM, LBM has not evaded criticism from the research community and is constantly evolving. These criticisms are mostly directed towards LBM's ability to schedule non-repetitive projects. However, Russell and Wong (1993) provided the mathematical foundation with which to also schedule non-repetitive projects with LBM. Many other improvements have been proposed, such as the usability of the method (Wang and Huang, 1998), and communicative abilities by linking location-based schedules to 3D computer models (Jongeling and Olofsson, 2007). However, one aspect that still has not been treated collectively and explicitly in LBM literature is the subject of *criticality.*

Criticality describes the logic within project planning and control methods of how tasks should be prioritized in project control. The word criticality is used to describe whether a task or activity affects a project's completion time if that task or activity is delayed, and is defined by the constraints that determine the progress of work (Flood et. al., 2006). A criticality principle is defined as the collection of constraints that determine whether activities or tasks should be considered critical within a given management method. Although the criticality of an activity might seem unambiguous, it depends on the applied scheduling and control method. The literature contains clearly defined descriptions of what constitutes critical activities in CPM. The critical path is a set of linked precedence relationships in a logic network that have zero float (e.g., Wiest, 1981), which define the longest path from the first node in a project to the last node. When projects are controlled, the criticality principle helps project managers to prioritize tasks that lie on or close to the critical path. Although the current literature describes the inherent constraints in LBM, their influence on the criticality of activities is only described sparingly and in fragments, while other parts lack detailed descriptions for the underlying reasoning and justifications. A collected criticality principle of LBM is yet to be defined explicitly. In particular, a central aspect of the criticality principle of LBM, which is the slowest critical task, was mentioned by both Carr and Meyer (1974) and Peer (1974), but its importance and reasoning have not been the subject of research in LBM literature since. Therefore, the purpose of the present article is to collect the constraints of LBM and relate them to criticality of activities and tasks, thereby describing a complete criticality principle of LBM. Subsequently, effects of the proposed LBM criticality principle to the scheduling and control techniques on construction projects are compared with those of CPM.

Research Methodology and Methods

The reasoning behind the results is based on an analysis of constraints in LBM and their impact on a project's lead time from current LBM literature, while the reasoning behind the importance of the slowest critical task that was proposed by Carr and Meyer (1974) and Peer (1974) is explored through a case study. Although case study research is criticized for its ability to produce generalizable results (Flyvbjerg, 2004), the case study targets the principle behind the slowest critical task in LBM and seeks to provide the general reasoning for its importance in relation to criticality in LBM. Therefore, the aim is to provide a principle case study that explains and justifies the emphasis on the slowest critical task that was proposed by Carr and Meyer (1974) and Peer (1974).

The case

The case project is a seven-story apartment building divided into two blocks (for the sake of clarity, only one block is used when the data is presented). The total size is 15,000m^2, consisting of 152 high-end apartments, each sized between 80m^2 and 120m^2. The entire project was documented during construction by other researchers who attended the site five times for 2–5 weeks per visit. These results were reported in Joergensen (2008). The report describes the entirety of the project, identifies 52 problems and links them in cause-effect relationships. In addition to the report, all managing project participants, schedules, and progress data were available. Two different control schedules were utilized on the project; one of the external works and one of the internal works. However, the two control schedules were managed independently. Some activities are presented in both sets of as-built data, and vary slightly. Progress reporting was performed in spreadsheets and Gantt charts that contained locations. However, the project was not controlled with location-based logic and the requirements of flow, continuous resource consumption, and respect for location constraints. A desired work sequence applied, but was not always enforced. Thus, the project was planned as LBM-based project but controlled as a CPM project containing locations. The progress recording of the internal works utilized percentage complete, and was recorded by a member of the project management team roughly 35 times for 44 activities in each of the 152 apartments. The external works were recorded 14 times for 81 activities in a Gantt chart.

Trends of completion

The as-built production data was plotted in a location-based view. The as-built data was transformed from the activity-based, percentage complete view to work tasks in a location-based view, and was subsequently subject to trend analysis. Trendlines of completion dates for each task; that is, collection of the same activities, were plotted for both the internal and external works. The plotted trend lines are not meant to be a highly precise mathematical description of a problem, but a practical and understandable approach to draw conclusions from vast amounts of data. The trend lines were drawn from data points of the completion dates of activities in each apartment of the project.

The apartments are not shown explicitly, but Figures 1 and 2 illustrate how similar activities were completed in one of the buildings that contained 72 apartments. The bold trend lines indicate trends of completion for the similar activities throughout the

72 apartments. Singular extreme cases of slow or fast productivity within few locations were ignored. The aim of plotting the completion times of each activity in each location was to illustrate how constraints of interdependent activities affect each other's progress, even though the project was not controlled with LBM logic, which provides supporting data for the proposals of Carr and Meyer (1974) and Peer (1974).

Constraints and Criticality in LBM

The collected criticality principle of LBM is suggested to contain the following points.

- Activities or tasks on the longest path or paths through a project's dependency network with zero float are critical.
- Activities or tasks that cause discontinuity of activities and tasks on the longest path or paths through a project's dependency network with zero float are critical.
- Activities or tasks are critical if they are allocated to a location that imposes time delays on activities on the longest path or paths in a project's dependency network with zero float.
- The activity or task that has the lowest production rate on the longest path or paths through a project's dependency network with zero float is the most critical.

The literature and reasoning behind this proposition is presented below.

Russell and Wong (1993) stated that activities in LBM must contain attributes such as numerous work locations, a sequence of execution, production rates, crewing structures, and continuity constraints. Thus, whereas CPM only operates with technical constraints, LBM also includes continuity and location constraints. In addition, LBM relies on production rates when defining and controlling work tasks. Accordingly, the production rates of tasks are also treated as a constraint as this is an easy way of describing how interdependent tasks can limit each other's progress.

Technical Constraints

Activities on the longest path throughout a project's dependency network with zero float are considered critical in LBM. Technical constraints are effectively the same type of dependencies as in CPM (Kenley & Seppänen, 2010). However, the technical constraints are handled collectively, as they are repeated for each location. Thus, activities with the same technical constraints are treated discretely in CPM, while they are treated collectively in tasks across relevant locations in LBM. Similar to CPM, time float is an important concept to criticality in LBM. Time float partly describes whether tasks are critical or near critical in LBM. As in CPM, tasks with no float are considered critical because any delay in them will delay the project (Kenley & Seppänen, 2010). Tasks with little float are near critical, while tasks with much float are considered non-critical because the float can absorb delays. LBM emphasizes free float; that is, the spare time that exists between two activities when both the predecessor and succeeding task starts as early as possible (Cooke-Yarborough, 1964). In contrast, total float indicates the amount of time that the task can be moved without delaying the project. The emphasis on free float is rooted in the desire for work continuity.

Continuity Constraints

Russell and Wong (1993) defined work continuity as the postponement of the start of an activity until continuous work is guaranteed. However, the continuity constraints should not be required in all cases. A task that consists of several similar activities can, in theory, be discontinuous and finish as early as a continuous task. The continuity constraints on tasks are a practical measure and a focal point of LBM, because discontinuous tasks can cause work crews to leave the construction site to work on other projects or cause the crews to work in random locations. Working in random locations can be difficult to manage and result in sub-optimal production or waiting time if work crews follow different sequences. Thus, the continuity constraints require activities to be performed in a specific location sequence (Russell and Wong, 1993), and ensure that the technical constraints are respected for each repeating string of activities in the dependency network for each location. This means that schedules can be compacted and flow lines can be placed closely together. If the work sequence is broken or new work faces are opened before the first ones are closed, succeeding work crews will experience waiting time if no float or buffer is available, which in turn will delay the project.

Kenley (2004) listed a series of question that must be asked in LBM regarding delays, including the aspect of continuous work:

- Does the delay disrupt the flow of a continuous activity?
- Does the delay impact on the flow of any following activities?
- Does the delay impact on the commencement of any following activities?
- Does the delay lead to the delay in project completion if flow is maintained?
- Can the delay be absorbed by interfering with the flow or pace of following trades such that the project is not delayed?

Although the questions were not stated explicitly in regard to the term criticality, they suggest an emphasis on flow and task continuity in regard to criticality in LBM. Further, Harris and Ioannou (1998) described how a controlling sequence can be identified in LBM that is different from CPM, although they were using the repetitive scheduling method (RSM). They described that the determining sequence in the location-based methods is typically different from CPM because it includes the demand for work continuity and may include both critical and noncritical activities in terms of float (Harris and Ioannou, 1998). Breaking the continuity of a critical task can disrupt the working order, which can cause delays to the project's lead time. Therefore, the emphasis on free float and the requirement of continuity of tasks suggests that activities or tasks that cause discontinuity of activities and tasks on the longest path or paths through a project's dependency network with zero float should be considered critical in LBM.

Location Constraints

A location constraint ensures that an activity does not share any of the work locations of its predecessors or successors (Russell and Wong, 1993). Location constraints can be modeled using CPM, although this is a tedious task that can result in thousands of activities on major projects, which can be hard to control. Repeating activities are collected in tasks in LBM, which copies the technical constraints to each location, thereby countering the discrete treatment of activities in CPM (Wang and Huang, 1998). The CPM algorithm does not contain elements that *ensure a smooth procession of crews from unit to unit with no conflict and no idle time for workers and equipment* (Arditi et al., 2002). Therefore, the location constraints ensure that activities do not take place in the same time and place, although these additional constraints can displace activities or tasks that are critical due to technical constraints. Although the technical constraints may allow work to commence for an activity that is critical due to CPM logic, activities from another sub-network may block the location and require the given critical activity to start later. Accordingly, an activity is also critical if it is allocated to a location that imposes time delays on any activity on the longest path or paths in the technical dependency network with zero float.

The Slowest Critical Task

Tasks in LBM are partly defined by production rates (Seppänen and Kenley, 2005), with a focus on production flow and balanced tasks (Lumsden, 1968). The durations of activities are considered variable according to resource provisions, such that there is a greater willingness to manipulate activity durations systematically within tasks. This engagement with productivity and continuity means that tasks typically align.

Peer (1974) suggested a series of planning steps, one of which was that managers must decide on the flowline that should dictate the progress of the project given financial or resource limitations. Peer (1974) stated that the slowest task (that is, the critical task with the lowest production rate), preceding tasks that affect the start point of the slowest task, and the task following the critical task, should all be considered critical. Thus, the fundamental slowest task in a dependency network determines the maximum production rate of succeeding critical tasks. Carr and Meyer (1974) did not explicitly deal with the concept of criticality, although they did state that the slowest activity in a line of balance (LOB) schedule is critical because any reduction in productivity will delay the project. It is this focus on the slowest task that is explored in the case study.

Harmelink and Rowings (1998) touched on the same subject as Peer (1974) and Carr and Meyer (1974). Harmelink and Rowings (1998) described how *productivity float* between tasks affect the criticality of sections of tasks. A task may not be critical in its entirety. Some sections may be critical while others may not; this is because productivity float can arise between the tasks if a task has a higher production rate than its successor. This is a more realistic way of perceiving the slowest critical tasks, because flowlines rarely align in actual production, as experienced by Russell and Wong (1993): *We were quickly disabused of the notion that real-life projects followed the nice, neat parallel lines of a pure flow model or for that matter, the precision portrayed by the traditional network diagram*. The slowest critical task is dynamic when projects are controlled and will change as the project progress and control actions are implemented. The critical task with the lowest production rate should therefore be considered the *most* critical task of the entire project because it impedes progress on succeeding critical tasks. However, the slowest critical task will change throughout a project, and should only be prioritized over other critical tasks until it is no longer the slowest.

Case Study on the Slowest Critical Task

The case study exemplifies the importance of the slowest critical task that was proposed by Peer (1974) and Carr and Meyer (1974), thereby elaborating on the reasoning behind it and providing data to justify it. Figures 1 and 2 illustrate the as-built production data of external and internal work from the case project in a location-based scheduling view. The lines are plotted from the finish date of each activity in 72 apartments; one line represents the finish date of 72 similar activities. Only critical tasks are visualized. The start dates and non-critical tasks are hidden for the sake of clarity. The data is plotted with the line of balance technique without start dates. When transferring the as-built data from the Gantt charts and spreadsheets to a location-based view, it is clear that the critical tasks align at several times in the projects. The critical tasks do not surpass or cross each other, even though LBM logic did not apply. This indicates that location constraints are inherent in the construction project which makes the slowest proceeding task limit succeeding tasks in several different times in the project. Thus, the as-built data supports the reasoning behind the recommended focus on the slowest critical task, which was proposed by Carr and Meyer (1974) and Peer (1974). This means that critical tasks are not equally critical. The slowest critical task is the most important critical task and should be prioritized by the construction management.

The implications of this view on the slowest critical task are elaborated on in the following description.

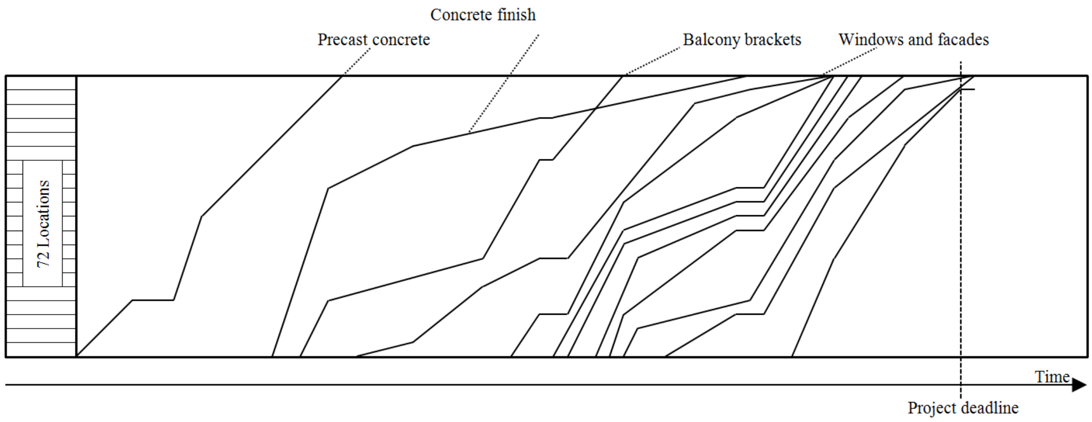

Figure 1: External production data plotted in a location based view

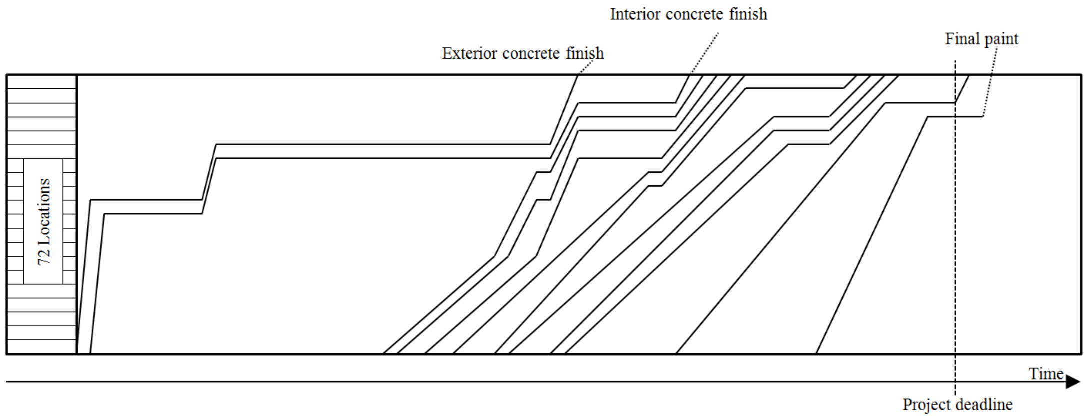

Figure 2: Internal production data plotted in a location based view

The Case as Described – Documented Causes of Inefficiency

Even though the case company considered the case project to be an overall success, several problems did occur that caused an increase in resource consumption, rework, and delays toward the final stages of the project. The report on the case project stated that most procedural problems in the building process originated from incorrect design specifications. For example, the electrical project lacked outlets and the bracket design for the balconies was not coordinated with the concrete rebar specifications. Although these design problems caused delays, the cause for productivity problems was also reported to have originated with the carpenters. In an attempt to be flexible, the carpenters started work on multiple apartments across the project, mainly with construction of dry walls. However, the carpenters were reportedly restricted by the placement of crane tracks, material deliveries, and late installment of brackets for the balconies. Subsequently, the carpenters' work sequence constrained succeeding tasks. The project management's reaction was to increase resource consumption, seeking to accelerate productivity for all late activities. However, many activities finished late, even though they had started early and consumed more resources than originally planned. Although the problems were mainly rooted in technical issues and were eventually solved on-site, there are some important points regarding the perceived criticality of the following activities that could potentially have reduced the cost, resources and time used on the project, which can therefore be considered as wasted.

The data of the external works

In contrast to the statements in the report, the as-built data (Figure 1) indicates that the balcony brackets were actually completed on time and did not delay the project. Instead, the completion of the *concrete finish*, *windows* and *facades* became the critical tasks towards the final locations. The brackets were finished significantly earlier than the *windows*, *facades,* and the *concrete finish* tasks. These three tasks limited the productivity of the remaining activities in the precedence network. Thus, the external as-built data indicates that the task of installing balcony brackets should not have been considered critical for the last apartments in the project.

The data of the internal works

The depiction of the critical tasks of the internal works indicates that the effectiveness of the increase in resources and early starts were limited to the production rate of the slowest tasks because the critical tasks align at several times through the project. Therefore, a change in perceived criticality by showing the additional constraints of LBM could have indicated the limit for effective resource increases on each task in the internal works. The effects of accelerating many of the critical tasks were limited at different points in time, especially in the last apartments (top part of Figure 2). This limited the work crew's productivity and the increase of resources became unnecessary after the productivity level of the slowest task was reached.

For example, in the middle of the project, the trend lines show that the work in the latter apartments was limited by the progress of the *concrete finish* tasks. The completion of the concreting was not described as a cause for delays, either in the report or by the project participants. However, it is evident from Figure 2 that the finishing of the interior concrete walls became the slowest task for the final apartments in the building at one point in time. This affected the remaining tasks in those apartments. This observation indicates that project management should only have accelerated the *concrete finish* task to begin with, until it was no longer the limiting task.

These findings were presented to the project management, who confirmed there were problems with the *concrete finish* task. Much of the precast concrete suffered from quality issues, and many concrete blocks arrived with damage to surfaces and corners. Additionally, many workers reportedly assumed that the entire concrete structure would be filled and painted, which made them careless about the finish. However, the concrete in the basements and staircases was to be left exposed and should consequently have been protected. The management reallocated *concrete finish* crews from the apartments to finish the concrete in the basement and staircases. The management argued that this transfer was the most likely reason why the multiple work faces were opened in the last apartments, but the task had not been completed until several months later. Therefore, the management had not realized that the transfer of crews from the apartments to the basements and staircases would limit the progress of the many succeeding critical task in the apartments. While the removal of crews to this critical task would also have been problematic in an activity-based control method, the point is that the management failed to realize that the remaining critical tasks could not be accelerated due to location constraints.

The problem lies in the control effort and the fact that locations are treated discretely in activity-based control methods. Once critical tasks in the dependency network were delayed, it was unclear how quickly the succeeding tasks could proceed. It was not clear to the management that acceleration of the critical tasks was limited by the slowest task. The use of percentage complete progress control data was not adequate for identifying core productivity problems. Gantt charts do not provide information about which activity is limiting the productivity of other activities in the precedence network, as the diagram does not include any productivity data, and because location constraints are not shown explicitly. . Therefore, because this is typical for site reports, the management was only presented with information indicating that specific activities were late and by how much. In this case, management's response was to accelerate all late activities on the critical path, as they appeared critical in the reports; in other words, the perception of criticality caused management to accelerate the late remaining tasks in the precedence network. These actions may seem logical as all late activities were on the critical path, and delays to either activity would cause final delays to the project. However, the production data shows that attempts to accelerate the late activities were wasted, even though they were on the critical path. This indicates the importance of propositions made Carr and Meyer (1974) and Peer (1974) regarding the slowest critical task. Even though CPM suggests that delays of any activity on the critical path will lead to a longer project lead time, it is not clear if an increase in resources will have the desired effect of accelerating them.

Implications of the differences in criticality

A series of implications to the scheduling and control effort became apparent from the case study and literature review when the LBM criticality principle was applied instead of the criticality principle of CPM. These are summarized as follows:

- The number of activities that are critical, and appears to be critical, increases.
- Critical activities can be prioritized by means of the slowest critical task.
- Consequences from slower-than-planned production performance of critical tasks are forecasted more negatively.
- Work crews' flexibility of work sequence through a building is reduced.
- The sensitivity to disturbances and fluctuation in production rates increases.

The number of activities that are critical, and appear to be critical, increases

Showing location constraints explicitly in LBM entails an increase in the number of activities that are perceived to be critical. Through the alignment of tasks, the case study exemplified that activities within these tasks could not progress in a location if its successor was not completed. It is important to underline that location constraints are dependent on task sequencing and the physical structure of the project, and will be a part of any project regardless of the control method. The question is whether project managers understand how these location constraints affect the progress of the project and the effectiveness of the increased resource consumption. Treating location constraints explicitly make sure that the technical dependencies are incorporated into every location of a schedule. The case study exemplified just that. A shift in the criticality principle could potentially have helped the project management to understand what limited the progress and how many resources they should have invested in each delayed task.

The location constraints were not identifiable in the as-built data in the spreadsheets or in the Gantt charts. The flow-line view of LBM makes location constraints explicit and it is evident if a location is blocked by another activity. The location constraints are inherent constraints within a project that exist regardless of the applied management method. A location constraint can delay an activity that is critical due to technical constraints, however this is simply made evident using LBM. The location constraints do not impose additional critical activities on the production system, although the progression of critical activities may be limited by activities that would not be considered critical in CPM in the given location.

Contrarily, the continuity constraints that can be imposed by LBM may lead to additional activities becoming critical compared to the activity-based methods. The continuity constraints that enforce seamless progress of work between locations and a common location sequence are seen as a necessity for optimized production. The continuity constraints not only ensure continuous production, but also production in the same sequence through the location break-down structure of a construction project, as explained by Russell and Wong (1993). Breaking the location sequence of critical activities will disrupt the flow of succeeding critical tasks and affect the project's lead time. The continuity constraints will impose additional requirements in the dependency network of activities, which potentially removes float and forces otherwise non-critical activities to interfere with the critical path and therefore become critical. While aligning tasks and abiding to the continuity constraints will compress a schedule, the number of critical activities will increase.

Critical activities can be prioritized by means of the slowest critical task

The importance and rationale of the slowest critical task, which were mentioned by both Carr and Meyer (1974) and Peer (1974), were explained in the case study. It is important to understand the limitations that the slowest critical task imposes on a construction project because it can be used to differentiate between the critical tasks. Therefore, the slowest critical tasks should be of higher priority than the remaining critical tasks. Using CPM, all critical activities in activity-based methods are considered to be equally important. Activity-based methods do not illustrate the limitations imposed by slow production of certain critical tasks, because location constraints and production rates are not explicitly shown. A Gantt chart will communicate that all late activities are late, which would signify that they should be accelerated, as was also done by the project management in the case study. The management cannot tell from the Gantt charts that one of the critical activities is limiting the progression of the succeeding critical activities. Therefore, the project management will see all the effects of a fundamental productivity problem, but the fundamental productivity problem itself will not be explicitly shown.

Slower-than-planned production is forecasted more negatively

The main difference between location-based and activity-based criticality in control is rooted in the continuous and discrete conceptualization of activities and resource usage, respectively. Tasks are allowed to be discontinuous in activity-based methodologies, as the logic treats them as discrete even though the tasks are repeated for each location and, in reality, the same work crews will perform similar activities. Therefore, forecasts are not inclined to change to correspond with actual performance in previous locations using CPM logic. The difference between discrete and continuous activities and resource usage is important to the criticality concept when projects are controlled. Without the expressed recognition provided by LBM, it can be difficult to recognize the consequences of slow activities when forecasts are optimistic and out of sync with the actual performance of work crews; this is because previous performance data does not influence the expectations for future production rates. Repeated activities are treated discretely, excluding the fact that the same construction crews perform the work for similar activities. Using the original estimates for future production can be misleading and portray an optimistic forecast for projects given actual performance. Therefore, project managers will identify what the consequences are if the planned productivity rate is reached for the remaining activities. If continuity constraints apply to similar activities, the performance data from completed locations will affect the forecast, and the project managers are presented with an outlook that illustrates the consequence if production rates remain the same.

Work crews' flexibility of work sequence through a building is reduced

Another significant difference between the criticality principles of LBM and the activity-based methods is that activity-based controlling rewards commencement in multiple locations. CPM controllers may commence work in multiple locations because production will appear to progress. For example, a Gantt chart will typically communicate progress in terms of percentage of planned completion if several work faces are started. However, initiating work in multiple locations will prolong a project's lead time because the first location will be blocked for a longer period of time, thereby hindering the progress of succeeding crews. This will incorporate float between the tasks and prolong the project lead time. Gantt charts do not clarify why a common work sequence is important. Location-based schedules will communicate that crews need to finish one location before commencing work in the next location, and will make it clear that progress must follow the desired work sequence in order to avoid flatlining in multiple locations (that is, work faces that are occupied by a crew for an extended period of time because they work elsewhere). This malpractice is not evident if location constraints are not made apparent, and failing to abide to a common work sequence will displace the project's time or result in discontinuous work. Thus, work crews' flexibility is reduced when the criticality principle of LBM is applied because the continuity constraints impose a common work sequence in optimized location-based schedules. Despite the reduced flexibility, the rigid completion sequence reduces float between tasks, which reduces the project lead time, because open locations are finished as fast as possible, thereby opening them up to succeeding crews.

Sensitivity to fluctuation in production increases

Exploiting the explicit view of production rates allows project managers to fully align tasks and create a compressed schedule (Kankainen and Seppänen, 2003). Although fully aligned critical tasks reduce the planned completion time of a project, they also increase sensitivity to fluctuation in the project. The sensitivity arises because either technical constraints, location constraints, or continuity constraints will cause displacement to succeeding tasks if any delays should occur, and no buffer is incorporated.

Therefore, if all activities have the same maximum production rate, all activities will be critical (Carr and Meyer, 1974). However, the project will be vulnerable to disturbances if all tasks are aligned at the same production rate because changes to some tasks will have a significant effect on later tasks if no float is incorporated in the schedule (Carr and Meyer, 1974). Any delay in a fully optimized location-based schedule will immediately cascade through the project and cause delays. Therefore, although LBM is useful for optimizing repetitive building projects, the additional constraints will mean that more activities become critical, which will increase the sensitivity to fluctuation in production and unexpected events.

Conclusion

The proposed criticality principle of LBM describes how practitioners should prioritize activities on construction projects when the LBM technique is applied. It is important that differences and effects of the criticality principles are clear, as perceived criticality from the control tool can cause construction managers to make vital decisions when projects are planned and controlled. The proposed collected criticality principle of LBM should provide practitioners with a better understanding of the underlying mechanisms of their LBM projects. Furthermore, the difference and effect of perceived criticality between activity-based and location-based criticality should indicate the advantages of treating more constraints explicitly. Although it is important for project managers to understand the consequences of delaying tasks on the critical path, it is equally important that they understand that an alternative criticality principle exists, which can help them prioritize amongst critical activities and locate inefficiencies in their construction processes that would otherwise be obscured by the prevailing management techniques.

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Article 4 - Applying Critical Chain Buffer Management Theory in LBM

Applying Critical Chain Buffer Management Theory in Location-Based Management

Abstract

This study proposes changes to the buffer management theory in location-based management (LBM) through the use of critical chain theory (CCT). CCT suggests that the common use of buffers entails inherent waste in the schedules and fails to protect both critical activities and projects. Critical chain theory builds on the assumption that each task is, either consciously or unconsciously, given a time buffer with which to cope with unpredicted events, and that these buffers become a large part of the project lead time. Critical chain theory assumes that time estimates become self-fulfilling prophecies, as practitioners tend to procrastinate, and the buffers are often wasted. In addition, excess time rarely benefits the project if activities do finish early, because succeeding activities are unlikely to begin before the planned date. Although the criticisms of CCT also apply in LBM theory, CCT is based on the critical path method, and must be adapted to the criticality principle of LBM. Accordingly, the present study applies CCT to suggest alternative application of buffers in LBM, which will ensure optimal placement of buffers.

By Rolf Büchmann-Slorup

Keywords: Location Based Management, Buffer Management, Critical Chain Theory, Construction Control

Introduction

Location-based management (LBM) has long been studied and utilized as an alternative to activity-based scheduling and control methods such as the critical path method (CPM) and the project evaluation and review technique (PERT) (Kenley and Seppänen, 2010). LBM is especially useful for repetitive projects, as it can simplify and streamline the flow of production. Location-based schedules collect similar activities in tasks, and display planned work across a predetermined location breakdown structure of the building. The aim of the method is to balance tasks, to ensure production flow, and to avoid multiple crews working in the same locations. The tasks are balanced by analyzing the production rates of work crews and by adding or subtracting work crews to the tasks. LBM has been reported to *reduce risk, reduce production cost, increase site harmony, improve subcontractor performance, reduce material waste, improve the quality of construction,* and *deliver more certain outcomes* (Kenley and Seppänen 2010). LBM also seeks to eliminate location conflicts, ensure continuous work flow, optimize resource consumption, and create an overview. This, in turn, removes causes for rework, damage to existing work, suboptimization, busy work areas, etc. (Andersson and Christensen 2007, Harris 1998)

Even though LBM has received attention since the 1930s, when it came to prominence with the construction of the Empire State Building (Kenley and Seppänen, 2010), it remains rarely utilized in the construction industry. The main contributors to the theory include Lumsden (1968), Peer (1974), Mohr (1979), Selinger (1980), Russell (1983, 1985), Kankainen (Kankainen and Sandvik (1993), Kankainen and Seppänen (2003), Arditi et al. (1986, 1988, 2001, 2002), and Kenley and Seppänen (2010). Finnish contractors and the Finnish research community have made particular contributions to the ongoing development of the method and software to support the workflow (Soini et al., 2004). There is a great deal of current literature on location-based management paradigms that explains the method, underlines its advantages, and constructs the theoretical and mathematical foundation (Lumsden 1968, Russell and Wong (1993); Seppänen and Kankainen (2004); Soini et al. (2004); Kenley and Seppänen, (2010)). Although these are all vital contributions, much can still be added to the body of knowledge. Buffer management in LBM is one aspect that has received limited attention in the literature. Only Lumsden (1968), Kaikanen and Seppänen (2003) and Kenley and Seppänen (2010) have addressed buffer management in the location-based methodology in any depth. The use of buffers in construction management has also been an important subject to the lean construction community. Buffers are generally applied to reduce the impact of variability to production flow (Hopp and Spearman, 2000). Flow can be affected by numerous disturbances and lack of prerequisites. The lean construction community has theorized about buffers in accordance with flow (Bertelsen, 2004). All of the seven streams of lean construction – previous work, space, crew, equipment, information, materials, and external conditions (Koskela, 2000) – can be buffered. Accordingly, buffers can be material buffers, resource buffers, equipment buffers, etc. However, this study is delimited to time buffers in LBM. Buffers are an important subject, as their incorrect use can lead to inherent waste in the construction process and discontinuous production flow (Bertelsen, 2004). Consequently, the present study explores the current use of buffers on LBM projects in a case company, and suggests changes to the current theoretical recommendations in the LBM theory regarding buffer management through the principles of CCT.

Critical chain theory (CCT) suggests an alternative approach to the management of buffers. Despite receiving attention from the LBM research community (Kenley, 2004 and Seppännen, 2009), CCT has not yet been applied in a LBM setting. CCT argues that schedules in general are loaded with buffers that become inherent waste, prolong projects lead-time, and fail to protect both activities and whole projects against delays. However, CCT is based on activity-based scheduling and control methods like CPM. LBM has a different *criticality principle* compared to CPM that requires a reformulation of how CCT should be applied in a LBM setting. The criticality principle is inherent in each management methodology and describes which activities and tasks should be considered critical at a given point in time. The criticality principle of LBM imposes more constraints on the activities than activity-based scheduling methods like CPM. Buffers are most often applied in LBM to safeguard continuity constraints and simply because more activities and tasks are made critical as production rates are aligned.

This study starts by introducing LBM, its buffer management theory, and the buffer management theory of CCT. A study of the use of buffers in LBM is then presented in order to comment on the extent and use of buffers, and thereby justify the study. Thirdly, a case is presented in which the buffer management theory of CCT was introduced to a LBM construction project. This last case is used to comment on the current buffer management theory of LBM.

The study contributes to the body of knowledge by contributing theoretically to buffer management in LBM through the application of the buffer management paradigm of CCT in a LBM setting. The study also contributes to the body of knowledge by investigating the use of buffers in a case company and provides a practical test to indicate the impact of the suggested changes on construction projects. The purpose of the study is to develop theoretical considerations of buffer management in LBM, which will ensure the advantages of LBM regarding flow, resource optimization and avoidance of location conflicts, while placing buffers optimally, ensuring that buffers do not become inherent waste in the LBM schedules.

Location-Based Management

Location-based management is an alternative to activity-based scheduling methods such as the critical path method (CPM) or the project evaluation and review technique (PERT). LBM focuses on task continuity, flow, and continuous resource consumption, as opposed to the discrete treatment of activities in the activity-based scheduling methods. The overarching goal is to avoid location conflicts and ensure that each resource can work fluently through the building without stopping and causing rework for other subcontractors. Location-based management has been formed from various similar theories, such as line of balance, the construction planning technique, the vertical production method, the time location matrix model, the time space scheduling method, disturbance scheduling, and horizontal and vertical logic scheduling for multistory projects (Harris and Ioannou, 1998). One important difference between activity-based scheduling and location-based management is the output view in flow lines. Location-based methodologies and activity-based methodologies both include locations. However, CPM repeats similar activities on each location, which adds up to hundreds or thousands of activities that can make projects seem complex and hard to control (Carr and Meyer, 1974). LBM collects the activities in tasks and displays them through flow lines over multiple locations. The complexity of creating and managing the schedule is reduced as similar activities are controlled through one task. LBM also utilizes information about production crews and rates to estimate durations and align production. The analysis of production rates can especially be difficult in the activity-based methods as they are not shown explicitly. In LBM, the aim is to align task production lines to avoid location conflicts and ensure that subcontractors can work unobstructed. Production alignment can be realized by regulating resource consumption and by splitting the location break-down structure into smaller areas to allow more crews to work simultaneously. The idea is to provide realistic productivity rates based on quantities and resources consumption. This is different from activity-based scheduling methods that base schedules on timely estimates with little regard for resource constraints (Seppänen and Kenley, 2005).

Criticality in Location-Based Management

The application of CCT was originally targeted towards CPM, and consequently uses the criticality principle of CPM. Applying the CCT to LBM will require alterations, as the criticality principle of the former includes the demand for work continuity and prevention of location conflicts, while that of the latter does not. Accordingly, critical tasks in LBM include tasks with zero float and tasks with free float. As in CPM, critical tasks are determined by the longest sequence in the dependency network that contains zero float. However, the longest path changes in LBM as it, in contrast to CPM, dependent on location and continuity constraints. The additional constraints link different tasks across locations and demand that tasks are completed without halt in production. The continuity constraint is weaker than the location constraint, and can be broken if necessary. However, the continuity constraint ensures that subcontractors can work without disturbances to their work flow, and thus ensure they do not leave the site, with the danger of late return.

Carr and Meyer (1974) noted that the slowest production rate of an activity in a location-based schedule is critical as any reduction in productivity will cause delays for the project. Therefore, if all activities have the same maximum production rate, and are positioned in the same locations, all activities will be critical. A fully optimized location-based schedule can consequently become very simple to schedule and control. However, the project will be vulnerable if all tasks are aligned with the same maximum productivity rate, as changes to any task will impact succeeding tasks as no float is present between the critical tasks. Thus, buffers are utilized between the critical tasks to reduce their vulnerability and to ensure flow. However, individual tasks are assumed to have varying maximum productivity rates on most projects. Consequently, one task in the chain of tasks with zero float will be the slowest task and this task will determine the progression rate of succeeding tasks due to the interdependencies and location constraints; in other words, succeeding tasks cannot progress until the locations are free. This slowest task corresponds to the bottleneck task in the CCT, which will be described later. Preceding activities that affect the start point of the slowest task, and succeeding critical tasks to the slowest task must equally be considered critical, as they determine the project lead time in LBM projects.

Buffers in Location Based Management

Lumsden (1968) defined two types of time buffers for line-of-balance scheduling: stage buffers and activity buffers. The stage buffers are used between major stages in projects to protect against unforeseen events such as weather. Activity buffers are applied to each activity to protect against minor incidents and fluctuations in productivity. The activity time buffers are not supposed to absorb major recurrent faulty productivity estimates. The buffers are used to protect the continuous workflow. Kenley (2004) stated that LBM emphasizes the minimization of disturbances by allowing buffers between activities and creating collective activities. Lumsden (1968) recognized the disadvantage of buffers but argued that the cost of buffers is low compared to the cost impact on the project if multiple activities are affected by delays. The buffers are believed to reduce risk in the schedule. More time buffers means less risk as delays will be absorbed by the buffers (Lumsden, 1968). It is this reliance on buffers that the CCT challenges, arguing that the buffers fail to protect both critical tasks and the projects. The placement of buffers is scarcely treated in the LBM literature. The CCT is consequently applied to provide general guidelines for the placement of buffers on LBM projects.

According to Kaikanen and Seppänen (2003), the application of buffers should be guided by the sensitivity of tasks. Buffers are placed strategically to minimize workflow variability. Kaikanen and Seppänen (2003) also stated that the size of the buffers is chosen as a balance between the desired duration of the project and the acceptable risk level. Recommendations of the size of buffers on LBM projects are also scarcely described in the literature. However, this study only comments on the placement of buffers. Kaikanen and Seppänen also argued that a start-up delay and a vertical location buffer should be placed between *space-critical tasks.* Weather contingency is also used to protect against the weather and *other unforeseen interruptions* (Kaikanen and Seppänen, 2003). Seppänen et al. (2010) described how SKANSKA applies LBM to establish baseline schedules, which are created at *phase scheduling* meetings from milestones in the master schedules. Any excess time that is available after establishing the base schedule is distributed as a buffer between tasks. However, Seppänen et al. (2010) proposed that subcontractors collectively allocate available buffers to sensitive tasks, instead of distributing them equally to all tasks.

LBM also contains location buffers (Kenley and Seppänen, 2010), which represent available work places where crews can work if they encounter problems in other areas. Construction crews can continue to work in the location buffers despite unforeseen incidents to locations in which they need to work later.

Float is an important aspect in LBM. Uher (2003) argued that float can be used as time contingency, which incorporates flexibility for the non-critical tasks. Although float is not technically a buffer, it is a significant contributor to the inherent risk in a schedule, and can be utilized as time contingency in some circumstances.

Float in Location-Based Management

Float is consumed at the expense of continuous work in LBM (Lowe et al., 2012). The total float in CPM scheduling describes whether tasks are critical or near-critical (Cooke-Yarborough, 1964). Tasks with no float are critical, as any delay to these tasks will delay the project. Tasks with little float are considered near-critical, whereas tasks with high float can absorb delays and are considered non-critical. The total float of a non-critical task indicates the amount of time the task can be moved without delaying the project. The float acts as a time buffer for non-critical tasks and is used to protect succeeding tasks against delays (Kenley and Seppänen, 2010).

However, current LBM theory only incorporates time float. Kenley (2004) stated that the concept of total float fails when LBM is applied. Considerations of total float become irrelevant due to the need for continuous work and resource utilization. In CPM, total float is the spare time that becomes available if preceding activities start as early as possible, while succeeding activities start as late as possible. Accordingly, total float is an indication of the maximum amount of time an activity can be delayed without delaying the project (Cooke-Yarborough, 1964). Therefore, the total float in CPM terms is purely dependent on the early start and late finish of activities and does not take location and continuity constraints of succeeding activities into account. Consequently, the concept of float is limited to free float in LBM. Kenley (2004) defines free float as *the amount of time that an activity may be delayed without affecting any other activity.* The protective features in LBM include time float as well as buffers, which means that the impact of time float is important when applying CCT to LBM. Applying CCT to LBM should not only consider tasks affecting the project deadline through the critical path; it should also include disruptions to continuous flow. Therefore, the conceptualization of float is affected by the difference in criticality principles between CPM and LBM, which, in turn, influence the application of CCT.

Productivity float in Location-Based Management

Preceding and succeeding critical tasks to the slowest tasks will contain so-called *productivity float*. The concept of productivity float was introduced by Harmelink and Rowings (1998), who applied it to sub-activities in order to divide critical tasks into smaller segments, called *control segments*, which allow project planners to treat sub-activities according to their criticalness. Productivity float is mentioned because it becomes an important aspect in the application of the CCT. Productivity float emerges in the effort of aligning the production lines. A buffer develops in front of a slow task if the predecessor has a higher production rate. Similarly, a surplus of available production capacity becomes available if a successor has a higher production rate than its predecessor. The difference from CPM scheduling is significant, as all critical tasks would be completed at the highest possible production rate in CPM. However, the criticality principle of LBM implies that tasks will be limited by the progress of the slowest task, in order to avoid location conflicts and ensure a continuous work flow. The productivity float is important to this study as all time buffers are removed from the critical tasks in CCT, and the productivity float can protect the slowest tasks without impacting either the project buffer or the project lead time.

Critical Chain Theory

The CCT reasons that buffers are inherent waste in schedules and delay the project unnecessarily while also failing to protect the activities due to procrastination. CCT a project management theory that was introduced by Goldratt (1997) and developed from the theory of constraints (Goldratt, 1988). The CCT is based on assumptions about human behavior and tendencies in project management (Leach, 1999). The first assumption is that humans tend to expand their work effort and use whatever time is available. The CCT suggests removing deadlines in order to avoid this tendency and to avoid unnecessary available time in each activity. The second assumption is that buffers on individual tasks fail to protect against delays, as the buffers tend to be consumed early, which leaves little buffer to protect the task in the end. The assumption is that, for example, subcontractors will procrastinate and consume excess time if time contingencies are incorporated into the estimated task duration. Therefore, buffers are typically consumed and fail to protect both single tasks and projects as a whole, as no buffer is available when complications do occur.

Time estimates are too long

The CCT also claims that safety is built into each individual task as the typical human tendency is to provide a comfortable timely estimate with high confidence of completion. Aggressive estimates are commonly avoided where possible in order to protect each task. Non-aggressive estimates will cause procrastination until a sense of urgency rules (Herroelen and Leus, 2001). Consequently, the buffer will not protect tasks as progress is inherently slow until the deadline becomes pressing. Furthermore, the CCT argues that this safe estimate contains excess time that is never harvested if the activity is completed early. Succeeding activities of an early-completed preceding activity will tend to start as planned and not early. Failure to exploit early completions will restrict the acceleration of progress and hinder any buffers to accumulate (Herroelen and Leus 2001). Therefore, the CCT recommends that all task estimates be created tightly enough to avoid work on other tasks or procrastination, which will eliminate all safety and due dates from the activities. The CCT recommends reducing task estimates to a 50 percent confidence level.

Reallocation of buffers

The CCT also advocates a shift from task estimates and intermediate milestones towards a holistic project view in which only the final deadline is significant. Buffers are removed from each task and only used before *bottleneck tasks*, before *non-critical chains* meet the *critical chain,* and at the end of the project. Critical and non-critical chains describe logical dependencies similarly to the paths in CPM. The buffers at the end of non-critical chains are called *feeding buffers*. Feeding buffers ensure that non-critical tasks remain non-critical, while a buffer at the end of the critical chain protects the entire project from being late. Buffers before bottleneck tasks protect the most critical tasks from slower preceding tasks. When the CCT is applied to a new project, buffers are taken out of each task estimate, collected, and distributed to vital areas of the plan, while ensuring that individual buffers in each task are not wasted.

The CCT also suggests that dates and milestones should be removed from the schedules, as this should remove any excuse to procrastinate. The CCT theory suggests that the work crews are asked how much time in advance they must be warned of upcoming work. Therefore, prior tasks must be monitored so a signal can be sent to succeeding crews in due time.

Protect Critical Chain of Activities

The key principle in CCT is to protect the project deadline from the critical chain of activities and ensure that non-critical activities do not influence critical activities. The CCT recommends that non-critical tasks be started as early as possible. However, the total or free float from non-critical to succeeding critical tasks might not provide sufficient safety. The chains of non-critical activities are therefore provided with a buffer at the end of the chain. The principles for the non-critical tasks are the same as for the critical chain. The accumulated buffer in a non-critical chain is placed at the end of the non-critical chain so it protects the critical chain. The buffers are then consumed before the chain of non-critical activities affects the critical chain. The aim is to maintain the critical chain, as opposed to CPM where the critical path changes continuously throughout a project (Herroelen and Leus, 2001). Keeping the critical chain constant should ensure that non-critical tasks remain non-critical, which should ease the management of projects.

Control Mechanism

The CCT control mechanism is based on the buffers. In addition to protecting against deviation from the plan, the buffers act as warning mechanisms (Herroelen and Leus, 2001). Herroelen and Leus (2001) stated that an alarm will warn the project management if *activity variation consumes a buffer by a certain amount.* E.g. The buffer can be divided into three stages. In the first stage, no extraordinary control action will be taken. The first stage allows small variations in productivity to occur and provides flexibility and room for project managers to maneuver. If the entire first stage of the buffer is consumed, an alarm will go off and contingency plans should be made. The contingency plans are implemented if the second stage of the buffer is consumed, which leaves the third part of the buffer to absorb the remaining delay.

Criticisms

Some criticisms of the CCT has been raised in the literature in terms of its originality (Trietsch, 2005), oversimplification (Herroelen et al., 2002), and the underlying assumptions of procrastination (Raz et al., 2003). The CCT's underlying assumptions were not proven by Goldratt (1997). The assumptions were based on his observations and practice in the industry. Therefore, the assumed behavioral tendencies are generalizations that might not be true. Trietsch (2005) also criticized CCT's assumptions, stating that they simply have not been proved fatal yet, so it is important to consider if the assumptions are likely to apply. This aspect will not receive further attention here. Despite these criticisms, the CCT has attracted interest from the research community, although its application should be seen as a conceptual and pragmatic method (Stratton 2009), which suggests how buffers should be managed. In this study, CCT has been employed to generate ideas and challenge the current use of buffers in LBM.

Applying Critical Chain Theory in Location-Based Management

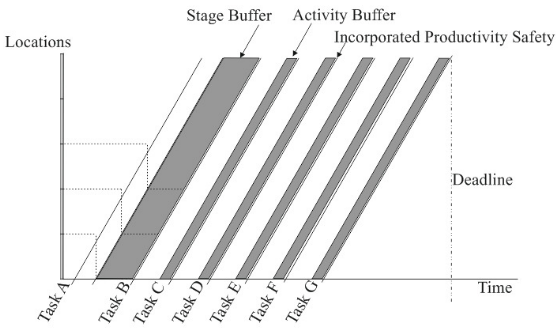
LBM and CCT have several commonalities. For example, both methods incorporate resource constraints in the criticality concept, align production to the slowest production rate, and advocate that the control process follows the remaining estimated time rather than the "percentage complete". However, inclusion of location constraints and continuous flow is not a part of the criticality principle of CPM and is therefore not included in CCT. The extra constraints change the application of CCT when it is applied in a LBM setting.

The following section suggests how the buffer management principles of CCT should be incorporated into LBM setting. In short, the aim of buffer management in the critical chain theory is to collect time buffers in the end of projects (project buffers), place buffers in the front of bottleneck tasks, place feeding buffers at the end of non-critical chains, and reduce task estimates to a 50 percent confidence level.

Collecting all Buffers at the End of Projects

Figures 1 and 2 illustrate the difference when buffers for critical tasks in LBM are redistributed according to the CCT. Figure 1 illustrates a fully optimized location-based schedule with a stage buffer, activity buffers and productivity float. Figure 2 shows how buffers would be placed according to the CCT. All buffers for the critical tasks are collected at the end of the critical chain to form a project buffer. The project buffer includes the gain of reducing the confidence level of each task, so the estimate is more optimistic.

A similar picture emerges if the example contains non-critical tasks. However, LBM-based projects will typically contain fewer non-critical tasks due to the additional criticality requirements. A location-based schedule can still contain non-critical tasks. Buffers for non-critical tasks will be collected at the end of the non-critical chain as a feeding buffer to the critical chain. Thus, the difference is simply that buffers after non-critical chains protect the critical chain and not the project directly.



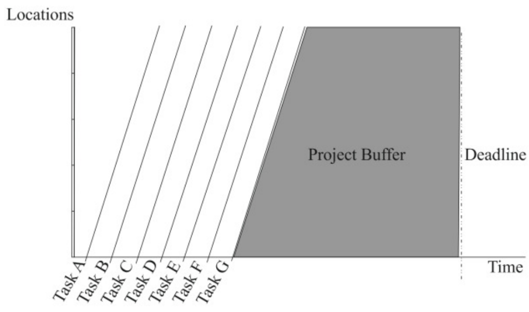


Figure 1: Aligned tasks in a location-based schedule with stage buffer and activity buffers. No project buffer exists.

Figure 2: Aligned tasks in the same location based schedule as in Figure 1. All buffers are collected and placed as a project buffer and productivity estimates are reduced.

Protecting the Bottleneck Task with Productivity Float

One advantage of applying CCT to LBM is that the bottleneck task is explicitly apparent, unlike in CPM. The bottleneck task is the slowest task. The CCT argues that the bottleneck task must be protected against delays at all costs, as it determines the progress of all succeeding interdependent tasks. This is equivalent to the slowest task in LBM. Forcing task continuity requires some subcontractors to proceed slower than possible. This entail that excess productivity potential is incorporated in the critical tasks, which enables utilization of *productivity float*. Productivity float describes the excess time that arises between tasks as the preceding task has a higher production rate than its successor. Productivity float is not a part of CPM and, therefore, not part of the CCT. Tasks are not slowed down in CPM due to location constraints and requirements of task continuity. Analysis and application of productivity float can serve two purposes. It can be applied in front of the bottleneck task; that is the slowest task in a LBM setting, and it can be used as part of a feeding buffer for non-critical tasks. The productivity float can potentially provide a buffer that protects the slowest task without affecting the project duration. Instead of aligning preceding tasks to the slowest tasks, productivity can be increased to create a buffer that increases in size as the crews work through the locations (Figure 3 and Figure 4). All tasks prior to the slowest task can be accelerated to a productivity rate of the slowest task in the critical chain prior to the slowest task.

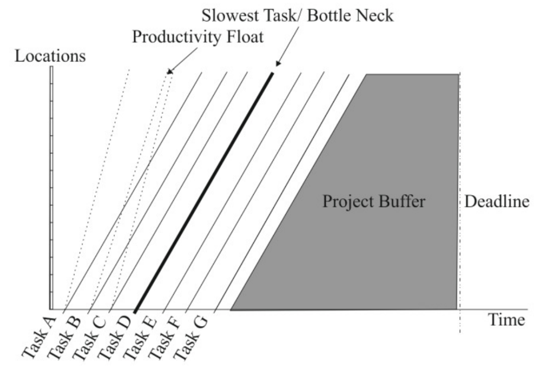


Figure 3: Dashed lines indicate productivity float.

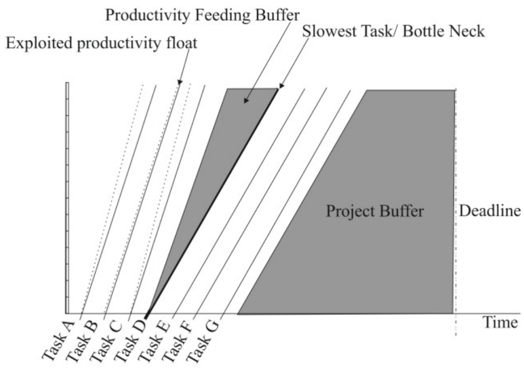


Figure 4: The productivity float from Figure 3 has been exploited to create a productivity feeding buffer.

Feeding buffers protect the critical chain, but cannot be exploited in terms of early completions. The productivity feeding buffer does not protect the first locations, as no time float will be available until the productivity feeding buffer accumulates throughout the locations. Therefore, the tasks before the slowest task remain critical for the first locations. However, a buffer will build after latter locations if subcontractors manage to complete their tasks faster than the planned slowest task. In Figure 4, for example, task D starts as soon as possible once task C has finished at the first location. A buffer accumulates if the productivity of tasks A, B, and C accelerates to a rate that all three tasks can obtain while still maintaining task continuity. Productivity feeding buffers will not be applicable after the slowest task, as successive tasks are limited by location constraints and the slowest task. Succeeding tasks to the slowest task will consequently consume the project buffer if they are delayed.

Method

The objective of this study was to contribute to the theoretical considerations of buffer management in the LBM theory. The empirical foundation for the study is based on two investigations. Firstly, several cases were investigated in order to gain insight into the current use of buffers on LBM projects in a case company. The analysis of buffers includes tender schedules and construction schedules. Activity buffers, stage buffers, and project buffers were recorded for all critical tasks. The analysis of buffers was supplemented with interviews of LBM scheduling experts and project managers in the case company.

Secondly, the buffer management theory of CCT was introduced to the management of a LBM project in the case company, which involved refurbishing 544 similar apartments within three years. Five or six apartments were collected in 94 blocks. All apartments were identical except for the placement of skylights and windows, which meant that the construction process was highly repetitive. The project management created an optimistic location based schedule with no activity buffers. Most critical and non-critical tasks were aligned in order to abide to continuity and location constraints, which meant the project schedule was highly compact. The project management had three months of buffer to distribute across the project lead-time of three years. This meant that minimal buffer was available to protect the project. Alternative ideas for buffer management were interesting to the project management, which led to the buffer management theory of CCT and LBM being discussed with the project management. The results of these discussions are used to comment on the use of the buffer management theory of LBM. The intention is not to generalize the results but to investigate the use of buffers in depth in order to suggest potential improvements in the LBM buffer theory. The applicability to other cases is assigned to future research.

Use of Buffers in Location-Based Projects in the Case Company

Fourteen complete location based projects from the case company have been analyzed. The investigation demonstrated high diversity in the application of buffers in the case company. The results have been assembled in Table 1.

Some projects contained a lot of spare time between critical tasks, due to unsuitable placement in the higher layers of the location breakdown structure. A great deal of time could be gained and reallocated as a buffer if tasks were placed lower in the hierarchical location structure. This spare time has not been included in Table 1, although it could be exploited and reallocated as a buffer. Further, only buffers for critical tasks have been included. Table 1 contains both schedules prepared for tenders and construction schedules.

No standard practice prevails in the case company, which causes inconsistencies in the schedules. Activity buffers, stage buffers, and project buffers are commonly used. Weather contingencies are only rarely incorporated. The placement and size of buffers is arbitrary. Schedulers have their own rule sets; for example, some schedulers always incorporate a three-day activity buffer for each critical or non-critical activity, while other schedulers only incorporate stage and project buffers. The amount of buffer that is incorporated also varies considerably. Some projects had no buffer at all, while the total amount of buffer in other projects represented as much as 47 percent of the total effective work time. Both extremes are problematic. Projects with no buffer are inherently associated with risk of delays. Interviews with practitioners, however, revealed that buffers are sometimes incorporated into the task duration estimates. In these cases, the buffers are not visible in the schedules. Incorporating buffers implicitly in task durations can be dangerous if the buffers *are* managed as an inherent part of the plan. If control schedules communicate that the project is on time because every buffer is used, there will be no reason for corrective actions and the buffers will become part of the project lead-time. Projects containing a total buffer close to half of the build time can potentially be completed earlier than planned. According to the CCT, the vast amount of buffer can extend project lead times unnecessarily due to procrastination, especially if the buffers are placed as stage or activity buffers.

Cases that predominately rely on activity buffers and minimal project buffer protect the continuous flow of work, but fail to protect the project as a whole. As Lumden (1968) described, the activity buffers rarely last for more than a few days and are indented to protect each task for fluctuation in productivity. Interviewed project managers supported the notion that major delays arise from few tasks that cascade through the project, which indicates that activity buffers will not protect against major delays. If the assumption of CCT is correct and the activity buffers are consumed and rarely accumulated as the project progress, projects that only rely on activity buffers to protect them are prone to risk of delay, especially towards the end of the project.

Some of the cases in Table 1 contain no activity buffers. The removal and reallocation of activity buffers is in line with the original recommendations of the CCT. However, the original CCT theory was based on CPM that does not include continuity constraints in the criticality principle. Flow is the cornerstone of LBM and should not be ignored. As previously noted, Seppänen et al. (2010) stated that only the most sensitive activities and tasks should be protected. Several cases in Table 1 contained activity buffers on each task that accumulate to several months of buffer. Combining the recommendations of Seppänen et al. (2010) and CCT, the activity buffers should be removed from non-critical tasks and only allocated to the most sensitive tasks in the critical chain.

Some projects in the case company contain many months of stage buffers. Nothing in the criticality principle of LBM prevents reallocation of the stage buffers to the project buffers. Placing the stage buffers last in the schedules should prevent the tendency to procrastinate and risk utilizing the buffers unnecessarily. Therefore, stage buffers should not be applied in LBM projects unless required by technical constraints, such as rental of very expensive equipment with long procurement time or limited availability. In these cases, the cost of a delay to the particular task should supersede the cost of consuming the allocated buffer.

Some case projects contained no project buffer, which presents great risk towards the end of the project; for example, if progress has been recorded optimistically due to performance-based payment plans. Project managers in this case study stated that the remaining work in the final stages is often underestimated. As build progress data from one of the cases exemplified, most tasks initially progressed with large percentage increments of completed work (around 20 percent), while recordings in latter stages declined to 2 percent progress each week. In this case, the lack of project buffers would leave the project subject to delays. The same applies in cases where unexpected events occur in the latter parts of projects when a prior buffer has been consumed. Accordingly, the project buffer should be prioritized as this will protect against delays to every task and reduce the temptation to utilize the available buffer on each task or after stages.

Project	Activity Buffer (Days)	Stage buffers (Days)	Weather Contingency (Days)	Project Buffers (Days)	Total buffer (Days)	Work Days	Buffer % of Workdays	Schedule type
1	5	148	25	60	238	510	47%	Tender
2	0	0	0	0	0	438	0%	Tender
3	9	76	0	0	85	328	26%	Tender
4	0	60	0	29	89	378	24%	Tender
5	60	0	0	0	60	648	9%	Construction
6	14	6	0	33	53	418	13%	Construction
7	25	105	0	101	231	630	37%	Construction
8	84	30	0	0	114	454	25%	Construction
9	94	0	0	50	144	714	13%	Tender
10	0	4	0	2	6	175	3%	Construction
11	0	16	0	0	16	152	7%	Construction
12	22	89	0	13	124	482	26%	Construction
13	0	0	0	19	19	381	5%	Construction
14	9	0	0	47	56	251	22%	Construction

Table 1: Analysis of the use of buffers on fourteen cases.

Behavioral Aspects

The interviews and test of the CCT in LBM projects revealed that some project managers are not interested in portraying schedules as accurately as possible when projects are controlled. Project managers sometimes exploit buffers to communicate that projects are on time or ahead of schedule. A case study that introduced the buffer management principles of the CCT, described below, provided insight into this behavioral aspect.

The case project had an estimated lead-time of three years and the project management estimated that the project could be finished in 2.5 years. This was made possible by removing all activity buffers and alignment of most tasks, which left six months of spare time. However, vacations and national holidays were not included in the tender estimate. Subtracting vacations and national holidays left three months of buffer to be distributed across the entire project of three years. The project management had originally decided to distribute the buffer to each month in order to protect against weather delays and other unforeseen events. A standard national table indicated the amount of buffer that should be allocated each month to protect against weather delays. For example, three days are allocated to January due to the winter weather, while only one day would be allocated to August as little rain is expected during the summer. In this case, the total weather contingency buffer totaled 21 days per year. The weather contingency buffer consequently consumed the entire available buffer and no project buffer was available at the end of the project. The project management expected to optimize the project further and secure additional buffer. However, the original intent of the project management was to increase all the monthly stage buffers to eight days before a project buffer would be built.

Placing a stage buffer after each month contradicts the recommendations of CCT, which say that the buffer will tend to be consumed by procrastination, and there will be little incentive to secure early finishes and build a buffer. Collecting the buffer at the end of a project should ensure that the buffer is only consumed if a delay does occur, and not due to procrastination.

However, the project management refused to place the buffers at the end of the project. The scheduler wanted to incorporate and distribute the buffer across the project. By distributing the buffer to each month, the control schedule will communicate that the project is close to the plan. The actual performance will appear worse if the buffers are collected at the end. The scheduler provided an example to explain their situation. Figure 5 shows a project that finishes on time.

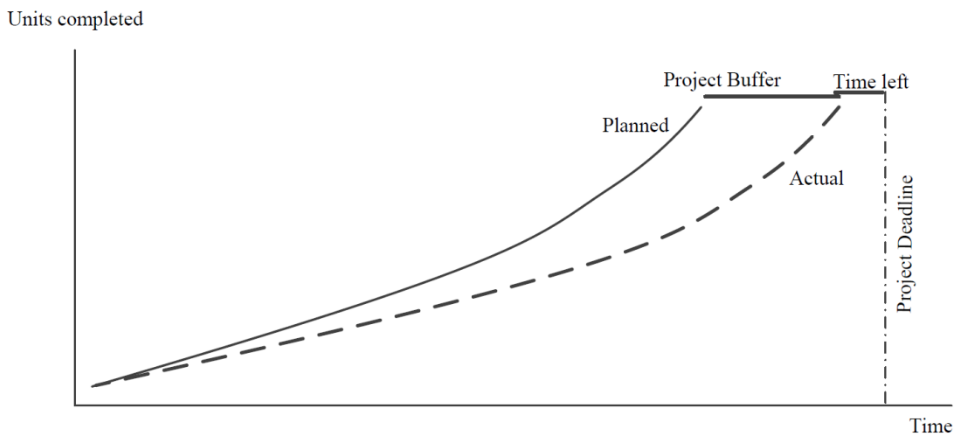


Figure 5: All time contingency placed as a project buffer.

If the buffer is accumulated and placed at the end of the project, the project will appear to be behind schedule for the entire duration of the project. It is not in the project management's interests to communicate this to either the head office of the construction company or the client. The project management wanted to ensure a calm work site, avoid interference from the head office, and demonstrate professionalism towards the client. Figure 6 shows the same project with the same actual performance. Placing the buffers in stages will communicate that the project is ahead of schedule.

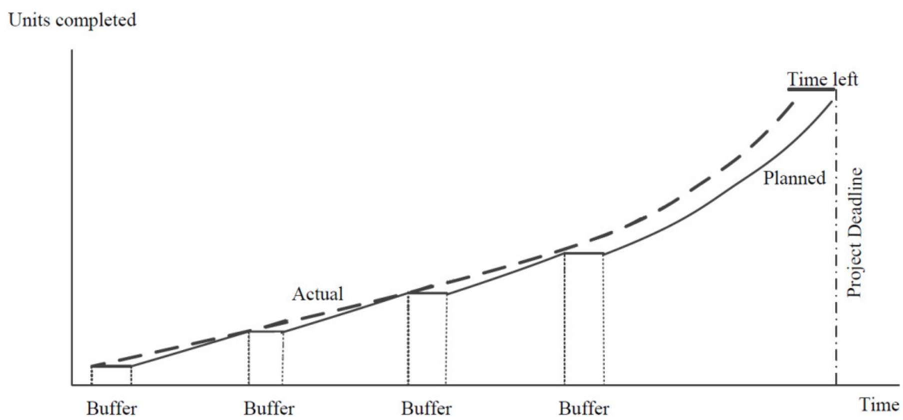


Figure 6: Buffers placed as stage buffers.

Thus, the project management preferred to present the schedule optimistically to the head office and the client. An aspect of interest to the present study is the consequences of this placement. Figure 7 illustrates a situation in which actual performance is worse than the planned performance and the project finishes late. Placing the buffers early can give the impression that actual performance is going according to plan. The buffers are consequently expected to be consumed. This practice increases risk, as there will be minimal buffer remaining at the end of the projects. Communicating better-than-planned performance by treating buffers as a part of the plan will affect forecasts and fail to warn about upcoming risks. The location-based schedule will fail to provide early warnings if the buffers are treated as a part of the plan. The difference between this method and collecting and placing the buffers late becomes apparent through the CCT control mechanism. Figure 8 illustrates the same actual performance as in Figure 7, except that the stage buffers are collected and placed as a project buffer.

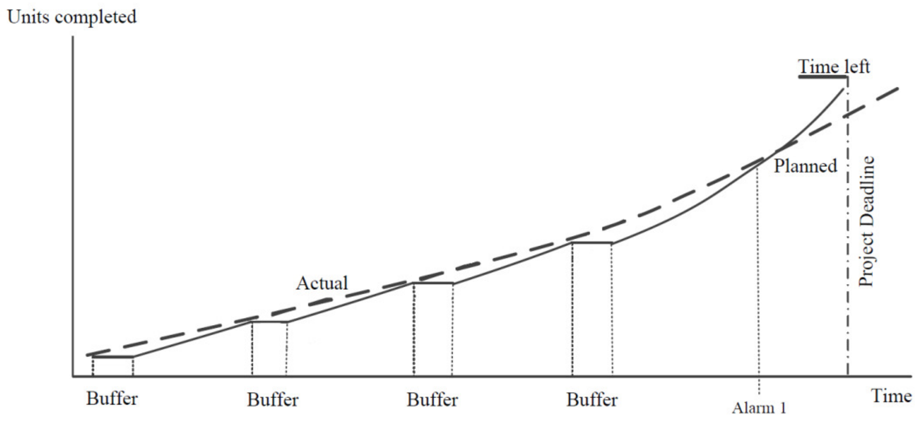


Figure 7: Alarm if buffers are incorporated in the planned performance.

Placing the buffer at the end will ensure that warnings can be generated earlier through the control mechanism in the CCT theory. Early warnings will sound if the first part of the buffer is consumed, which leaves room for the project management to act within certain limits. Two additional alarms will signify continuing deviation from the plan and provide a warning when the buffers are consumed, which will leave time to create and implement contingency plans.

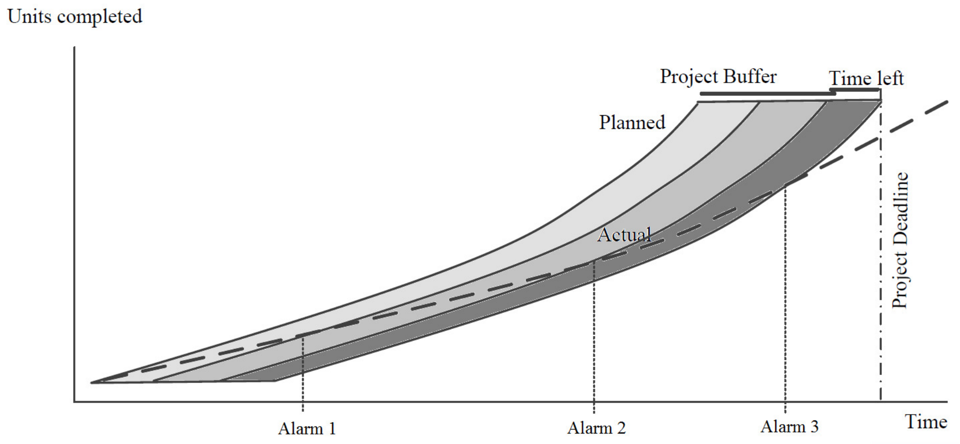


Figure 8: Alarms if the all buffer is placed last, and the CCT control mechanism is applied.

Therefore, the placement of buffers at the end of projects should not only be implemented in order to prevent inherent waste of buffers due to procrastination, as recommended in the CCT. The buffers should also be placed last in order to provide the best means of control. Placing buffers early will hide poor performance. The project's performance will be portrayed more realistically and the inherent risk will be more obvious if buffers are collected as a project buffer, as the project management will be warned earlier of any systematic discrepancies in production.

Conclusion

This study explores the challenges related to the buffer management discipline in LBM and suggested improvements in this regard. CCT is applied to provide reasoning behind the suggested change. It is argued that LBM projects should avoid applying stage buffers and weather contingency, should apply activity buffers to sensitive critical tasks, and should exploit productivity float in front of the slowest tasks, leaving the project buffer predominant.

There are several reasons to distribute buffers in LBM according to the buffer management theory of CCT. Placing all time contingency as activity or stage buffers can fail to protect latter activities, if the buffers do not accumulate. Activity and stage buffers that are placed early in the schedule can be consumed by procrastination and ultimately fail to protect the project against delays. Furthermore, signals of insufficient productivity will occur earlier in LBM if buffers are incorporated in the end of schedules. Placing buffers early will delay warnings of late completion as the buffer becomes part of the schedules. Distributing buffers throughout the schedule also reduces the final project buffer, which leaves little time contingency towards the last parts of the project and therefore increases the risk of late completion.

A question remains for future study regarding removal or substantial reduction of activity buffers. The activity buffers were introduced to LBM to ensure continuous work flow. Aligning all tasks and removing the activity buffer makes the LBM project more vulnerable to fluctuation in productivity. Even small changes at the beginning of projects will affect late succeeding critical tasks. Removing the activity buffers can potentially be disruptive to the focal point of LBM; that is, the continuous work flow and resource utilization.

In the case project involving the 544 apartments, the project management planned to micromanage the project and exploit off-site location buffers to eliminate the activity buffers. Micromanagement and off-site location buffers could be subjects for future research. Micromanaging of LBM projects would require detailed definition of the location breakdown structure and work packages. The management on the case project planned to commit subcontractors to finish each work package in one day, regardless of early completions or the need to work overtime. Their intention was to provide daily achievable workloads that are likely to finish. In addition, off-site facilities would be provided for preparation of work for subcontractors who are retained by fluctuation in production by preceding subcontractors. Lean construction initiatives could also be a potential way to reduce or remove activity buffers, through the meticulous management principles of the Last Planner System (Ballard, 2000; Seppänen et al., 2010). However, the application of micromanagement, off-site facilities and continued merger of LBM and Lean construction initiatives to reduce the activity buffers is assigned to future research.

This study does not deal with the sizing of buffers. The size of buffers in the original CCT has been explored in the current literature (e.g., Tukel et al., 2004). Applying theoretical considerations of buffer sizing from CCT to LBM projects will also be a topic for future research.

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