CHALMERS
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Implications of time-space constraints in construction sites

Master's Thesis in the Master's Programme Design and Construction Project Management

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Construction site in Old City, Jerusalem, photo: Petros Zeglis, 2015.

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ABSTRACT

Among the distinct characteristics of construction is the inefficiency of operations, especially compared to other industries. The notion that construction management suffers from deficiencies is held by various researchers, emphasising on the frequency of phenomena of separation of execution from planning and after-the-fact variance detection. In order to identify and target the appropriate areas, a clarification and decomposition of processes is necessary. Systems that strive for productivity improvement in construction are indivisible from logistics aspects, such as resource management and utilisation. According to several researchers, the conflicts that the scarcity of space per time unit produces in construction sites are one of the major drivers for productivity loss. At the same time, state-of-the-art software solutions are not widely adopted and integration of such tools is poor and limited in the design, rather than in the construction phase.

The purpose of this thesis is to investigate what are the impacts of spatial constraints that can lead to on-site time-space conflicts, in regard to cost, time scheduling and productivity. Moreover, drawing on an explorative case study, this thesis aspires to provide an understanding on how time-space planning is currently performed in the case of complex projects, and juxtapose the position from a contractor's point of view with that from the IT point of view. The thesis is carried out drawing on a small sample of qualitative data synthesised with an extensive theoretical framework. The qualitative data is obtained in collaboration with three firms, a contractor and a consultancy firm in Sweden and a multinational software developer in Denmark.

Industry practice and literature indicate that the most significant constraining factors for time-space conflicts are technological dependencies, construction methods in particular, temporary facilities, availability and continuity of resources, and availability of information. Resource levelling is often used to compensate for problematic activities, while certain working routines can hinder a thorough assessment and the subsequent identification of constraining factors. Eventually, there is a need to include the attribution of resource demand in activity scheduling and address the challenges of assumed unlimited and continuous resource availability and critical activities with no precedence. In parallel, the use of big databases paired with sophisticated software is suggested.

Key words: *time-space conflicts, constraints, scheduling, resource demand*

Contents

Preface

In this study, the issue of time-space constraints in construction sites has been examined, both from theoretical point of view, as well as with complementary insights from three major actors in the industry. The study builds a theoretical framework in order to explore how implications of the scarcity of space are perceived, integrated, and planned against. The project is carried out at the Department of Construction Management, Chalmers University of Technology, Sweden.

In order to obtain a point of view from the industry and juxtapose this to the theoretical framework, the study considers inputs from three private firms in Sweden and in Denmark. The author would like to thank NCC AB, Prolog bygglogistik AB, and RIB Software AG for their cooperation and involvement.

Göteborg October 2015

Petros Zeglis

1 INTRODUCTION

The broad picture

The increasing demand for productivity improvement in construction, following a trend that begun in the japanese manufacturing industry (MacDuffie et al., 1996) with Toyota establishing a *lean production system*, led to attempts to implement lean principles in the construction industry. The transition of the lean approach from manufacturing to construction has been extensively discussed in research (Gann, 1996, Jørgensen and Emmit, 2008, Nahmens and Mullens, 2011), with authors arguing that there are particular aspects that differentiate construction radically from other industries (e.g. the automotive industry) and make the implementation problematic (Koskela, 1997; Winch, 2005; Forbes and Ahmed, 2011). Subsequently, productivity improvement has been a hot topic in construction, with several areas still lagging behind manufacturing operations. But *lean construction* was not the only movement to aim to better performance and certainly production operations were not the only area that left room for such improvements.

Among the various sub-disciplines of construction project management, it is planning and monitoring that currently exhibit the most opportunities for improvements (Sriprasert and Dawood, 2002b). In order to identify and target the appropriate areas, a clarification and decomposition of processes is necessary. According to the role of construction project management and the authors cited above, it is planning, coordination and control that need to be managed, within predefined boundaries of cost, time and quality. Further breaking down the terms, construction site management involves a sequence of processes of site layout design, material management, organisation of work groups and their respective allocated spaces, as well as schedule, cost and quality management (Zeng, N., Liu, Y., Li, X., and Xu, B., 2014).

The notion that construction management suffers from deficiencies that are not well-supported from traditional project management theory is held by various researchers (Ballard, 2000; Koskela and Howell, 2008), highlighting the frequency of phenomena of separation of execution from planning and after-the-fact variance detection (Sriprasert and Dawood, 2002a). Furthermore, it is argued that one of the most distinct characteristics of construction is the inefficiency of operations (Dubois and Gadde, 2002). Cross-country studies exploring project success factors indicate that theoretical support is not widely used in project management practice (Todt, 2001). Therefore, it is concluded that there is a need to improve productivity in construction and that it is essential to deploy suitable IT tools and production-oriented management (Sriprasert and Dawood, 2002a).

Resources

According to Oxford dictionary, *resource* is defined as "*a stock or supply of money, materials, staff, and other assets that can be drawn on by a person or organization in order to function effectively*". In traditional economics, resources are categorised into three groups: *land, labour* and *capital* (Samuelson and Nordhaus, 2005). In order to align the terminology to the construction industry and bring it to the thesis' specific focus, it is essential to define each group of resources. The term *land* refers to both the production site space and the natural resources. *Labour* (or *human resources*) includes the physical and mental work of humans towards the creation of a product or service, whereas *capital* includes manufactured goods used to produce other goods or services, such as factory, storage and transportation facilities (McConnell, Brue and Flynn, 2012). For the purpose of this study, we regard the space in construction sites as a resource (land), that can be available or not. Materials and labour are also regarded as resources that can critically affect the production process in construction.

Systems that strive for productivity improvement in construction are indivisible from logistics aspects, such as resource availability, which in turn are dependent upon planning. In fact, Forbes and Ahmed (2011) highlight that the effective implementation of lean principles lies in better utilisation of resources.

Conflicts and constraints

The issue of *spatial conflicts* and *congestion* on construction sites has come to focus in research the last decades. *Spatial conflicts* can be described as situations of interference where a specific amount of space is claimed as necessary for two or more activities at the same time, usually as a result of inefficient planning. Erroneous time planning or unforeseeable schedule overruns are common causes for scarcity of space, especially for activities that take place in close proximity. The factors that limit or restrict the use of space are therefore called (spatial) *constraints*, or as defined by Riley and Sanvido (1997), "*project constraints consist of any outside factors that affect the decisions in the space planning process that are beyond the control of the planner*". Nevertheless, what the aforementioned succeeding research is pointing to, is that the management and/or mitigation of these constraints is a problematic area that offers room for improvements.

Constraints can be of physical, temporal or of mixed nature. Physical constraints consist of tangible obstacles that can hinder, limit or alter the effective design and execution of the sequence of construction activities. These factors can be geographical, geological or accessibility. Temporal constraints contain factors that can affect time schedules, such as logistics aspects (e.g. delivery times) or weather phenomena. Temporal constraints do not rightfully belong in the group of spatial constraints; however, they need to be considered as they are inextricably linked to physical constraints, due to their ability to affect them. For instance, inefficient time schedules can result to congestion and subsequent spatial conflicts between activities. At this point, it is useful to refer to Akinci et al. (2002), and the authors' definition of time-space conflicts, where in a "*demand for space per time unit*", "*an activity's space requirements interfere with another activity's space requirements, or with work-in-place.*" In praxis, project managers lack a consistent solution to predict and manage spatial conflicts at the design stage (Akinci et al., 2002).

Spatial conflicts in construction sites are associated with a plethora of impacts, such as productivity and material loss (Mallasi and Dawood, 2004; Tawfik and Fernando, 2001), inefficient resource use, increased risk and safety hazards and conflicts among subcontractors, among others (Tawfik and Fernando, 2001). In particular, several researchers argue that time-space conflicts and path interference between activities in construction sites are one of the major reasons for productivity loss (Howell and Ballard, 1997; Guo, 2002).

Researched solutions

Recent literature suggests that issues of on-site management were attempted to be identified and solved with the help and in parallel with the development of BIM (Building Information Modelling). Although the wide adoption of BIM among practitioners is fairly recent, its application has been extensively researched. However, research indicates that BIM contributes more in the design stage rather than in the construction phase on-site management (Zeng, N., Liu, Y., Li, X., and Xu, B., 2014). According to two case studies in China, the Chongqing Real Estate Tower project and the Galaxy SOHO project, both of which used BIM consultation services, the reasons for the inadequacy of BIM past the design phase lie in the inability to follow the dynamic construction sequences and in insufficient coverage of the different aspects of on-site management (Zeng, N., Liu, Y., Li, X., and Xu, B., 2014).

The development of IT-based methods offers a wide range of optimisation models with the use of genetic algorithms (Mawdesley and Al-Jibouri, 2003), neural networks (Yeh, 1995), and hybrid intelligence (Zhang, Liu and Coble, 2002), among others. In spite of their accuracy, these methods suffer from a lack of integratability into the design and construction processes, due to i) a lack of sufficient knowledge of construction professionals on sophisticated IT methods and ii) a lack of technical support and compatibility among design and construction tools and IT-based optimisation tools. In addition, such models are particularly costly and seen as a justified risk and tradeoffs for additional costs that might be saved should conflicts do not materialise. Besides IT-based methods, there has been a significant development of construction industry-initiated methods, such as first planning (Johansen and Wilson, 2006), Last Planner®, and critical space analysis (Winch and North, 2006), among others. Perhaps the most complex feature of construction processes is the dynamic nature that governs them, in combination with their interdependencies. Consequently, there is a need for methods that instead of static conceptualisation can incorporate the dynamic nature of construction operations, as it is an essential feature that needs to be addressed. Such are constraint-based simulation models that can take project requirements and conditions as the defined constraints (Beißert, König and Bargstädt, 2007).

Research questions

RQ1. What are the constraining factors that can lead to time-space on-site conflicts, impacting on cost, time scheduling and productivity?

RQ2. Drawing on explorative cases, how is time-space planning currently performed in praxis in the case of complex projects?

RQ3. On what foundation should a framework be based to enable the identification and methodological integration of time-space constraint management into the construction planning process?

Orientation

The present, introductory part of this thesis aspires to provide an adequate understanding of the topic and the necessities that make it eligible. For this purpose, certain references to previous research are made; although this chapter is limited to serve as summary of background information, for further examination of the role of time-space constraints in construction projects.

The second chapter, *Methodology* and research design, explains the rationale behind the chosen methodology and describes in detail the steps followed to reach the thesis' set objectives.

The third chapter, *Theoretical framework*, uses relevant and detailed information from previous research in order to serve as a backdrop for the thesis' argument.

The fourth chapter, *Empirical findings*, presents a description of and the data obtained from the explorative case study, in order to set the ground for the following discussion. The description of each set of data is presented in the respective number of subchapters.

The fifth chapter, *Discussion*, deploys both the Theoretical framework and the Data analysis in a juxtaposition that will lead to in-depth interpretation and the subsequent drawing of conclusions.

The sixth chapter, *Conclusion*, summarises the answers to the thesis' research questions and highlights areas for future research.

2 METHODOLOGY AND RESEARCH DESIGN

The current thesis' topic was own developed and emerged after an extensive literature search and through active discussions with the academic supervisor. No alterations were requested from the department during the topics approval. For the preparation phase and to establish a better understanding of the philosophy of science, the book *Theory and reality* was used, by Peter Godfrey-Smith (2003).

For the overall structuring and organisation of the thesis' approach, several aids were deployed. The search for literature to support the main argument was overarching the thesis' timeframe and is analysed below. The theoretical framework was founded on several types of literature, such as journal articles, doctorate theses, books and professional press.

For the refinement of the thesis, the formulation of the methodology adopted and certain overall structuring adjustments, the handbook *The Good Paper* was used, by Lotte Rienecker and Stray Jørgensen, 1st edition, (2013), translation of *Den gode opgave*, 4th edition (2012). More specifically, the handbook provided useful guidance for the formulation of the research objectives, criteria for literature search and assessment, as well as the preparation for and the handling of the data. Moreover, the book *Academic Writing* by Lennart Björk and Christine Räisänen was used, 3rd edition (2011), for general orientation and writing process advice.

Purpose

The purpose of this thesis is to investigate what are the impacts of spatial constraints that can lead to construction site time-space conflicts, in regard to cost, time scheduling and productivity.

Moreover, drawing on an explorative case study (i.e. project), this thesis aspires to provide an understanding on how time-space planning is currently performed in the case of complex projects, and juxtapose the position from a contractor's point of view with that from the IT point of view.

Finally, by synthesising the empirical data with earlier research findings, the thesis aims to examine the foundation, which a framework should be based on, in order to enable the identification and methodological integration of time-space constraint management in the construction planning process.

Adopted methodological approach

In order to juxtapose previous research with and gain insights on current practice in major construction firms, inputs from working professionals are necessary. Nevertheless, due to the short timeframe of this thesis, it is not possible to gather the amount of data necessary in order to build a representative sample for the implications and management of time-space constraints. Moreover, practices can vary significantly among construction firms, management leadership and project teams. The purpose of the aforementioned juxtaposition is to gain valuable insights on how leading project teams see the state-of-the-art space-time optimisation techniques and their views on such techniques' demand and future applicability. Small amount of data might be inadequate to be comprehensive, but can be analysed thoroughly in order to demonstrate the complexity and context of the discussed phenomenon (Rienecker and Jørgensen, 2013).

Theoretical framework and literature search

Due to the nature of under researched topics, such as the one the present thesis focuses on, the literature search was performed deploying a combination of various search methods. The search was carried out from late December 2014 since early May 2015, with a few additions throughout the whole thesis' timeframe.

The primary phase was of exploratory nature and involved a systematic search of article databases, namely Chalmers' library portal (www.lib.chalmers.se), Google Scholar and Scopus, using the search terms *spatial conflicts construction*, *spatial construction layout*, *construction space management*, *construction space planning* and *confined construction sites*. This search resulted in articles dealing with either broader or bordering topics. More specifically, a large number of the search results were IT-focused papers, approaching the topic with various types of algorithms, such as genetic algorithms, ant colony optimization algorithms, etc. Another part of the results were construction-focused papers, some of which were built on case studies. A third group of papers were based on previous IT work and subsequently proposed simulation tools. Other results involved papers dealing with the identification of space-time conflicts, the deployment of Building Information Modelling (BIM) software to reveal potential conflicts, and applications of mathematical multiobjective solving.

In order to establish a narrower focus, references from the most relevant papers from the first phase were used. This method yielded a number of articles, most of which were published in the journals *Automation in Construction*, *Construction Engineering and Management* and *Construction Management and Economics*. The feature of recommended articles in *Science Direct* was extensively used, and many articles used in the thesis were derived as such.

A third round of searches was initiated with revised key words, after examining and thoroughly reading the most relevant of the previous results. The new round included both the introduction of the terms *scheduling* and *constraints*, as well as a parallel search for papers in order to present background information and support the argument in a broader sense. The latter aimed for papers examining the causes for low productivity in construction, success factors of construction projects and resource management in construction sites.

In the fourth round of search was performed including different combinations of the previous search terms with the term *congested sites*. This search resulted to one relevant article, and another two from the recommended relevant articles in *Science Direct*.

In parallel to the process described above, a search in conference proceedings was performed. Specific conference proceedings were first discovered through the chain search (second phase, as described above), which were then developed into a systematic search in the aforementioned journals and portals.

Due to the relatively little existing research with a construction focus and the narrow scope of this topic, the criteria for inclusion had to be limited to material relevance and place of publication. Articles from highly respected journals or conferences have been prioritised when possible.

Limitations

Due to the thesis' topic and its absence from the most common current practices, the main argument is founded on the chosen literature that constitutes its theoretical framework. Nevertheless, a connection to praxis is seen as useful, in order to establish reference points, expose the chosen theories to working professionals, examine their responses and ultimately juxtapose them with the theories and with other sectors. Given the thesis' timeframe, the collection of qualitative data is adjunctive, and is not in any way considered a representative sample.

During the planning of this thesis, there was the idea of exploring if a spatial planning IT-based model would fit in a case of a large and complex project. More precisely, if the chosen company’s working routines would permit, or hinder such an implementation. However, due to the company’s practices in the chosen case study, which will be described and discussed in Chapters 4 and 5 respectively, the thesis course of action was changed, in order to benefit from the current practice in this case.

Empirical data

The empirical data collected from the aforementioned various sources, are presented in Chapter 4, *Empirical findings*. However, the qualitative data presented comprise only a part of the interviews, and parts that do not relate to or are not used in the subsequent Discussion chapter, are omitted.

Case study: Tingstad trafikplats, NCC Construction

The chosen project of reference is the Tingstad Interchange (case study), a subproject of the Marieholm Connection project. The Marieholm Connection project is an ongoing, large-scale traffic link under the Göta Älv river in Gothenburg. The project is assigned to multiple contractors, namely three of the largest ones in the area. The Tingstad interchange, a part of the project, will also be a part of the E6 expressway, connecting Gothenburg and Oslo. NCC has been assigned with the construction of roads and bridges for the project, in coordination with Trafikverket, scheduled for completion in June 2020. The area bears a heavy traffic of about 80,000 vehicles daily. The order is worth SEK 633 million and will be implemented as a turnkey contract, employing up to 50 individuals. Work will commence in January 2015 and is scheduled for completion on June 30, 2020.

The project was chosen on the basis of its relevance, close proximity, time of commence, and size. Projects of this size where construction takes place in already used areas are likely to exhibit high complexity. Furthermore, the fact that the physical area is, and will continue to be extensively used, makes the case suitable to study time-space constraints.

The starting point for the gathering of the data was a site visit to the construction site, in February 2015. Due to the early stage, the working area was not fully developed, and the visit covered areas from the other subprojects’ sites. Subsequently, a meeting with the entire project team was arranged, in order to observe and enable interaction among the members, as while clarifying their roles and responsibilities. After discussing several different settings with the production manager of the project, a group interview with the entire project team (from now on referred to as “the group”) was arranged. The choice of a group interview lies upon its ability to provide information (i.e. data) based on the synergistic effect of the group (Green, 2003). Given the relatively under-researched nature of the thesis’ topic, it was regarded useful to consider different experiences, points of view, and anecdotal information. Experiential information is considered in research as the major advantage of groups (Carey and Smith, 1994). In addition, communication among the project team members can explore the major issues of importance, and members have the opportunity elaborate or argue on their answers (Kitzinger, 1995). Furthermore, there is a possibility for the group members to theorise about their potentially different points of view (Kitzinger, 1994). An additional advantage of group interviews is that, in contrast to individual interviews, different points of view can generate discussions among the members, whereas such a confrontation could prove alienating during an individual interview (Kidd and Parshall, 2000). Notwithstanding the productive discourse, group interviews entail significant challenges; given that members presume a common frame of reference, it is likely that they will modify their statements, in order to bridge potential inconsistencies (Kidd and Parshall, 2000). Moreover, there is a controversy in literature on the effects of group conformity and censoring (Carey and Smith, 1994). For the interview, several questions and topics were prepared in advance, which the interviewer had to oversee that they will be covered throughout the discussion. The focus group members were not presented to the thesis’ purpose in advance, in order to avoid biases. Rather, they were informed that the discussion will revolve around the general topic of construction site management. For the last part of the interview, the focus group was briefly informed about the thesis' topic and certain recent research developments on the topic of time-space constraint management on construction sites. The case study data collection closed with a second site visit, on June 15th, 2015, where final observations were recorded.

In order to have a clear understanding on the terms that appear throughout this thesis, there is a need to establish alignments between the local (i.e. swedish and/or danish) terms and the international, or widely known ones. Therefore, the term *APD plan*, or *arbetsmiljöplan*, is the swedish term for what is otherwise known in the literature as *plan of work* (*POW*), or *site plan*. More specifically, the APD plan is a work plan for a project, produced before the establishment of the construction site and used throughout the project. *The APD plan describes the organisation of the work environment, and regulates the health and safety measures. The contractor is obliged, except in the case of minor works, to provide prior notification to the Swedish Work Environment Agency (*Arbetsmiljöverket*) before the commence of works (to the region where the construction site is located), as in §7 of the Provision AFS 1999:3 Building and construction work. The contractor shall ensure that a copy of the notice posted at the construction site and kept up to date* (av.se, 2015).

Consultancy firm: Prolog bygglogistik AB

In order to juxtapose the collected data from the contractor's point of view with that of consultants' point of view, the swedish logistics consultant firm Prolog bygglogistik AB was approached. Prolog is a construction logistics consultancy firm that operates into three main business areas (*tjänster*), change management (*förändringsledning*), competence development (*kompetensutveckling*), and project management (*projektledning*).

In addition to the firm's focus, it was chosen on the basis of recent experience, since it has undertaken the implementation of a Building Logistics Centre (BLC) in Stockholm's Royal Seaport, to serve as the cornerstone of effective operations of many construction sites in parallel. The Royal Seaport is one of the city's environmental urban districts, aiming to set an example of sustainable development in urban areas (Logistics Centre Stockholm Royal Seaport: For sustainable and resource efficient construction, 2015).

Information on Prolog's current practice, philosophy and the aforementioned project, was obtained through an meeting with the project manager and Head of the Gothenburg office, in June 2015. The interview was performed as an open discussion, with several specific questions prepared from the interviewer in advance, to ensure that the themes of interest will be covered. The interview started with a brief description of the topic from the interviewer (omitted from the transcription). The interviewee then gave a description of the company's business areas, employees, strategic goals, and roles and responsibilities, both on organisational and on individual level. During the last part of the interview, the interviewee was asked to give some examples of projects that the company has undertaken.

Software developer firm: RIB Software AG

Deriving from the thesis research questions, the research design includes inputs from a software developer; in particular, one devoted to the construction industry. The choice of a software developer seeks to satisfy two functions: *i)* to enhance the empirical data with a third point of view regarding the management of time-space constraints, complementary to the ones from contractors and consultants, and *ii)* to examine a state-of-the-art product and its in praxis implementation, in order to juxtapose it to the case study. This comparison aspires to provide valuable insights regarding the methodological integration of state-of-the-art tools, as described in RQ3.

RIB Software is a multinational firm providing construction and building information modelling (BIM) software. Among the firm's products is iTWO, a 5D end-to-end solution with six functions: *BIM design*, *Estimating*, *Schedule*, *Procurement*, *Project Management*, and *Controlling*. By reconfiguring the IT landscape in construction planning, iTWO attempts to address and overcome several traditional problems in construction, such as cost and time overruns, low margins, high risks, and change orders, among others (rib-software.com, 2015).

In accordance with the firm's organisational structure and working routines that incorporate a *change management based* training cycle in iTWO 5D Lab, the research design is divided in two parts at this stage. The first part includes a webinar offered by RIB, in order to describe and analyse the firm's products and services, strategic goals, and basic operations. The second part includes a Lab visit in the firm's offices in Copenhagen, as well as a semi-structured interview and open discussion with RIB's Business Development Manager for iTWO Sales.

3 THEORETICAL FRAMEWORK

During the last decades, research in construction has generated quite a few groups of studies that examine productivity issues, each from a different point of view: labour productivity, resource productivity, planning and scheduling efficiency, and several kinds of optimisations, ranging from site layout to crane operations. Although the issue of low productivity in construction is usually brought up from a comparison to manufacturing, the two industries are characterised by fundamentally different operations and degrees of uncertainty. For instance, manufacturing operations are unaffected by adverse or unpredictable weather, archaeological findings, human motivation, and so on. Construction production operations might be far from being fully optimised, nevertheless several attempts for improvements based on previously successful practices in manufacturing have often been fruitful for construction.

In order to examine the roots of low productivity, and its influence in space management in construction sites, there is a need to look in neighbouring research fields too. More specifically, it might be prolific to look for spatial constraints as a *consequence* of other activities, such as delays or inefficient planning and scheduling. At this point, it is very important to highlight that spatial constraints are not always lack of sufficient space in the construction site, but it can be lack of availability of certain spaces at a certain time, for instance due to uncoordinated activities (i.e. spatial conflicts), lack of detailed planning or disregard of certain spatial needs (e.g. physical space of workers). Therefore, consequences of insufficient planning and scheduling can be *expressed* as spatial constraints or conflicts. In other words, there are cases where the aftermath of phenomena such as delays, can only be seen later, in the form of spatial or additional temporal conflicts.

The need for productivity improvement in construction

The issue of low productivity in the construction industry has been widely discussed in research. When construction is put side by side with other industries, and the common practice is to compare to manufacturing, it is obvious that construction is suffering. Although these comparisons might not be well-founded in a sense that they disregard the fundamentally different nature of construction operations when compared to manufacturing, they can provide useful insights in the quest of continuous improvement.

Labour productivity in construction is many times seen as a representative indication for production efficiency and subsequently, higher profitability (Rojas and Aramvareekul, 2003). More often than not, low productivity of labour and/or planning and scheduling is manifested in time and cost overruns. Assaf and Al-Hejji (2006) conducted a survey to evaluate the different factors that result to delays in large construction projects in Saudi Arabia. The research presents a detailed list of causes, both regarding their frequency of occurrence, their importance and severity, ranked by three groups of professionals, owners, contractors and consultants. Among the identified factors there is a significant number of productivity-related issues, such as *low productivity of labours* or *slowness in the decision-making process by owners* for all groups of professionals. Rojas and Aramvareekul (2003) conducted a survey during which a sample of sixty-four working professionals from various areas in construction (e.g. general and sub-contractors, owners, consultants) ranked major labour productivity drivers, among those that have been actively researched. The responses were grouped under four categories, including *management systems and strategies*, *manpower*, *industry environment*, and *external conditions*. Every category was further analysed into its own drivers, which were ranked according to their relative relevance to labour productivity. Illustrated in Figure 3.1 below is the first category, management systems and strategies, where *management skills* and *scheduling* receive top rankings (i.e. 100% normalised relevance) due to their influence on resource allocation. Furthermore, management skills are often associated with certain human related factors quoted in the same research as important drivers for the performance of workers, such as *motivation* and *seniority*.

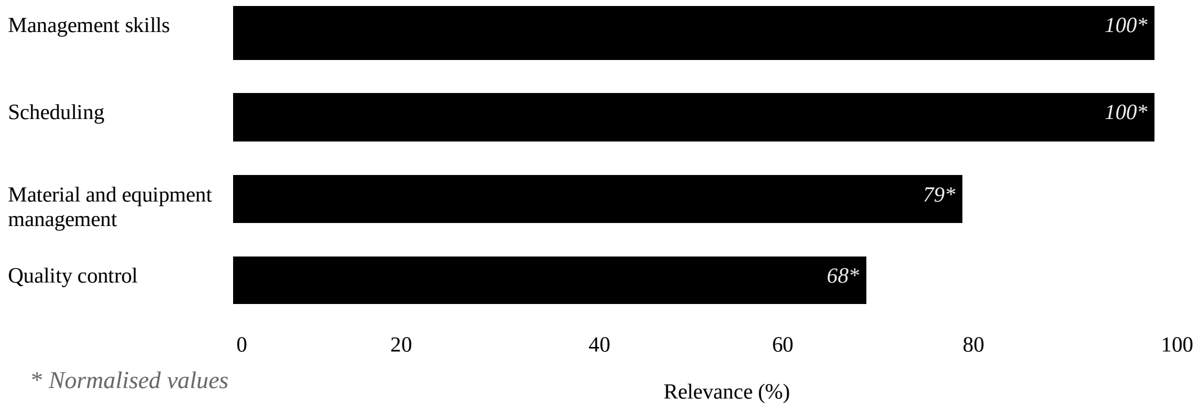

Figure 3.1: Management systems and strategies (Rojas and Aramvareekul, 2003)

Another factor that enhances construction complexity and contributes to the decline of labour productivity is that of *uniqueness*, ranked second in the group *Industry environment* by the respondents in the same survey. The issue of project uniqueness in regard to its design, materials, location, production time and a variety of additional factors has been extensively addressed in research. Consequently, the design and subsequent optimisation of the construction sites' layouts and processes can be extremely challenging when based on previous data.

The category labelled *activity interactions* in Figure 3.2 refers to the activities that constitute the production process and their interdependencies. According to the survey respondents, activity interactions have an influential role in construction labour productivity, while the survey conductors argue that these reflect the constrained optimisation problem of construction processes. Activity interactions can be particularly complex, since they are dependent on resource availability, which in turn relies on resource supply rate (Howell, Laufer and Ballard, 1993). Supply rates on the other hand, are extremely difficult to specify in advance (Koskela, 1992).

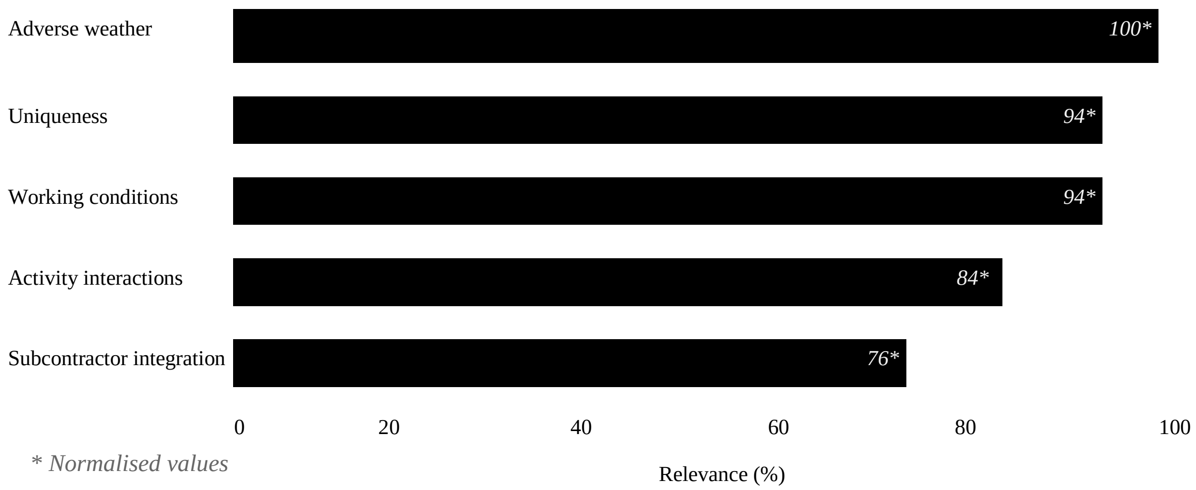

Figure 3.2: Industry environment (Rojas and Aramvareekul, 2003)

The above findings are in agreement with earlier ones, such as in Chan and Kumaraswamy's (1997) study of causes of delays in construction projects in Hong Kong, where the top factor causing delays in building and civil engineering projects (as ranked from the respondents) was *poor site management and supervision* (Table 3.1 and 3.2 respectively).

Table 3.1: Relative importance indices of the five most significant factors causing delays in building works (Chan and Kumaraswamy, 1997)

Hypothesised factors	Clients	Consultants	Contractors	Weighted average
Poor site management and supervision	0.763	0.858	0.822	0.813
Unforeseen ground conditions	0.763	0.842	0.756	0.785
Low speed decision making involving all project teams	0.733	0.808	0.800	0.779
Client-initiated variations	0.741	0.808	0.763	0.769
Necessary variations of works	0.756	0.783	0.778	0.772

Table 3.2: Relative importance indices of the five most significant factors causing delays in civil engineering works (Chan and Kumaraswamy, 1997)

Hypothesised factors	Clients	Consultants	Contractors	Weighted average
Poor site management and supervision	0.878	0.792	0.710	0.796
Unforeseen ground conditions	0.826	0.816	0.800	0.814
Low speed decision making involving all project teams	0.755	0.783	0.743	0.761
Client-initiated variations	0.757	0.768	0.743	0.757
Necessary variations of works	–	0.776	0.733	0.756

Poor site management and supervision was ranked as top significance factor in construction project delays by all working groups (i.e. clients, consultants and contractors). Evidence included in the same research suggests that poor site management and supervision can be traced back in the contractors' inadequate site planning and organisation.

In addition, *low speed decision making involving all project teams*, the third most significant factor, reflects the efficient handling of information across the project organisation, which in turn can influence the resource management of a project (Chan and Kumaraswamy, 1997). The same view is also shared by Assaf and Al-Hejji (2006), who present their research findings on the frequency and importance of delay causes in large construction projects. In particular, *slowness in decision making process by owner* is ranked as one of the top causes from contractors.

Areas lagging behind in productivity in construction. Planning and monitoring as problematic areas

If the competence of a contractor lies in their ability to organise and monitor the construction site processes and resource use and allocation, it naturally puts them in a central role for productivity improvement through effective planning and monitoring.

From the study of causes of delay in large construction projects by Assaf and Al-Hejji (2006), it is apparent that, at least according to owners and consultants, planning and scheduling by contractors are problematic. Presented in Table 3.3 below, are the top identified factors as ranked by each group of professionals, according to their importance.

Table 3.3: Importance of delay causes in large construction projects in Saudi Arabia (Assaf and Al-Hejji, 2006)

S. no.	Owners	Contractors	Consultants
1	Shortage of labors	Delay in progress payments by owner	Type of project bidding and award
2	Unqualified work force	Late in reviewing and approving design documents by owner	Shortage of labors
3	Ineffective planning and scheduling of project by contractor	Change of orders by owner during construction	Delay in progress payments by owner
4	Low productivity level of labors	Delays in producing design documents	Ineffective planning and scheduling of project by contractor
5	Hot weather effect on construction activities	Late in reviewing and approving design documents by consultant	Change of orders by owner during construction
6	Conflicts encountered with sub-contractors' schedule in project execution	Difficulties in financing project by contractor	Low productivity level of labors
7	Poor site management and supervision by contractor	Mistakes and discrepancies in design documents	Difficulties in financing project by contractor
8	Inadequate contractor's experience	Late procurement of materials	Poor site management and supervision by contractor
9	Effects of subsurface conditions (soil, existing of utilities, high water table, etc)	Inflexibility (rigidity) of consultant	Poor qualification of the contractor's technical staff
10	Change of orders by owner during construction	Slowness in decision making process by owner	Delay in material delivery

According to the above findings, *ineffective planning and scheduling of project by the contractor* and *poor site management and supervision by the contractor* constitute two of the most severe factors for delays, as assessed by owners and consultants, a view shared by Chan and Kumaraswamy (1997), seen in Tables 3.1 and 3.2 above.

Reviewing the literature, the scope of delays and the spatial conflicts as consequences show an interesting correlation between the two. In particular, Guo (2002) argues that there is a correlation between congested worksites and productivity decrease and delays. In an episode recorded by Sundman (2015), a project manager responsible for seven similar projects evaluated the one with the shortest completion time as the one with the lowest performance, due to the spatial conflicts that took place on-site. However, given the challenging task of detecting causalities in such a complex environment as construction operations, a clear causal relationship up to this point is ambiguous.

By examining more than 200 projects, Gibson et al. (2006), concluded in a direct relationship between detailed pre-construction project planning and project performance. Moreover, sources of spatial conflicts and deviations from time schedules can be sought for in the early design phase. As Waly and Thabet (2002) describe, planning during the preconstruction stage is done at *macroplanning* level, which involves the design of broader strategies rather than detailed planning, as a direct consequence of the amount of available information at that time; nevertheless, the macroplanning phase yields in critical decisions, on which the successful delivery of the project depends. The effective consideration of all the data that must be included in order to avoid deviations from the detailed planning can be particularly challenging, due to the large amount of information.

Furthermore, complexity increases due to the dynamic nature of the construction process. Both space availability and available information change throughout the process, both for space that can be allocated for particular activities and space that might no longer be available as it becomes part of the building structure (Winch and North, 2006). For instance, there is space allocated for temporary works (e.g. scaffolding, mortar preparation, equipment assembly), site installations, access points, material stock, etc. A part of the available space will eventually turn into fixed elements.

Execution planning of construction processes is in many cases nowadays still performed by experience and in a reactive manner against the dynamics of construction sites (Beißert, König and Bargstädt, 2007; Winch and North, 2006; Riley and Sanvido, 1997;), without any detailed planning as a result of prior optimisation.

Resource use as a problematic area in planning & monitoring

All construction projects need enough available space to place temporary facilities such as material storage, offices and equipment, in order to carry out the work as planned.

Space and time as resources

Planning the work sequences and designing the suitable construction site layout is a challenging task, as it involves a plethora of factors that need to be considered, while characteristics of many of which change over time. Such characteristics (or *attributes*) can be the physical position, the volume and the occupied space, among others. Space planning combines the inputs of other factors as well, such as workers, material, equipment, temporary and fixed facilities), calling for consideration of space as a resource, in order to handle the increased complexity (Guo, 2002).

As early as 1994, lee and Gatton (1994), among other researchers, investigated the reasons that cause low productivity in construction. In fact, the authors classified the reasons from other researchers' findings based on their impact. The causes are grouped under three major areas, namely *job inefficiencies*, *low crew morale* and *other external causes*. According to Lee and Gatton (1994), a major cause for productivity decline in construction, is the unrealistic scheduling methods, due to their assumption of unlimited resource availability. As illustrated in Table 1 below, based on three surveys, A, B and C (Garner, D., 1979; Rogge, D., 1981; Kim, Y. S., 1993), resource unavailability of various resources has been ranked in the highest impact positions.

Table 3.4: Summary of sources of job inefficiencies by decreasing importance (Lee and Gatton, 1994)

A	B	C
Material unavailability	Equipment unavailability	Unreasonable schedule
Overcrowded work area	Crew interference	Resource unavailability
Tools unavailability	Material unavailability	Engineering problems
Crew interference	Crew moving	Poorly skilled workforce
Inspection delays	Instruction delays	Inadequate materials
Instruction delays	Tools unavailability	
	Overcrowded work area	

Resource unavailability
Spatial conflicts
Other causes

As seen in Figure 3.1, working professionals highlight the impact of management skills on construction labour productivity. This is not in conflict with Table 3.3 above, as the high ranking of management skills according to the authors of Figure 3.1, is attributed to managers' power to handle resources and schedules (Rojas and Aramvareekul, 2003).

Conflicts and constraints

Even though managerial skills are important for labour productivity, even experienced managers might be unable to identify all the constraints and conflicts in a given situation (Guo, 2002). Furthermore, as mentioned in the first part of this chapter, spatial conflicts can appear 'disguised' as a consequence of other uncoordinated activities. Likewise, the potential for improvements or de-congestion, is often hidden in other operations. For instance, exterior spaces during construction are often allocated to temporary facilities and equipment, whereas interior spaces are not used for material storage, due to the complexity of such modelling of the interior spaces, critically affecting the material logistics on-site. Said and El-Rayes (2013) present a model for congested construction logistics planning (C2LP) for optimal utilisation of interior building spaces under construction. By optimising the use of space and in coordination with time schedules, this model can minimise both total logistics cost and the scheduling implications of interior material storage. The optimisation is essentially seen as a tradeoff between minimised logistics costs and schedule criticality.

Building on previous literature, Sripasert and Dawood (2002) classify constraints in three major categories, each of which is further subdivided, illustrated in Table 2 below.

Table 3.4: Constraint categorisation (Sripasert and Dawood, 2002)

Physical constraints	Contract constraints	Enabler constraints	
– Technological dependencies – Space – Safety – Environment	– Time – Cost – Quality – Special agreement	– Resources • Requirement • Availability • Capacity • Perfection • Continuity	– Information • Requirement • Availability • Perfection

Each subcategory further contains various constraints. Technological dependencies include both topological characteristics (e.g. buildings locations, adjacency, etc.) and construction methods (e.g. equipment deployed, temporary facilities, etc.). Contract constraints include all the characteristics that derive from the contractual agreement that governs the works, such as project start and finish dates, budget, specifications, etc. Enabler constraints include characteristics of resources and their use (e.g. types and amount of resources required for each task), their availability and capacity, as well as workmanship characteristics and requirements.

Attributions of criticality

Criticality is more often than not attributed to factors of temporal, rather ones of spatial dimension. However, space criticality is required, if we aim to analyse and manage the spatial dimension of operations, especially when spatial congestion so often leads to lower productivity and safety hazards (Tawfik and Fernando, 2001; Winch and North, 2006). Moreover, spatial constraints don't only affect productivity, but also the critical path, resulting to schedule interference (Guo, 2002). Even though criticality is a useful attribution for the time-space conflict resolution, it should not blind us to the fact that there is a need for multi-factor evaluation. Depending on the adopted technique to identify constraints to form the subsequent scheduling, the identification might prove inadequate, with a variety of reasons behind such unsuccessful scheduling. Techniques that use *Critical Path Method* (CPM) inputs, are likely to omit critical constraints that don't have precedence, as illustrated by Sripasert and Dawood (2002). Therefore, there is a need to include a variety of otherwise disregarded constraints, such as the ones illustrated in Table 3.4 above. In fact, the consequence of this omittance is illustrated in the article's review of 23 key research projects in planning and control system, where all projects concerned technological dependencies, most concerned resource requirement and cost constraints and many concerned space constraints.

The most severe weakness of existing CPM variants is perhaps its inability to tackle the *resource critical* activities problem: activities that are not critical (i.e. having positive float) can critically affect the project duration due to their ability to restrict resources, which are in turn necessary to critical activities (Lu and Li, 2003). Therefore, there is a need of resource critical attributes in activity scheduling and heuristic levelling procedures (Fondahl, 1991). Additional weaknesses of CPM include the difficulty to evaluate and communicate interdependencies and the inadequate support at operational level (Sripasert and Dawood, 2002). Lu and Li (2003) propose a variation of the CPM-based resource scheduling to synthesise resource requirements and criticality in the sense of interdependency. The proposed *resource-activity critical-parth method* (RACPM) variation integrates resource criticality as an input, respectively adjusting the start and finish times of activities and floats. The method adopts a heuristics technique to establish the criteria for more effective working schedule. The basic attribution of activities is the *work content* (number of resources required times the activity duration), the larger the size of which gives a higher priority to activities. The representation of this method is illustrated in Figure 3.3 below.

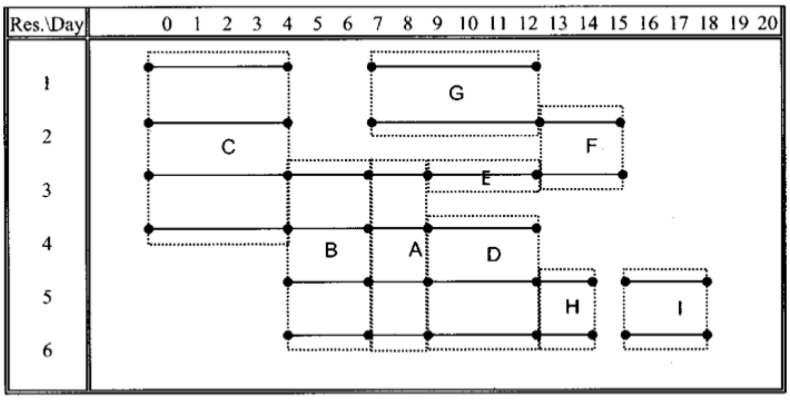

Figure 3.3: Resource-activity critical-path method schedule highligting resources, time, and activity (Lu and Li, 2003)

As seen in Figure 3.3, activities are represented by rectangles, in which resources (i.e. vertical axis) have a start and finish times. The method involves a resource-activity interaction working table, Table 3.5 illustrated below, with the attributes for each resource used in the project. In the table, there are three columns that hold attributes for the current status of resource-activity interaction for a given activity, columns (a), (b), and (c). Column (a) holds the *ready-to-serve* (RST) time of a resource, column (b) shows the *participation* of a resource (flagged '1' for involved resources, blank for non-involved), while column (c) contains the *idle time* (IDT) of a resource (Lu and Li, 2003).

Table 3.5: Resource-activity interaction working table (Lu and Li, 2003)

Cur.Act.			C			B			G			A			D			F			E			I			H			
Pre. Act.			0			0			5			0			10			8			10			17			14			
EFT									8															14						
(1)	(2)	(3)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(4)
1	L	0	0	1	0	5			5	1	3	14			14			14						14			14			14
2	L	0	0	1	0	5			5	1	3	14			14			14	1	0				17			17			17
3	L	0	0	1	0	5	1	0	8			8	1	0	10			10	1	0	10	1	0	17			17			17
4	L	0	0	1	0	5	1	0	8			8	1	0	10	1	0	14						14			14			14
5	L	0	0			0	1	5	8			8	1	0	10	1	0	14						14	1	1	14	1	0	20
6	L	0	0			0	1	5	8			8	1	0	10	1	0	14						14	1	1	14	1	0	20
EST			0			5			8			8			10			14			10			17			14			

The earliest and latest starting (EST/LST) and finishing times (EFT/LFT) and floats (FF/TF) are then calculated as follows: the EST is determined traditionally by the EFT of precedent activities. Then, the IDTs are calculated, i.e. IDT=EST–RST, later used to calculate the EFTs. The EFT is also the new RST for the resources of the given activity. A backwards pass is then performed, to determine the finishing times and the floats, thus seamlessly transforming the activity-on-node method, to incorporate resource criticality and updated floats calculation.

Given the fact that the project plan will lead to the design and execution of the work sequence, it is important to examine the common assumptions that govern this decision making process. In particular, the adoption of a certain scheduling strategy, such as resource allocation or resource levelling, presupposes that certain variables can be determined; subsequently, the means to fulfil the set objectives will be decided upon the variables' approximation. For instance, the adoption of a time-cost tradeoff presupposes the precise cost estimation (which may be a project requirement and therefore known in advance in cases of design-build contracts, but more complex in design-bid-build contracts) and the precise estimation for each activity duration, which is unrealistic to estimate far in advance (Liao et al., 2011). Therefore, in order for the project planning to be aligned with the scheduling of the activities, it is imperative to obtain adequate information.

Dynamic vs. static, the need for a two-dimensional approach

In stark juxtaposition to manufacturing, construction operations are characterised as more dynamic, involving complex factors that reflect the variability of work execution and consequently, duration and performance (Forbes and Ahmed, 2011). Resource availability is critical to prevent productivity losses and to ensure effective execution of construction activities; in contrast to early planning methods that assumed constant resource availability, researchers point to the need to consider the temporal changes in it (Lee and Gatton, 1994). The criticality of space availability becomes even more distinct in combination with tight schedules and short slack times. In fact, activities that occupy a certain space past the designated time period imperil the planning, and bring about interferences and delays for the activities that the specific space is allocated to next. According to the definition quoted in the first chapter (Akinci et al., 2002), conflicts occur for a limited amount of time. The temporal aspect of spatial constraints is emphasised by several researchers, as an essential feature in order to handle them, and the need to approach this as a two-dimensional problem (Zouein and Tommelein, 1993; Akinci et al., 2002, Zhang et al., 2007; Marx et al., 2010), instead of treating spatial availability as a separate static resource constraint. More specifically, Guo (2002) points out that many of the earlier researchers disregarded or oversimplified the impact of time on space availability.

But the dynamic nature of space availability extends past the temporary facilities-building space diptych, expressed in a temporal dimension. Continuity and linearity of operations should not be assumed during the diptych phases themselves: the spaces themselves change, not only from available to built, but also from available to occupied by various working trades. Winch and North (2006) present two derivatives of construction space planning, that divide the problem in two areas of research: the *space scheduling problem* and the *site layout problem*, focusing on the planning of activity spaces and the location of temporary facilities respectively.

Spatial arrangements and representation

According to several researchers who address the problem of ineffective planning and control (Sripasert and Dawood, 2002; McKinney and Fischer, 1998; Retik and Shapira, 1999;), the future for identification, incorporation and management of constraints is suggested to deploy current 4D and Virtual Reality (VR) software as visualisation techniques, as well as the inclusion of constraints in scheduling techniques. After scheduling adjustments and criticality attribution features are put in place, there must be a concrete foundation on which to base the spatial arrangements on-site. In other words, while contract and enabler constraints are identified (although not necessarily represented in scheduling or in a visual way), physical constraints are not fully derived, neither from the project requirements, nor during the design phase. Of course, certain physical constraints are already known, such as construction methods or external topological characteristics. Nevertheless, internal topological constraints (i.e. regarding the construction site topology) might not be known in detail, since their constraining ability depends on a multitude of factors, including among others locations for temporary facilities, resource use, workforce, and access points.

This issue is often addressed in IT research, but seldom applied in real-life situations. Saleh Farham, Süral and Iyigun (2014), solved the Weber problem for congested regions with entry and exit points, a suitable match to constructions sites. The Weber problem in location theory, as defined by the Online Encyclopedia of Mathematics (2014) is a problem that requires finding for the optimum location of a facility in the plane intended to serve several users. The location should be one from which the total weighted distance to *n* destination points is minimised. When restricted areas in the plane are involved, the variation is called *restricted location problem* (*RLocP*). Saleh Farham, Süral and Iyigun (2014) consider the single facility (*RLocP*) in congested regions with entry and exit points (*RLocP-CR-EE*), representing congested regions as *arbitrary shaped polygonal* areas on the plane. Transportation though the regions is limited to certain paths with entry and exit points and each movement has its respective fixed cost. According to relevant literature, there are three types of restrictions (Saleh Farham, Süral and Iyigun, 2014):

- *Barrier* regions, where passing is not allowed or possible;
- *Congested* regions, where passing is possible, but with an additional cost;
- *Forbidden* regions, where passing is possible but the facility location is forbidden.

Although the three types above didn't originally refer to construction sites, we can draw some parallels without bending the problem solving. Barrier regions in construction sites include excavated areas, foundations, wet cement, material storage areas etc. Forbidden regions represent areas that must be kept free for the moving of the various work trades and passing of vehicles, or areas that are assigned to other facilities in the future. Parallelising congested regions might be more complex. Even though congested regions exist in construction sites and passing is in fact possible, the additional cost of passing is not always a direct consequence. Moreover, there are cases where there is not an alternative. In such cases the costs are not considered *additional*, but are accepted at face validity. The expression of the additional costs also varies; for instance, hazards and accidents are additional costs, but they are not often expressed as such.

This solution could be translated to a spatial optimisation and applied to construction site planning, with the inclusion of different parameters for each case. However, there are numerous implications in such an implementation, some of them deriving from the assumptions of the classical Weber problem itself, and others concerning the RLocP-CR-EE variant.

In the classical Weber problem, a two-dimensional space is considered, which of course is not the case for construction sites. In simple layout cases, where 2D analysis is appropriate, the Weber problem still does not succeed to provide a reliable representation, as it assumes homogenous production: labour supply, inelastic demand, single product, among other factors (Tellier, 1972).

Both in the classical Weber problem and the RLocP-CR-EE variant, it is assumed that moving between two points in the plane is possible unless for restrictions described above. However, this assumption would ignore the temporal dimension in construction operations.

Perhaps the most important weakness of the Weber problem approach, for both variants, is that they are defined in a static spatial plane, therefore disregarding the dynamic nature of construction operations. However, this is not necessarily a limiting factor, as the solving can be modelled in respect to the construction operations dynamics. In praxis, this kind of detailed and single site-specific modelling becomes computationally expensive and is usually counterbalanced by the additional costs imposed when spatial arrangements planning is not incorporated. Moreover, there is the problem of unavailability of information at a given point (e.g. design phase) to build such a detailed model. The middle ground in this problem is to divide the project in a number of phases, in order to have a limited number of less expensive static models.

An interesting correlation can be drawn from Tellier's (1972) early industrial complex approach. Tellier (1972), drawing on Weber's traditional problem explains how for a polygon with more than three sides, the combinations of forces that will result to equilibrium are innumerable. He continues to suggest that our analysis with this framework should be restricted to a limited number of inputs-outputs combinations. The author also argues that it is far an easier task to define the forces for the optimisation of a given location than to define an optimal location for a set of given forces. This can be particularly useful in the case of multiple solutions in the decision making process during the construction site planning. Even though heavy maneuvering is not common for most construction processes, with alternating the movements or the locations of material storage areas, locations of temporary facilities, or entry and exit points can be easier optimised.

However, minimum travelling distances only optimise the transport costs (Guo, 2002). Said and El-Rayes' (2013) C2LP model for logistics plans optimisation considers four types of decision variables to model space allocation: i) material procurement; ii) material storage plan; iii) temporary facilities layout; and iv) scheduling of non-critical activities. According to the *Just-In-Time* (JIT) principle this model adopts, material procurement include specific ordering time periods in order to establish delivery in regular intervals and consequently satisfy the demand on-site. This will allow to overcome the assumption of homogenous production in the Weber problem, as the delivery plan is designed according to the production demand variables or representing a *Just-In-Case* (JIC) procurement plan (Said and El-Rayes, 2013).

4 EMPIRICAL FINDINGS

4.1 CASE STUDY: TINGSTAD TRAFIKPLATS, NCC CONSTRUCTION

As mentioned in the second Chapter, this thesis uses a case as a reference point to juxtapose with the theoretical framework. Information about the case is obtained from three sources, the company's official press releases and reports, a group interview with the project team, and observations from two site visits, the first in February 2015 and the second in June 2015. In addition, information regarding the construction site planning and insights on the challenges entailed from an early stage perspective, were vocalised during the visits' guidance by working professionals from both the side of the contractor and the client. Nevertheless, the term *case study* might not properly reflect the role of the case in the thesis, due to the limited insights that this setting permits, compared to the more in-depth inputs of extensive case studies.

The selected case is the *Tingstad trafikplats* (tr.: interchange), a large construction project undertaken by NCC (from now on referred to as "the contractor") in Gothenburg. The Tingstad Interchange is a part of a larger project in the area, the Marieholm Connection, an ongoing, large scale traffic link under the Göta Älv river in Gothenburg. The other three subprojects are undertaken by other contractors. The Tingstad Interchange will be a part of the E6 expressway, a connection between Gothenburg and Oslo. NCC has won the tendering for the construction of the roads and bridges for the project, in coordination with the Swedish Transport Administration, Trafikverket. The order is worth SEK 633 million and will be implemented as a turnkey contract, employing up to 50 individuals. Work will commence in January 2015 and is scheduled for completion on June 30, 2020.

The expressway E6 passes right through the construction area. According to the contractor, there is a great challenge in undertaking a project in such a heavily trafficked area, of approximately 80,000 vehicles per day. The contractor, after prescribed instructions from Trafikverket, is going to redirect the traffic in order to initiate the operations. The redirection of the traffic flow will change for each of the four phases the project is divided in, however only the first is prescribed by Trafikverket; it is the contractor's responsibility to plan and execute the rest. During the first phase of redirection, the flow will be redirected east, and it will have a maximum duration of 24 months.

In addition to the above, the contractor emphasises their environmental concerns for the construction phase. More specifically, in a press release, the Executive Vice President and Head of the Civil Engineering segment states that [they] "are placing major emphasis on noise suppression and our objective is to minimize disruptions for surrounding residents". The construction area is not densely populated, although the roads that lead there pass through the nearby neighbourhoods, wherefore noise and disruptions are more likely.

Site observations, February 2015

Due to the early stage of this site visit, the construction site was fairly new and with few operations going on. Furthermore, the site visit covered an area that contains both the Tingstad Interchange and the Södra Marieholmsbron (South Marieholm bridge), a subproject undertaken by Skanska and MT Højgaard A/S. The guidance was performed by a site manager of Skanska, supported by three managers from the client's side.

During the site visit, it was observed that the existing expressway and elevated interchanges pose significant challenges to the organisation of the construction site. More specifically, the limitations divide the oblong area into smaller parts, leaving relatively little space on the sides of the roads.

Site observations, June 2015

The second site visit took place on June 15th, wherefore the works have progressed significantly, without major problems or deviations from the schedule. Nevertheless, some incidents of spatial conflicts relating to temporary material storage were reported, causing minor delays in the daily schedule. The site manager argued that these delays were compensated easily with increased workforce.

Group interview

The project team currently consists of three professionals, as listed below.

Rikard Andersson (RA), Produktionschef (tr.: production manager)
Fredric Bohman (FB), Platschef för väg (tr.: site manager for road works)
Jan Linder (JL), Project manager

The interview follows the group interviews methodology, and several questions and topics were prepared in advance, which the interviewer had to oversee that they will be covered throughout the discussion. The focus group members were not presented to the thesis' purpose in advance, in order to avoid biases. Rather, they were informed that the discussion will revolve around the general topic of construction site management. For the last part of the interview, the focus group was briefly informed about the thesis' topic and certain recent research developments on the topic of time-space constraint management on construction sites.

The discussion opened with a brief description on the project team's planning of the layout of the construction site. There are some calculations on the available space being done since the tendering phase, and a general sense on the layout, as well as a check for water and electricity supply. In the tendering phase in this case, the plan was to put some of the temporary facilities (e.g. the temporary offices) in a different location, on the other side of the E6. However, a building in close proximity was available for rent, and the group has its temporary offices there. The group mentioned that in other cases, after the tendering phase, they normally check the possibility for obstructing houses, and possible locations for the temporary facilities. They emphasised the importance of deciding on the location of their temporary offices, and to be able to come on site as early as possible, in order to establish efficient communication channels. Specifically, RA states "*Maybe that's the most important thing to bring very early all the people together and then to arrange an office very early on so that you can put the organisation at the same location, so we can start working together*". The strategic positioning of the temporary facilities was also an important concern for the project team. The *strategic position* was perceived as central in relation to the working area, and with water electricity supply from an early stage. In addition, the relocation of the facility due to the changing nature of the construction site and the built area was brought up, as something that should be avoided, if possible, or at least minimised. The group also mentioned that often, including in this case, they have several temporary facilities (offices), in order for the workers to not have to go all the way back in the facility where they check in for each break, but have another facility in close proximity to the working area instead.

Regarding the construction phase, the group stated that the construction site planning is the contractor's responsibility, while only in rare circumstances the client is involved in this. When asked about a specific planning process, the group described the APD plan, which is also their starting point. The APD plan is used to decide on the temporary facilities' and material storage locations. At this point, the interviewer was presented the APD plan, and several locations were pointed out, namely the modular buildings, the entrance and exit points, the parking lots, and first aid material. The APD plan is updated as the works progress, although there are many cases where the update is delayed, resulting to a misalignment between the APD plan and the works.

When asked how the decisions on the organisation and planning of the construction site are taken, the group said that there are not any specific methods that they follow, rather than the contractor's experience and judgement. The factors taken into account they mentioned are *thinking strategically*, *shortening the distances* and *location of material storage areas*. At that point, the group brought up the case of "congested areas", in order to describe this case and give an example on the placement of modular buildings according to the length of the working site. The group mentioned the use of IT tools, such as Google SketchUp, but merely for visualisation and communication purposes. Other IT tools include Nova Point, which is used for the traffic redirection, and was said to be a planning tool.

The interviewer then asked what (other) factors the group takes into consideration, and gave an example of material delivery, in order to illustrate the manner in which the aforementioned "busy roads" can affect the decision making. The group mentioned the location of the cranes, but said that the traffic situation is the biggest challenge. They explained that (due to the location of the current traffic situation) it divides the working area in smaller parts. A group member proceeded to give an example where during material transportation across the site (from north to south), lorries have to take a lengthy detour to return to the starting point. He also said that there is no alternative to that. Another group member underlined that it would be dangerous and forbidden for the lorries to turn back without driving a long distance, because they would have to cross one of the (heavily trafficked) roads.

The redirection of the traffic flow, is performed in different stages, where the first, with a maximum duration of 24 months, is prescribed by Trafikverket. The group will have to plan for the traffic redirection for the remaining time of the project. When asked, they said that they don't plan a long time in advance, but a few months before the plan will have to be realised. When asked about what is taken into account when planning the traffic redirection, they mentioned that the working area is very narrow in their opinion and that the client poses many (traffic) rules that limit their choices, usually resulting in one or two alternatives. Examples of the traffic rules are a two-lanes per direction minimum, and a three-metre lane width minimum.

The interviewer exposed the group to some of the current research developments by briefly describing techniques for dynamic optimisation, spatial planning and scheduling, in order to see the members' viewpoints on that matter. The group was then asked to reflect on their way of planning if they used such tools. One member said that these tools are actually very helpful, although there is a need for a person to understand and use them accordingly. He then proceeded to say humorously that construction is an industry that lags 20 or 30 years behind when compared to other industries. Another member voiced his disagreement with the view that such tools are useful, but ultimately explained that his discontent rose from a case where the chosen software was not what he thought suitable and consequently caused disruptions in the working process, concluding that there must be a careful selection on the tools. The interviewer asked the group if they think that the necessary information would be available to them, as an early input to such advanced planning tools. The group was categorically opposed, highlighting the uncertainties driving the construction processes, bringing up the weather as an example.

When asked whose responsibility is the allocation of space and the frequency of conflicts, the group said that conflicts such as material blocking the way "happen all the time". The group noted that this is a common reason to move material in the construction site. In the case of subcontractors, it is the contractor's responsibility to decide the space allocation for subcontractors. They also said that such events occur because even though there is the APD plan, it is difficult to inform everyone about it. Moreover, in the case of material delivery, the lorry driver and/or the lifter operator are not informed about the APD plan, therefore unloading the material in the most convenient location for them, instead of the pre-decided location. In most cases, the APD plan contains information on material storage locations. Nevertheless, it is not always more detailed than specifying a broader area, such as having area divisions for each material. In this project, the material is stored on the other side of the expressway, where the group's office is located, and then transported to the working area when needed. The reason for not having it in closer proximity to the working area is the lack of available space, while the transportation to the site is the contractor's responsibility.

In the occurrence of unexpected time overruns, the group explained that significant delays have to be announced to the client. Delays were said to be compensated, when possible, by changing the course of action, and adding more resources (workforce and equipment). A member of the group emphasised the importance of "the big picture" of the schedule, although he pointed out that in an event of a delay, action should be taken immediately, instead of waiting for the relatively long process of decision making by the client. The group said that they don't have more specific milestones than the start and finish times of the phases of the project, and that these serve more as checkpoints.

Concerning evaluation, the group admits that their organisation is "*not good in evaluation*" and lacks a proper evaluation procedure, due to the fact that after the completion of a project, employees are redistributed in new projects. Subsequently, the group agreed that through the duration of a project like this, there are great opportunities for organisational learning, but they are not taken advantage of. They also explained that during a period of five years (that this project is planned to last), changes in employees' positions are possible and in other cases common.

4.2 PROLOG BYGGLOGISTIK AB CONSULTANTS

In order to create a juxtaposition and enhance the understanding of the topic, the input from a consultancy firm was seeked. The consultancy firm selected is Prolog bygglogistik AB, both due to the firm's focus and on the basis of recent experience. Prolog has recently undertaken the implementation of a Building Logistics Centre (BLC) in Stockholm's Royal Seaport, to serve as the cornerstone of effective operations of many construction sites in parallel. The Royal Seaport is one of the city's environmental urban districts, aiming to set an example of sustainable development in urban areas (Logistics Centre Stockholm Royal Seaport: For sustainable and resource efficient construction, 2015). At present, Prolog has three employees in Gothenburg, four in Stockholm, and ten in Malmö.

Interview

The interviewee is Prolog's project manager and Head of Gothenburg office, Tobias Nordlund (TN). The interview is performed as an open discussion, with several specific questions prepared from the interviewer (*Q*) in advance, to ensure that the themes of interest will be covered. The interview started with a brief description of the topic from the interviewer. The interviewee then gave a description of the company's business areas, employees, strategic goals, and roles and responsibilities, both on organisational and on individual level. During the last part of the interview, the interviewee was asked to give some examples of projects that the company has undertaken.

The discussion opened with the interviewee describing the company's three types of offered services (*tjänster*), in particular change management (*förändringsledning*), competence development (*kompetensutveckling*), and project management (*projektledning*). He said that change management is the core competence and the main attraction from a customer's point of view, while the other two are necessary supporting services. He went on to explain that in order to add knowledge during the change management phase, a competence development function is imperative. Furthermore, he underlined the importance of "*knowing the industry*", when it comes to construction, due to the dominant local characteristics and cultures, as well as the uniqueness of construction projects. This is what justifies the function of a project management service, according to TN. According to the company's website, they adopt "a holistic approach combining hard and soft parameters". The interviewee explained that, there are two types of consultants in the [swedish] market, technical consultants (*tekniska konsulter*) and management consultants (*ledningskonsulter*), giving examples of firms such as McKinsey and Accenture, and Sweco and ÅF respectively. These two areas of expertise overlap, and change management takes place in their common area. However, in the swedish market, according to TN, there are few, or any management consultants familiar with the construction industry, consequently making the rest strive to learn its characteristics when hired. Furthermore, TN claims that Prolog can perform as a management consultant, while having an engineering base of knowledge. He gives an example of a claim that argues that in the construction industry, 80% of R&D is devoted in new materials, or better tools, while 20% of the capital is left for management-related research. But what the backtracking of the construction site's activities reveals, when the desired results were not achieved, is that in 80% of the cases the cause was the human factor.

Prolog's consultants are often (approx. 30% of the cases) hired from an early stage, and take the lead of the planning before the construction, and the monitoring during the construction phase. In most of the cases they are not hired on the basis of unique or hard to find competences, rather as additional personnel for a project. For the early design phase, Prolog adopts the Last Planner® System, via a *visual planning* technique with post-it notes. With inputs from all the working trades of the project, Prolog aspires to involve everyone in the decision making process, plan the duration and sequence of the activities according to their needs, which are in turn evaluated and examined in-depth, and subsequently minimise alterations and compress the total project duration, reporting a 30-40% compression. Activities are examined in regard to their criticality, interdependence with other activities and estimated risk of delays. TN argues that there are specific characteristics, such as demand for resources, that are not represented in traditional techniques such as Gantt charts, and exemplifies with an anecdote of a carpenter team that called in an additional number of workers in an attempt to catch up with the schedule.

When asked what responsibilities Prolog takes in the construction phase, TN explained that they mostly monitor the earlier planning. TN takes either the role of a project manager, or supports a project manager. During that phase, he has a close cooperation with the contractor's site manager, among others. Their purpose is to have operations run uninterrupted and with no deviations from the planning. In the event of conflicts, TN describes the ideal situation that Prolog strives for. In particular, he uses a plumber and an electrician to exemplify a hypothetical scenario where these two working trades have a conflict arising in the construction phase. TN argues that working professionals that have undergone adequate training, such as the one offered through Prolog's competence development service, will be willing and able (i.e. have the *knowledge* and *judgement*) to solve them without the interference of management. TN reports that sometimes there are deviations from the schedule, but mostly due to unprecedented events (e.g. weather, sick leave, delayed deliveries).

TN described in detail the company's way of thinking when it comes to the top-down or bottom-up approach. According to the Last Planner System, the decision making is shaped from the lower levels of hierarchy and upwards, to ensure that all activities will be allocated enough time to be completed. TN was opposed to the top-down approach, as he thought it is ineffective and results to a *reactive* way of thinking and a problematic working environment with limited understanding of the activities' interdependence across the organisation.

When the interviewee asked to report any experience related to spatial conflicts, he chose to describe a recent project that Prolog was involved in, namely the Building Logistics Centre (BLC) in Stockholm's Royal Seaport area. The Royal Seaport is one of the city's environmental urban districts, aiming to set an example of sustainable development in urban areas (Logistics Centre Stockholm Royal Seaport: For sustainable and resource efficient construction, 2015). Construction took place in a very limited area, with many construction sites operating in parallel. The traffic situation in the broader area was an additional challenge for the transportation from and to the construction area. The role of the BLC was to schedule material deliveries during construction, as well as handle waste recycling. Deliveries have to be booked earlier, ideally five days in advance, and the material -with the exception of concrete- is unloaded and stored in the BLC. The BLC then manages the material flow to the working area in accordance to the demand per time unit, using smaller electric vehicles, therefore reducing greenhouse gas emissions, waste, resources and occupied physical space. Furthermore, the logistics centre fosters efficient planning and consequently an increase in value-adding time and lower construction costs (Logistics Centre Stockholm Royal Seaport: For sustainable and resource efficient construction, 2015). In order for construction to keep a short time of completion, there is a need for the activity sequence to avoid delays. When TN was asked if the use of a logistics centre compromised the possibility for the contractors to always book their desired time, he explained that this was not a problem, because of their intervention and contractors' engagement in a collaborative process. He also explained that this was the reason behind the five days slack in the booking process that asked contractors to keep, and that rescheduling was almost never necessary. TN highlighted the role of a fence and numerous gates around the building area, to ensure the exclusive use of the BLC and discourage uncoordinated deliveries and workers parking their cars in the area.

When the issue of space allocation and layout came about, the interviewee explained that Prolog's philosophy is that spatial constraints can foster detailed planning, which will in turn create the need for greater control and monitoring during construction. TN argues that, once resources are invested in such planning, problems during operations will be eliminated to unforeseeable events (e.g. weather). More specifically, TN states that "*if you have limited space, you need to have everything in its place; I think it's a good idea, to keep it narrow*". Prolog's philosophy is reportedly influenced from lean principles, identifying *waste*, as defined by the lean thinking, as an obstacle to efficient construction operations. Similar to space allocation, TN stresses the importance of temporal coordination and scheduling. He stresses the promising results of *just-in-time* (JIT) deliveries, although arguing that for construction operations is might be useful to attempt JIT deliveries in a step-by-step process. In particular, start scheduling JIT deliveries for one material (e.g. windows), in a second stage add another JIT delivery, and so on. The rationale behind this claim is that, in the same way as change management accepts that lasting change is an incremental and iterative procedure, a change in the traditional construction status quo comes in the same manner.

Concerning information availability, as a planning resource, the interviewee quotes Dwight D. Eisenhower: "*plans are nothing; planning is everything*", and further explains that according to the Last Planner technique, detailed planning is a continuous process, wherefore information is added as soon as it becomes available. He also mentions that once participating in the aforementioned meetings, one is aware of the consequences of changing course of action, regardless of one's position in the organisation. TN reports that examination of alternative scenarios is rarely the case, unless the undertaken project entails a critical stage, such as the case of hospitals, or schools, that have certain rigid requirements and/or dates of completion.

4.3 RIB SOFTWARE AG

Deriving from the thesis research questions, the research design includes inputs from a software developer; in particular, one devoted to the construction industry. Therefore, the focal point was the firm's software, iTWO, which is a 5D solution, where 5D stands for geometric properties (3D), time and resources (4D), and a cost dimension (5D). RIB strives for an enhanced 6D version that will include facilities management (FM) data. iTWO focuses on the integration of virtual processes, and their full alignment with the physical world, where the latter follows the former as planned, rather than the former being a "checklist".

Webinar

As described in the Methodology and Research design chapter, this part of the research consists of a webinar offered by RIB, in order to set the ground for a more informed and better prepared subsequent lab visit, as well as an opportunity to communicate the thesis' subject matter and steer the discussions to the points of interest. The webinar was conducted by Sarah F. Procter (SP) RIB's business development manager for iTWO Sales. During the webinar, SP described in detail the business objectives that iTWO aspires to satisfy, its intended applications, as well as certain technical aspects of the software, such as the compatibility with BIM models built in various other platforms. Furthermore, SP exhibited various examples of iTWO, explaining how the program works.

According to RIB's core objectives is the linking of the different stages of a project for efficient planning, through transparent information spillovers. Illustrated in Figure 4.1 below, are the IT-landscape and information silos of traditional processes, according to RIB.

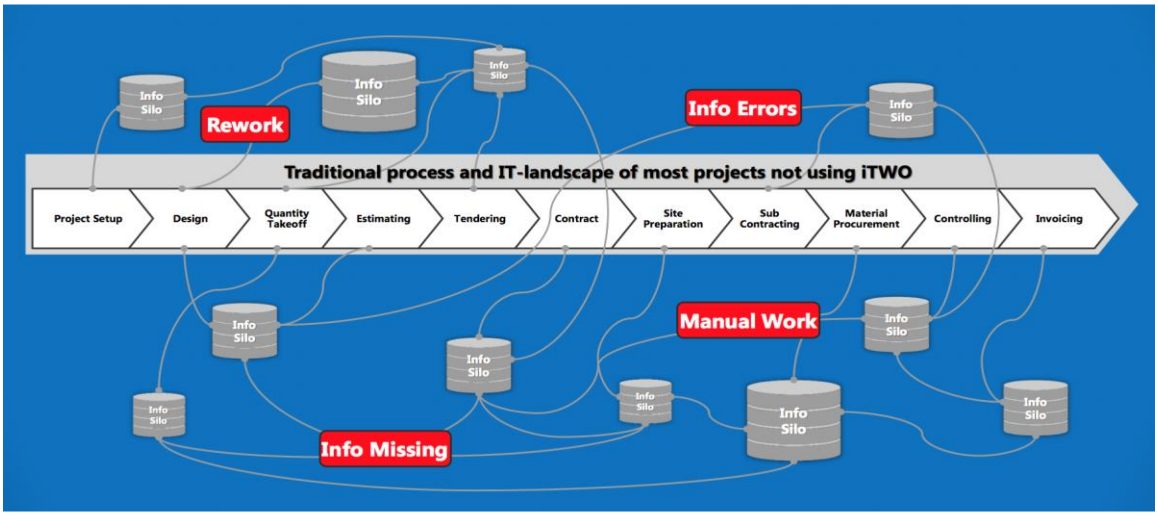

Figure 4.1: Information landscape throughout a project (RIB Software AG, 2015)

RIB is normally hired by other firms, in order to make a full implementation of their system, and ensure its intended operation. This includes either the local installation on a firm's server, or a "cloud" solution. The available information is then shared throughout the organisation through the licences RIB issues. From an early stage, the design is incorporated in iTWO; the architectural design, that can be built in any CAD system and in any level of detail, such as Revit or Autodesk is exported in iTWO by a plugin. In order for iTWO to generate cost information, material quantities and other values have to be filled in. Information is added as soon as it becomes available and throughout the project. The program also supports the side-by-side comparison of different scenarios and a preparation of the tendering documents. Such data can be imported from popular computational tools, such as Microsoft Excel .xml files. As soon as the information is imported, the program generates a dynamic simulation of the project, in parallel with dynamic functions of different variables, such as cost development, revenue, or any KPIs the organisation intends to follow.

According to RIB, the decision making process is crucial, and the model is built on a collaborative process. The firm then forms an *iTWO 5D Lab Team of Experts*, which consists of several members of the organisation, as seen in the figure below. These members are trained in a 4-day seminar conducted by RIB, in order to be able to fully operate iTWO throughout the project, simulating completed projects of the firm.

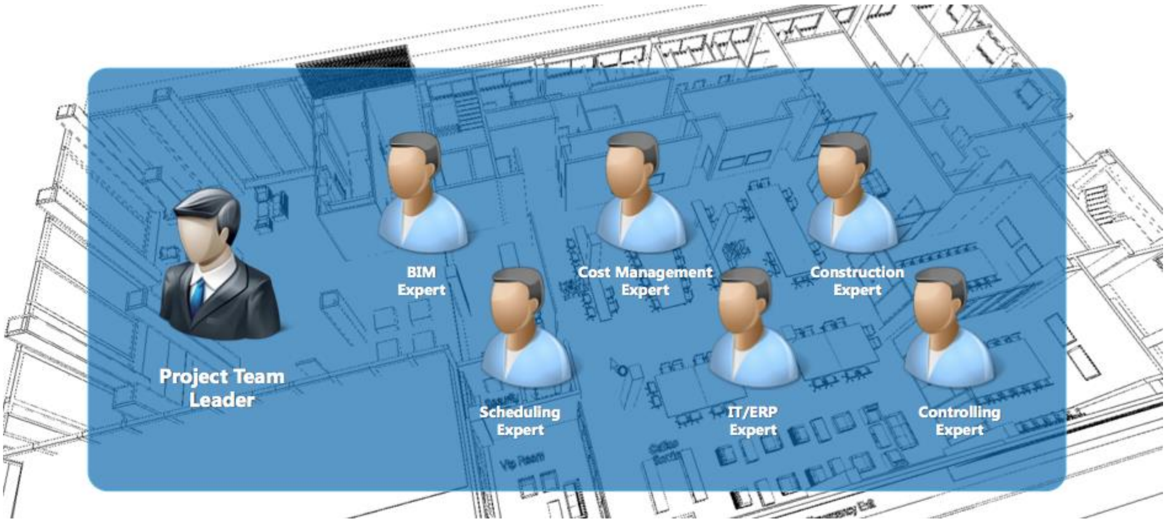

Figure 4.2: Formation of iTWO Lab Team of Experts (RIB Software AG, 2015)

SP highlights the importance of efficient integration of iTWO and the updated workflow, for the intended resource savings, more efficient processes, and minimisation of defects, among the intended results.

Lab visit and interview

After the above webinar, a lab visit and an interview were arranged in RIB's quarters in Copenhagen. The interview is done with Sarah F. Procter (SP), Business development manager, with contributions from Andreas Foldager (AF), Senior consultant for iTWO Sales. The interview is performed as an open discussion, with several questions prepared from the interviewer (*Q*) in advance, to ensure that the themes of interest will be covered. The interviewees were prompted to answer the questions elaborately, in respect to the company's business areas and strategic goals.

RIB's products and services require an early phase planning approach, utilising as much information as possible. Early phase planning involves, among others, the establishment of a common base for all (i.e. it can be as abstract as a concept or as specific as a LOD50 model for instance), on which information is added, while clash detection and alterations are performed. AF explains that the parameters (i.e. virtual properties) of the elements can be manual inputs and have a custom tolerance function that applies to all properties. Every parameter that can be expressed as a numeric value can be added. For instance, a slab can be set to be able to carry up to a given load and the user can set the point from which a clash will be detected. Therefore, clash detection can exceed the traditional, exclusively geometric based identification. In fact, the suggested implementation pushes the client (i.e. RIB's client) to strive for information as early as possible, because, according to SP, it is essential for efficient planning. The whole process, as suggested by RIB, follows a sequence of stages where information is added in the model as soon as it becomes available and enables information spillovers from one stage to the next, as opposed to the traditional information silos illustrated in Figure 4.1. While information accumulates, the system (i.e. iTWO), produces more detailed solutions, scenarios, and simulations. More specifically, there are multiple elements, such as a BIM element, a calculation element, a scheduling, pricing, tender, controlling, and financing system, of which one can monitor the development on a time axis. Early decision making is supported by the utilisation of a big database, where information on aspects such as unit pricing, wages, and quantities, among others, are kept. Early scheduling is also based on past experience, and usually starts with only two or three basic lines of activities, expanding as information is added. In parallel, the process involves loops where information forces the decision making to oscillate back and forth, slowly progressing. SP argues that this is a learning dialogue and can be the basis for more precise cost estimations.

When asked about the benefits of early phase planning and the contractual framework the planning takes place into, SP explained that early phase planning is essentially seen as an investment, where more funds are put in the earlier phase of the project, in order to eliminate alterations, additions and uncertainty as much as possible. This strategy requires a support environment with transparent processes and increased quality of the models (i.e. BIM). As a result, the costs saved (area between the lines from the intersection point and to the right of the chart) outweigh the additional initial investment (area between the lines from the intersection point and to the left of the chart), as shown in the simplified chart (Figure 4.3).

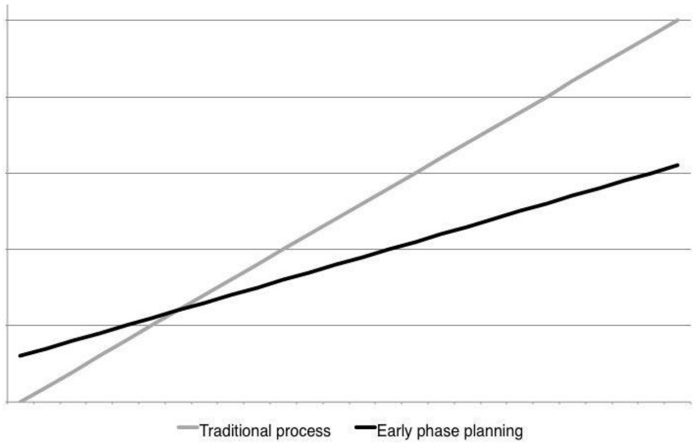

Figure 4.3: Traditional cost development vs. Early phase planning (simplified)

Moreover, according to SP, the period that follows the tendering phase, where traditionally all drawings are aligned and checked for mistakes and clashes, is characterised by low quality work, and opportunities for architects and engineers who can consciously ignore mistakes and clashes, in an attempt to create more work for them later. SP claims that this is what "breaks budgets", and long-term sustainable thinking will enable the industry to continue building equal amounts, just more cost efficient.

As shown in Figure 4.2, RIB's suggestions for the planning responsibilities in this process are to be assigned to a project team, consisting of the client's employees. When asked about the responsibilities of adding information in the model throughout the process, SP explained that the implementation varies according to the type of their client. More specifically, if the client is a large contractor, which is what iTWO was intended for, then it is important for them to build *catalogues*, containing all the client's information regarding contacts, cost codes, cost elements, wage groups, and work categories, among other data. SP argues that these databases hold the potential to be constantly enhanced and used in future cases, contributing to an automated process. In addition, RIB encourages their clients to train one or two employees as specialists and devote them to such tasks, in order to be able to overcome complex problems.

SP stresses the importance of resource management and information, with the latter being the cornerstone of the effective implementation of an integrated process. iTWO incorporates an ERP (Enterprise Resource Planning) system, which is synced with the physical processes of the project. Resource availability is a concern for RIB, and SP argues that the large databases can contribute to overcome the problem of assumed continuous and unlimited resource availability. More specifically, data from previous projects can be used statistically, in order to achieve more precise estimations (e.g. material quantities). Moreover, keeping such data can help clients to attain a deeper knowledge on the local market, for instance know which materials are easy or hard to find. Eventually, resource planning serves as a basis for controlling for RIB. Although used resources and time passed are not reliable measures for evaluation according to SP, *installed quantities* is a promising controlling function, for two reasons. First, it is based on actual, installed elements on the project. Second, it is compatible with automated processes brought up by recent technological developments, such as drones, and their ability to detect installed quantities. The drones are then programmed to automatically feed the information to the model.

SP used various examples of RIB's clients where resource criticality was important. It is common for hospital and school projects, which are typical cases with inflexible delivery dates to display resource critical moments. Although resource criticality as a separate attribution is not yet a part of iTWO, there are parameters that can have "zero tolerance", so that delivery dates for instance can be achieved in such cases.

Even though scheduling is not the primary focus, there is a scheduling module in iTWO. SP mentions that another danish company is further ahead in this area, although it lacks integration. Scheduling is based on Gantt charts and can be either imported from popular software, such as Primavera or Microsoft Project, or built in iTWO. Like all modules, scheduling is synced to the overarching information, and generates charts such as BoQ (Bills of Quantities) structures, which are presented side by side with the simulation.

SP explains that since production was the primary focus of iTWO, the issue of logistics and on-site deliveries has not been addressed yet, although she acknowledges the importance of it.

When asked about the time-space constraints issue, SP exemplified the role of iTWO with three cases. The first case was a hospital project, where the constraining factor was mainly temporal, as the hospital had a rigid delivery date and the budget was rooted in funding, which meant that overruns would not be allowed. iTWO was not used in this project, but SP argues that iTWO can be both a tools for better planning, and a medium for risk mitigation, which can lead to cost savings in the long run. Overruns are also something that clients are insured against. In the second case, a hotel project, the delivery date was again inelastic. RIB collaborated with a company that prepared the visualisations for the hotel, in order for the client to take certain decisions, such as the colour of the walls or the design of the reception desk, as early as possible. SP argues that, with such rich virtual information, the clients can be well prepared to take such decisions early and with confidence, knowing the consequences on time and cost. The third case was a project that exhibited congestion on the construction site, something that SP agues will be the future of building in urban areas. SP mentions that the contractor in that project used iTWO, although found useful to 3D print it and take decisions regarding the spatial allocation on the physical, scaled model.

SP was presented to a common argument against early planning investments, namely the tradeoff between the solution and the benefits. The argument questions that the cost to acquire the solution is always justified according to the cost overruns that would occur without it. SP explains that end to end solutions like iTWO are primarily designed for a certain scale. In particular, a single project with a budget of 500MDKK or more would justify the use of iTWO. However, this cost mark is lower for the long term and extensive use of the system.

Next, the interviewees were asked about issues concerning the implementation of newly introduced solutions such as iTWO. They both acknowledged the significance of successful and as seamless implementation as possible, especially when they reportedly had clients whose bigger concern was not to change their way of working. In fact, SP mentions that practically no employee is willing to change their way of working, as this is always seen as a disruption. Therefore, SP argues that there are certain factors that should be taken into account in the implementation process. First of all, the employees who are going to be working with the system need to be IT-literate up to a point where they will not cause a lag in the process. However, SP claims that nowadays, every person is IT-literate enough to handle at least an informative use of iTWO, such as what on-site workers would have to do. Another factor is the notions that employees are afraid that they will be soon replaced, that they are not needed anymore, or that they would have to work more after the introduction of the new platform. SP asserts that this is not the case, even though it takes time to make the most out of it. In particular, SP mentions five years for past clients, and says that nowadays the same implementation would take about three years, due to the learning from previous experience. Finally, SP underlines that "*it requires a lot of engagement from the management side*", and that "*it needs to be in the middle of the business strategy*".

At the end of the interview, the interviewees were asked to share recent developments and future plans for iTWO. SP described an on-site version of iTWO where workers on-site can use to check the daily and weekly schedule and follow current processes. The increasing use of drones is also among future plans for automated processes. Finally, SP mentioned the recent use of Google Glass, in order to enable better communication with and make a strong impression to the clients regarding the look of the deliverables of a project.

5 DISCUSSION

The issue of low production efficiency in construction operations is often a concern for all kinds of firms across the industry. The argument that low productivity of planning and scheduling is manifested in time and cost overruns, often cited in literature, is shared among all working professionals interviewed for this thesis. Time and cost overruns, or the lack of, are also common *measures* for planning and scheduling efficiency. In the contractor's project, the measuring and evaluation was conceptualised in the classic *iron triangle* manner, with a supplementary concern for additional resource utilisation, while there was no evaluation process. In the consultant's case, the same three-variable balance was seeked, with the firm focusing on the compression of the time variable, while keeping the other two stable, as prescribed from the project requirements and specifications. Again, the success of the planning and scheduling is evaluated on the basis of timely and in-budget delivery. Moreover, the consultant argues that there is an opportunity to reduce the costs and duration of certain activities. Whether the saved time and cost are then used as compensations for other activities (i.e. levelling) is not a concern at this point, due to the scheduling flexibility that the process in this case aimed at. In other words, there is no specific information for the problematic activities, in order to be able to proceed to an investigation of the constraining factors respectively, since the evaluation is performed overall for the project. Therefore, there was an inherent incompatibility between the firm's working routine and the objective of identification of problematic activities. It was only the temporal dimension of activities that was kept tracked on. In the case of the software developer, although there was a more detailed analysis on resource use, cost development, and timely delivery, there was not enough detail on scheduling efficiency, since the scheduling module of the software in question was not the primary focus at the time. Nevertheless, other, real-time modules (e.g. cost development) can support the decision making process in regards to resource levelling, by monitoring peaks on the produced curves. At this point, it is clear that even the simplest organisational structures can influence critically the success of a process of constraint identification.

During the collection of empirical data for this thesis, the productivity issues that came up were mostly related to resource productivity, planning and scheduling efficiency, and labour productivity. The notion of optimisation is not seen as strict in praxis, but it often seems to come as a result of a continuous improvement and a competition-leading way of thinking. The empirical data are similar to earlier research findings where *productivity of labours* and *slowness in the decision making process by owners* are ranked as significant factors for project delays (Rojas and Aramvareekul, 2003).

Rojas and Aramvareekul (2003), mention *construction methods*, *administrative systems*, *strategic management and planning*, and *use of goal-setting techniques* as areas of interest about labour productivity in the construction industry. According to the same research, and shown in Figure 3.1, *management skills* and *scheduling* are ranked highest in the productivity drivers' chart. Management skills are often influential due to managers' ability to handle resources and modify schedules and working methods, three major constraining factors in praxis, according to the empirical evidence. Management of all three can be extremely challenging, due to these factors' interdependence. Resource reallocation can be a result of rescheduling, which can be a result of delays. The most significant factors for delays, in turn, are *poor site management and supervision*, which can be traced back to *contractors' inadequate site planning and organisation*, *unforeseen ground conditions*, *low speed decision making*, and *client-initiated variations* (Chan and Kumaraswamy, 1997). Contractors' inadequate site planning and organisation is traced back to a lack of experience and training, both regarding the technical and the managerial level, an issue that came up in all three cases examined in this thesis. In the case of the Tingstad Interchange, the project group asserted that the organisation and planning of the construction site is an ad-hoc, rather than a planned decision making process. At the technical level, the group confirmed that they lack the technical training and expertise to handle sophisticated planning software, something that was not asked from them though. This group had the IT tools prescribed, and could use additional ones, but that was reported as very rare. Further drawing on the prescriptive manner of the software, the group emphasised the importance of the selection and suitability of the IT tools, and expressed a concern that "unsuitable" software can cause disruptions on the work process. It is perhaps characteristic and appropriate to mention at this point, that the use of IT tools merely served a visualisation need, rather than supporting a planning process, even though both of these were the objective. In the case of the consultant, the firm operates in precisely that area, offering a change management service in order to compensate for the lack of expertise of consultants and their clients specifically in the construction industry. As the interviewee reported, there are few, if any, consultants familiar with the swedish construction industry, and most consultants strive to grasp its characteristics after they are hired, consequently losing time to adapt, and further delaying a project. In the case of the software developer, the firm's objectives are aligned with the idea that project success is dependent on technical and managerial expertise, thus the contractual agreements between RIB and their clients address this issue, either by setting up an iTWO Lab Team of Experts (Figure 4.2), or by mitigating the risk to their client. Therefore, there is a need to address the issue of contractors' adequate experience and training at technical and managerial level, as well as the selection and effective integration of software in order to proceed to productivity of labours improvements.

Slowness in the decision making process by owners is perhaps a controversial issue; in fact, two out of the three groups of Assaf and Al-Hejji's study (2006) identified this as a delay factor (the third being the owners). Nevertheless, slowness in the decision making process was mentioned in all three cases studied for this thesis. This issue has two trajectories manifested in the explorative cases: one concerning the early phase planning, and another concerning the handling of delays and unprecedented events. In order for early phase planning to yield results of more effective resource use and identification and management of time-space conflicts, detailed information about the project and the methodological requirements is imperative. The earlier the decisions are taken, the more information spillovers between the different stages of a projects, as illustrated in Figure 4.2 and argued by RIB's business development manager. More precisely, RIB's argument is that with the early phase planning approach, the suggested implementation *pushes* the client to strive for more information and decisions as early as possible, which in turn produces more detailed solutions and alternatives, more informed simulations, as well as more precise estimations. The enhanced information map of the project will overcome Waly and Thabet's (2002) macroplanning barrier, according to which critical decisions are taken based on inadequate information, which jeopardises the successful delivery of a project, a concern that was expressed in all the explorative cases. More specifically, sources of time-space conflicts and deviations from schedules are likely to be prevented in this stage.

Although it looks like the stark contrast lies between the two sides of the tradeoff between a detailed space management plan and an experience-based space allocation and the respective costs and risks each one entails, it is crucial to underline a fundamental difference between the two approaches. According to conventional practice, the site manager or the project manager allocates space to the various activities that take place in the construction site, on a daily basis (Guo, 2002). However, this allocation does not derive from each activity's actual *need* for space, but from a holistic approach to avoid overall schedule overruns, according to the manager's assessment. This approach can be especially problematic, for two reasons. First, resource critical activities can be compromised in the expense of others, something that can cause an avalanche effect on resource availability. Second, prioritisation of activities, although decided upon the manager's experience, can be biased in a manager's attempt to avoid bad evaluation according to the specific criteria of assessment. One of the major contractors in Scandinavia uses a five parameter evaluation for managers, for cost performance, environmental impact, number of accidents, ethical breaches and defects. Likewise, in an anecdote recorded by Sundman (2015), activities were grouped according to their cost sum, in an attempt to level each group's total costs and keep them to a minimum, due to the evaluation system of the contractor. Consequently, the evaluation and the financial system in place didn't reflect the actual reasoning for activity scheduling.

The early decision making model that is suggested here, can be particularly challenging. First, the required large amount of information that results from complex projects can be difficult, or even impossible to handle in a traditional manner. The use of sophisticated IT tools is seen as necessary to proceed to complex optimisations from a large amount of data and in a dynamic environment. Furthermore, the optimisation will likely yield a variety of parameters of concern, such as cost development, revenue margins, resource use, etc. Following this logic, and in regards to previous cases reported by RIB, the client is taking decisions that would otherwise be taken later in the process. However, this forced early decision making process might be a reason for alterations later. In addition, the amount of information required for this model is not entirely consisting of client decisions. Spatial conflicts can be reduced by early planning and handling of issues such as crew interference, but issues such as resource unavailability are more difficult to predict and might rise later in the process. To proceed to greater degree of optimisation, there is a need to address decision variables regarding the material procurement and storage, and the categorisation of restriction of regions (i.e. barrier, congested, forbidden areas). Therefore, there is a need for detailed information on the *resource demand* of activities, and an integration of this attribution into the scheduling process, in order to overcome some of the CPM-based problems. On the other hand, reported cases from the consultant and the software developer included in this thesis, suggest that early phase planning can be a profitable investment, since it can eliminate additions and alterations, especially those that root in overlooked specifications, design errors, and poor workmanship.

Regarding the earlier hypothesis that spatial constraints can be *hidden* behind issues other than topological characteristics or construction methods , such as activity scheduling, material storage, resource management, and delivery scheduling, the findings suggest that this occurs in several cases. In particular, based on the interviewees' previous experience, it seems that many problems arise from deliveries scheduling, material storage and handling of unprecedented events. Deliveries scheduling often results to uncoordinated and ad-hoc material storage, which in turn occupies space in the construction site, often blocking the way of other activities, as reported in two of the cases in the previous chapter. Again, we see the interdependence of the temporal and spatial dimension, when space can be temporarily available or unavailable, and the need to introduce the availability attribution. In the case of the Tingstad interchange, the interviewed group was concerned about congested areas, although mostly for the physical restrictions due to the expressways and the material storage blocking, which was something reportedly challenging to overcome. The group reported that although they have detailed enough plans to avoid such events, the plans are not communicated or adopted by the deliveries' subcontractors (e.g. lorry drivers who bring materials into the construction site), something that reflects Chan and Kumaraswamy's (1997) hypothesis that poor management and supervision can be traced back to contractors' inadequate site planning and organisation. This view is shared by Assaf and Al-Hejji (2006), where according to owners and consultants, contractors' planning and scheduling often results to project delays. In praxis, scheduling is still based on CPM inputs, and the levelling procedure is performed accordingly. However, both literature and the empirical evidence suggest that even this CPM-based scheduling is only adopted at management level, while contractors and site personnel rely on own experience and operate in a reactive, ad-hoc manner, at times contrary or regardless of the plans. In the case of Prolog, activities are evaluated and planned according to their criticality, interdependence with other activities and estimated risk for delays. In this way, activities are given more or less time and slack according to the risk they carry, in an attempt to minimise delays and alterations. However, although the interviewee in this case acknowledges the need for a resource demand attribution on activity scheduling, this process disregards the aforementioned problems of assumed unlimited and continuous resource availability and critical activities with no precedence. Moreover, criticality here is an attribution given in regard to activities' risks and the severity of the consequences should the risks materialise. Therefore, once a risk becomes a reality, time is lost in the form of unnecessary slack while other activities, in particular the ones delayed, are in need of resources. Resource criticality, on the other hand, was a concern only for the software developer in this research, although the other two firms acknowledged the problem of assumed unlimited and continuous resource availability. In this respect, Lu and Li's (2003) proposed resource-activity critical-path method (RACPM) looks promising to incorporate resource critical activities into scheduling, and using a heuristics technique, set up the levelling criteria, such as the aforementioned work content attribution. Nevertheless, this method does not solve the issue of availability of space in a dynamic environment, or the critical activities with no precedence.

One of the most significant problems with scheduling and resource management according to both literature and the empirical evidence presented, is the assumption of continuous and unlimited resource availability. This issue can have serious repercussions in cases where additional resources are seen as a safety net, should overruns occur, as exemplified by the Tingstad interchange project team in Chapter 4. Although it is widely acknowledged, at least from the working professionals interviewed for this thesis, that resources are indeed limited, the demand rates and the on-time availability often pose additional challenges. RIB's business development manager exemplifies the need for this by describing iTWO's utilisation and constant enhancement of large databases, in order to be able to make more precise estimations on the availability and predict better the fluctuating demand of resources. Although the larger the amount of data means better estimating ability, there are certain issues with the statistical manner in which the data is being used. One of the most distinct characteristics of the construction industry, is that projects are unique. Therefore, the statistical use of large data might be useful for issues such as resource availability in a certain market and general ERP systems, but not for other characteristics, such as the broader category of physical constraints, as defined by Sripasert and Dawood (2002). More specifically, technological dependencies such as topological characteristics and construction methods require specific information and modelling. On the other hand, large databases can contribute to the handling of contract constraints, since aspects such as delivery dates, cost development, and project specifications, depend on the precision of estimations, which in turn are dependent upon the calculations on the correct quantities and minimisation of alterations.

Taking into consideration the aforementioned challenges towards an effective identification and integration of time-space constraints both in visualisation and scheduling, a proposed software will eventually have to tackle the lack of representation of the attribution of spatial conflicts, e.g. according to Saleh Farham, Süral and Iyigun (2014) taxonomy of restrictions into *barrier*, *congested* and *forbidden regions*. According to the software developer in this thesis, this attribution can not be implemented at the time, due to the lack of parameters such as crew location. Furthermore, detailed data such as crew location, material storage, and lorry routes are usually not specified at all, especially not per time point, and thus far from being used for optimisations. A partial solution to this problem was reported in the case of the consultant presented in Chapter 4, with the introduction of a Building Logistics Centre to organise and schedule deliveries to an area of several construction sites with common entry and exit points.

6 CONCLUSIONS AND FUTURE RESEARCH

There seems to be a convergence between literature and industry practice on the constraining factors that can lead to time-space on-site conflicts that affect cost, time scheduling and consequently, productivity. In the category of physical constraints, technological dependencies predominate, with the subcategory of construction methods being the most significant variable, in contrast to location and topological characteristics, which are perceived as more rigid. In this subcategory, utilisation of IT tools is a crucial feature, manifested in various elements in the juxtaposition of the cases of the contractor and the software developer in this thesis. Furthermore, temporary facilities were also an important factor, for all three cases in this thesis. Topological and location constraints are in most cases permanent, and planned against since the conceptualisation of a project. However, topological constraints influence the planning against the constraints we find in the subcategory of construction methods. Likewise, contract constraints are also seen as less flexible, often consisting the project deliverables.

In the category of enabler constraints, there are certain key factors that contribute to on-site conflicts, both regarding resources and information. For the subcategory of resources, we find *availability* and *continuity* to be the most significant attributes both to understand and integrate resource-related constraints. For the subcategory of information, *availability* played the most significant role in all the three cases.

In the case of complex projects, time-space planning is not given enough consideration, at least not as planning per se. In all three cases investigated in this thesis, there are certain concerns regarding the avoidance of conflicts and their respective actions during the planning and scheduling, though not articulated in a clear spatiotemporal dimension. The constraining factors are in most cases hidden behind working routines, which do not permit thorough assessment of problematic activities that can lead to the identification of such constraining factors. Instead, it is common that deviations from the time and cost axes are often a cause for alarm, though the evaluation is not performed on activity basis, but overall, that way impeding the generation of information that can contribute to an earlier decision making process. Backtracking the most common causes for delays according to literature, we find that contractors' lack of experience and training on both technical and managerial levels can often lead to inadequate site planning and supervision, low speed decision making, and client-initiated variations, as well as interfere with the development of management skills and scheduling efficiency, which are key productivity drivers in the industry.

In order for time-space constraining factors to be managed, there is a need for a standardised process of prior successful identification. Subsequently, there is a need for an early phase planning approach, where all parts of the project strive for the earliest possible availability of information, in order for the earliest possible generation of precise estimations, detailed solutions and alternatives, more informed simulations, and the fostering of a faster and earlier decision making process. Nevertheless, an early phase planning approach requires additional information, concerning the resource demand of activities, as well as a need to address the issues of assumed unlimited and continuous resource availability and critical activities with no precedence. In order to incorporate the attribution of resource criticality into CPM-based scheduling and set up levelling criteria accordingly, Lu and Li's (2003) RACP method is proposed, in combination with sophisticated software that can utilise large amounts of information, be an effective monitoring tool, and support an early decision making process. In parallel, a heuristics technique is necessary, to overcome the non-precedence critical activities. Furthermore, the utilisation of large databases is promising, as illustrated in the case of a software developer in this thesis; although their use is limited to estimations that can be based on statistical grounds, such as resource availability in a certain market.

In addition to the need to incorporate the above remarks into a process supported by the appropriate technological applications for the successful identification, incorporation and management of time-space constraints, there is a need to adjust the decision making processes and criteria, as well as the theoretical context on which these were founded.

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