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A survey comparing Critical Path Method, Last Planner System, and Location-Based techniques

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Abstract

In construction, the most relevant systems used for project management (PM) and project production management (PPM) in the planning and control phases are: Critical Path Method (CPM), Last Planner System® (LPS®), and Location-Based techniques (LB). Studies have addressed these systems, mostly in isolated fashions. This study aims to compare and contrast their use in terms of PM and PPM and clarify industry benefits in order to eliminate potential misunderstandings about their use. A survey was administered to construction professionals in Brazil, China, Finland, and the United States. No single system addresses all needs of PM and PPM. CPM is the dominant system when considering these characteristics: primary industry types, type of organization, size of organization, professional position within the organization, and area of work. Contributions to knowledge include that CPM is a contract requirement with perceived benefits associated with critical path analysis; LB and LPS have perceived benefits regarding continuous flow and use of resources, treatment of interferences, and improving production control. All systems were found to have a similar level of benefits for management of contracts, delay and change, and evaluation of the root causes of delays. The industry can benefit from aligning project scheduling methods with project needs.

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Introduction

Several systems have been used by project teams to plan, schedule and control projects and production. Due to their importance and being widely recognized by industry and academia, currently the most relevant systems are the Critical Path Method (CPM), Location-Based techniques (LB), and the Last Planner® System (LPS), which have been used for several decades. CPM has been applied in construction projects since 1960s (Burns et al. 1996) and in all types of projects (e.g. Hegazy 2005, Shi and Blomquist 2012). It is the most common system used in the United States and United Kingdom for planning and controlling projects (Galloway 2006, Olawale and Sun 2015). Additionally, LB techniques have been used since 1929 in innovative projects such as the Empire State Building (Willis and Friedman 1998). Since then, these techniques have been applied in many projects and countries, such as Finland and Brazil, where they are widely used as production planning and control tools (e.g. Kemmer et al. 2008, Lucko et al. 2014). Similarly, LPS has been implemented since 1993 (Ballard 2000) in construction projects around the world (e.g. Alsehaimi et al. 2014), and it is one of the most discussed topics in the conferences of the International Group for Lean Construction (IGLC).

Previous studies have investigated the use of CPM (e.g. Tavakoli and Riachi 1990, Galloway 2006), LPS (e.g. Fernandez-Solis et al. 2013, Khanh and Kim 2014), and LB (e.g. Kim et al. 2014) among construction companies and professionals, exploring the observed benefits and limitations of these systems. However, these studies are usually focused on only one system and limited to a specific country, whereas this study obtained data from four different countries as indicated later. Additionally, this paper seeks to distinguish how these systems are used to manage projects versus managing production and identify their perceived benefits as indicated by practitioners. The definitions adopted for Project Management (PM) and Project Production Management (PPM) are considered as follows.

Project Management (PM) considers the management of contracts and contractual requirements, including but not limited to the relationship between project stakeholders (e.g., clients, contractors, designers, suppliers, regulatory agencies) and their rights and responsibilities to deliver the project considering its overall requirements. In general, the PMI (2013) indicates that PM addresses five main process groups comprising the life cycle of a project: 1) initiating, 2) planning, 3) executing, 4) monitoring and controlling, and 5) closing. "*Project management develops and implements plans to achieve a specific scope that is driven by the objectives of the program or portfolio it is subjected to and, ultimately, to organizational strategies*" (PMI 2013, p.7). In the United States, for instance, construction projects usually have project executives, project managers, and project engineers who oversee these areas for the entire project (or subsections of it) and serve as the connection between the owner and those involved in designing, inspecting, and building the project.

Project production management (PPM) can be viewed as a subset of project management, which focuses more specifically on operations management. This includes but is not limited to production flow management and control; specifically, how tasks are defined, executed, and controlled where they are executed. PPM focuses on the resources, means and methods of production, and their organization to deliver value to the client. To illustrate this focus on production and operations management, Schmenner (1993, p. 2) provides the following explanation about tasks associated with operations management: "*The operations function itself is often divided into two major groupings of tasks: line management and support services. Line management generally refers to those managers directly concerned with the manufacture of the product or the delivery of the service. They are the ones who are typically close enough to the product or service that they can "touch it".(…) Support services (…) carry* *titles such as quality control, production planning and scheduling, purchasing, inventory control, production control (...)".* In the construction industry in the United States, these roles are usually attributed to superintendents, field engineers, and foremen who are in direct contact with field resources used to deliver the project.

The aim of this study is to compare and contrast the use of CPM, LB and LPS in terms of how they support PM and PPM, using the results obtained through a questionnaire survey from four countries: Brazil, China, Finland and the United States. The research objective is to identify the perceived benefits associated with each method from practitioners' perspectives. This research is divided into three parts. First, a comprehensive review of relevant literature was done for each of the three systems (CPM, LB and LPS), providing the basis for the definition of ten hypotheses, which are presented in the first sections. Second, in order to test the hypotheses, an on-line questionnaire survey (see supplemental document with the questionnaire) was applied to gather quantitative data. The hypotheses were statistically tested and are discussed. Finally, conclusions are presented, and future research is suggested.

Planning and control systems

CPM is a planning, scheduling and control method (Kelley and Walker 1959) widely used in construction projects (e.g. Galloway 2006, Benjaoran et al. 2015). This method includes defining logical relationships between activities and using the CPM algorithm to identify the longest path (the critical path) through the network (Kelley and Walker 1959). It is a diagrammatic representation of a plan, presented as an arrow diagram (activity-oriented network) or as a precedence diagram (event-oriented network) (Antill and Woodhead 1990). In current practice, the plans and schedules are usually developed with globally available software packages such as Microsoft Project®, Primavera®, Asta PowerProject, or local packages such as TCM Planner in Finland, which make it possible to plan and visualize the schedules in either precedence diagram or Gantt chart formats. The availability of planning and scheduling software packages has contributed to the widespread use of this method (Hegazy and Menesi 2010, Bragadin and Kähkönen 2016). However, CPM has been considered inappropriate for PPM (Howell and Ballard 1994, Koskela et al. 2014) and criticized due to its shortcomings on generating continuous workflows (Arditi et al. 2002, Olivieri et al. 2018), improving crew balancing (Russell and Wong 1993, Hamzeh et al. 2015) and facilitating the continuity of resources usage such as labor, material, and equipment (Mattila and Park 2003, Benjaoran et al. 2015, Olivieri et al. 2018). Furthermore, the CPM method does not clearly address interferences between activities (Laufer and Tucker 1987) or uncertainties and constraints related to tasks (Koskela and Howell 2002, Hamzeh et al. 2012).

Linear, repetitive, and location-based scheduling systems (LB) form a family of workflow-oriented scheduling methods (Lucko et al. 2014), which use locations (e.g. towers, floors or rooms) as fundamental planning elements. Several different methods exist in this category. For example, Harris and Ioannou (1998) introduced the Repetitive Scheduling Method (RSM) named as such because construction is usually characterized by repetition. Other methods include flowline, line-of-balance (Lumsden 1968), linear scheduling (Johnston 1981), takt planning (e.g. Frandson et al. 2013) and the Location-Based Management System (e.g. Kenley and Seppänen 2010). In addition to planning and scheduling, these tools can include controlling tools such as control charts or forecasts, providing the ability to plan control actions. Location-based methods can be used manually or by using software tools such as Excel, Vico Schedule Planner, TCM Planner, TILOS and DynaRoad. However, based on our literature review, LB has not normally been associated with the management of delays and changes. In addition, although LB tools are frequently required by owners for subcontractors as a way to determine common goals for the crews (Galloway 2006), the literature does not identify LB tools as a contractual obligation. Overall, the literature suggests that LB emphasizes PPM benefits but also includes some PM functions such as time and location management and dissemination of information (Kenley and Seppänen 2010, Lucko et al. 2014).

LPS considers planning and controlling as a social process focused on collaborative planning, reliable commitments, and continuous learning (Ballard 2000). The system contains five main elements which are used to connect the long, medium, and short-term planning levels (e.g. Ballard 1997, Ballard 2000, Koskela et al. 2010): 1) master planning or milestones schedule; 2) phase scheduling, which is the division of the master planning in phases and can be considered the link between the long and medium term plans; 3) look ahead planning, which drives actions on detailing activities and addressing constraints; 4) weekly work plan or commitment planning, where the weekly plan is detailed and root causes for failures are identified and treated and; 5) learning, percentage of plan completed (PPC), which is a metric comparing what was planned with what was completed. LPS focuses on improving the reliability of plans by implementing a social process where plans are collaboratively created and transparent metrics are used to identify the reliability of commitments. LPS includes a continuous learning process where every broken commitment is analysed with a root cause analysis to ensure that the problem does not happen again (Ballard 2000). However, differently from CPM, LPS is usually not a contractual requirement, and shortcomings have been reported about its use in long term planning (Huber and Reiser 2003). In addition, based on our literature review, LPS has not been associated with the management of delays, changes, or contracts in construction. Thus, we would assume that the users of LPS would emphasize benefits related to PPM but not so much those related to contract or change management.

Project and production management in construction

This section presents the literature review used to develop the hypotheses considered in this study. It starts with a discussion about the use of CPM in construction projects, followed by potential explanations for its widespread use in the construction industry. Additional claims supported by the literature are made regarding the use of LB and LPS, and related hypotheses are presented. Additionally, the hypotheses address received traditions from the field of project management (e.g., CPM use as a contractual requirement) and how these materialize in construction projects (e.g., use of CPM to manage delays and claims).

Considering the vast documentation of CPM use in the literature, and also based on the authors' experiences, CPM is usually a contractual requirement in the United States (Galloway 2006) and it is largely used by contractors to address owners' requests for a baseline schedule once the project is awarded (e.g. Tavakoli and Riachi 1990). Thus, we hypothesize that:

Hypothesis 1 (**H1**): CPM is frequently used due to contractual requirements.

CPM was developed to organize the schedule activities toward a common goal, defining orders of the activities based on project technological requirements and using resources to determine durations of activities (Kelley and Walker 1959). The main output of a schedule is a long-term plan. In CPM, based on the order of activities, managers can define prioritizations about what work must be done first and in which sequence (Meredith and Mantel 2012). The critical path, which results from the calculations of the CPM algorithm, provides information about the longest path to complete a project and identifies activities for which a delay can impact the overall end date (Orouji et al. 2014). Previous research about the use of CPM (e.g. Galloway 2006) has not asked the respondents whether logic links are used in most or all of the tasks in their schedules. Therefore, the following hypothesis about the perceived association of CPM and critical path analysis is not trivial:

H2: CPM is the tool of choice for critical path analysis.

In construction, CPM has been used for strategic decisions and as a contract management tool (Galloway 2006). For example, after the definition of the project duration, cost can be allocated to the activities, creating a connection between the CPM schedule and Earned Value Analysis (EVA) and facilitating project performance analysis (e.g. Brown 1985, Sears et al. 2015). In light of the characteristics identified in the literature about CPM use, we hypothesize the following relationships between CPM and PM tasks:

H3: CPM is used to support the management of contractual requirements (e.g. schedule, preconstruction tasks, estimating/bidding, project understanding).

CPM has been used to analyse delays and changes (e.g. Arditi and Pattanakitchamroon 2006, Yang and Kao 2012), providing an early warning system for delay mitigation (Al-Reshaid et al. 2005). Furthermore, in the United States, CPM has been accepted by courts as a proper tool for delay analysis (Levin 1998). Thus, we hypothesize that:

H4: CPM is used to support the management of delays and claims.

Different from what is indicated in the literature for CPM schedules, the goal of LB systems is to achieve continuous flow, maximize the continuous use of labour, improve productivity, balance production, and improve the visualization of schedules. For example, the LBMS algorithm simplifies the schedules by focusing on repetitive tasks, logic-patterns, and heuristics to enable continuous workflow (Kenley and Seppänen 2010). LB schedules are usually developed based on the order of activities, take into consideration productivity rates of the resources, and define a long-term plan, which will be monitored during the control phase. The focus consists in achieving better workflow and better use of the resources, generating by consequence lower interruptions in production (Kenley and Seppänen 2010) and increasing productivity and production control (Lucko et al. 2014). Through the analysis of the project performance, which can be more visible in LBs, root causes of delays are investigated, aiming to solve production problems (Kenley and Seppänen 2010). Accordingly, we propose the following hypotheses:

H5: LB use is credited with generating continuous flow and improving the use of resources.

H7A: LB is credited with supporting and improving production control.

H8A: LB is credited with supporting and improving the identification of the root causes of delays.

Alternatively, LPS emphasizes that activities are inter-related and interfere with one another and have uncertainties and constraints, such as resources availability and preconditions of work, which must be treated before the work starts (Ballard 2000). LPS applies collaborative planning concepts, where workers are involved in the definition of common goals of the production system they are part of, and in a discussion of how to improve their productivity (Ballard 2000). Reported LPS benefits includes reduction of uncertainty and constrains (e.g. Ballard 2000), increased workflow reliability (e.g. Fiallo and Revelo 2002, Olano et al. 2009, Fernandez-Solis et al. 2013), fewer day-to-day problems (e.g. Kim et al. 2007), identification of the root causes of delays (e.g. Ballard 2000), and improved production control (Ballard and Howell 1998).

Considering these arguments about LPS, we propose the following hypotheses:

H6: LPS is credited with supporting and improving the analysis of constraints.

H7B: LPS is associated with supporting and improving production control.

H8B: LPS is credited with supporting and improving the identification of the root causes of delays.

While all the reported CPM benefits are related to PM topics, such as delays and change management, the reported benefits of LPS and LB are mostly related to PPM topics, such as generating workflow, reducing waste, and improving productivity. Therefore, we would expect, that the users of CPM perceive benefits related to PM but see challenges with PPM. The users of LPS and LB are expected to follow the opposite pattern and emphasize benefits related to PPM. Thus, based on the evidence from the literature review, it is assumed that while the users of CPM might emphasize PM related functions, practitioners using LPS and LB might emphasize PPM functions, given the fundamental focus and use of each tool. Accordingly, we hypothesize the following:

H9: The perceived benefits of CPM by users are mostly related to the PM approach.

H10: The perceived benefits of LB and LPS by users are mostly related to the PPM approach.

Figure 1 shows the hypotheses and summarizes the two main lines of work addressed in the literature review, Project Management and Project Production Management, how the systems discussed relate to each, and what functions they support (e.g. contractual management, management of delay and change, and promotion of continuous workflow). A project manager is usually required to manage the effective implementation of planning, scheduling, estimating and cost control, contract management and purchasing (Edum-Fotwe and McCaffer 2000). Thus, in this paper, topics identified as contract management, such as scheduling and time control, were grouped into PM topics, namely: contractual requirement, critical path analysis, managing contracts, and management of delays and change. On the other hand, topics identified as production control were grouped in PPM topics, namely continuous flow and resources, reduction of uncertainty and constrains, identification of root causes of delays, and improvement of production control. The same approach was used when identifying questions related to each topic. Thus, while questions related to contract management, scheduling and time control were correlated with PM topics, questions exploring production control aspects were correlated with PPM topics.

Insert Figure 1 about here

Research method

In this paper, the survey research design process suggested by Forza (2002) was adopted, containing six steps: 1) link to the theoretical level, 2) design, 3) pilot test, 4) collect data for theory testing, 5) analyse data, and 6) generate report. In general, a survey is a collection of information from individuals (Rossi et al. 2013). Additionally, before the data collection started, a research protocol was submitted to the Institutional Review Board at Towson University (protocol # 1612011775) and approved.

Based on the literature review, the unit of analysis defined was the production planning and controlling systems CPM, LB, and LPS. The hypotheses were proposed based on the literature review. Aiming to test the hypotheses and gather quantitative data, a questionnaire survey was developed. To gain focus, reduce variation and simplify analysis, purposeful sampling was adopted for the case selection approach (Patton 1990). Architects, engineers, and construction managers working with construction management were defined as the target. Brazil, China, Finland, and the United States were selected as primary data collection countries; these countries have several documented case studies of each type of planning and controlling system. Furthermore, collecting data across multiple countries can allow for future work of cross-culture analysis.

The first draft of the questionnaire was developed in English language. The questions were proposed based on the literature review and previous research of Tavakoli et al. (1990), Galloway (2006), and Khan and Kim (2015). After that, the questions were validated by a team formed by professionals from Aalto University (Finland), San Diego State University (USA), Towson University (USA), North Carolina State University (USA) and University of Campinas (Brazil), which are working in a wider research effort investigating management in construction. A pilot test with five master's students in Brazil and ten master's students in the United States was done, and after gathering feedback from these students, adjustments were made, such as logic rules and definitions, contributing to the modification and finalization of the document. The questionnaire was then translated to Portuguese, Chinese, and Finnish languages, and two native speakers in each language validated each version.

The final version of the questionnaire is structured in four parts (see supplemental document). The first section contains questions about professional experience in production planning and control systems, companies, and culture. At the end of section 1, respondents were able to select the systems they had experience with (CPM, LPS, and/or LB). Aiming to facilitate the respondents' understanding of the systems and reducing possible doubts about the concepts related to them, a brief description of each system was inserted in the beginning of the survey. The questionnaire was configured to show only questions about the system that the respondent selected. For example, if the respondent indicated the use of CPM and LB, only questions about CPM and LB were presented to be answered. Sections 2, 3 and 4 of the survey contain questions about CPM, LPS, and LB, respectively. The online platform Qualtrics was used as the survey software (Qualtrics 2017).

Considering that directly interviewing each of the 500+ anonymous respondents and also directly observing their use of each tool is not feasible, a survey was used to capture their opinions and perceptions. Although this is a limitation, this paper offers the construction engineering and management community a discussion based on what is stated (broadly) in the literature and what practitioners themselves experience. Claims stated in the literature reviewed are based on either smaller samples than what is reported in this paper or observations from a much smaller number of examples. To our knowledge, this is the first study comparing these three systems using a single instrument, with similar survey language for all three methods (covering uses, advantages, disadvantages), and translated to four different languages in order to address practices on different continents (Asia, Europe, and North/South America).

A goal of 100 valid responses from each country was established by the research team to support the validity of findings. Moreover, by targeting 100 responses per country normality was assumed, via the Central Limit Theorem (CLT), and allowing for variation without misrepresentation of outliers as trends. Additionally, the team used Galloway's (2006) research on a similar topic published in this journal, as a comparator. Her study had over 400 responses, like the present one, and different organizations were also contacted to help and distribute the survey. Similar to our study, Galloway (2006) did not indicate the total population numbers to compare to the 430 responses obtained, as it would not be feasible to determine the entire population of construction industry practitioners who could be potentially targeted by these surveys in four different countries.

Furthermore, the authors did not use any incentive to promote or increase the response rate; no specific organization or field was targeted by the authors to avoid any bias in the responses received.

The survey was distributed via many channels: 1) the survey link was posted by the research team in social media platforms such as LinkedIn and Research Gate, 2) construction industry institutes in the four countries were asked to distribute the survey among companies and construction management professionals, 3) construction companies and universities were contacted to share the survey link with their employees, 4) the research team shared the survey link with their own professional network. The survey was distributed and remained open for collecting data during six months, from January to June of 2017.

After finalizing the data collection, data was treated and cleaned through the following steps: 1) data was exported from Qualtrics to the software IBM® SPSS® Statistics 25 (IBM 2018); 2) a unique SPSS file was created, containing data from the four countries; 3) aiming to track responses, a code number was inserted for each response; 4) aiming to facilitate analysis, unnecessary columns were excluded, such as dates of responses, and remaining columns were renamed, replacing codes by titles (e.g., country, industry, position); 5) responses were excluded if the respondent did not accept the terms of the survey; 6) as the focus was the four countries, responses were excluded if where the respondent was working in a country other than Brazil, China, Finland or the United States; 7) responses were excluded where the respondent had not selected at least one planning and controlling system (CPM, LPS, or LB). Furthermore, during data cleaning, it was discovered that a logic error existed in the Chinese translation of the survey, which resulted in no system questions appearing for respondents who chose LPS as a system used. Therefore, 54 Chinese participants who had selected LPS as a system did not see any follow-up questions; data for that system in that country was not collected. To ensure consistency in comparative analysis, all Chinese respondents who selected LPS as a method were removed from the data. There were other cases with missing data. Much of the missing data was random but survey fatigue caused some systematically missing data where respondents dropped out of the survey in the middle and did not answer remaining questions. Respondents were not forced to answer any question in the survey that was specific to a method, and some respondents simply skipped questions that were presented to them. In analysis, these missing data points were taken into account by list-wise deletion.

Data related to demographics (first part of the questionnaire) was used to obtain the general profile of the respondents. To evaluate the hypotheses, questions related to each topic in the model of Figure 1 were identified and analysed. See Table 1 for each hypothesis and related data. Chi-squared non-parametric tests were run in Excel to analyse differences between planning systems related to each question. Additionally, aiming to identify the perceived benefits that CPM respondents see when using CPM associated with LPS or LB (or both), a filter was applied to identify those respondents with the questions then analysed.

Insert Table 1 about here

Results

Demographics

The survey initially resulted in a collection of 736 responses. After cleaning the data using the seven steps previously discussed, 532 responses remained: 168 from Brazil, 102 from China, 132 from Finland and 130 from the United States. The profile of the respondents is shown in Table 2, where the percentage indicates the number of responses for each topic with the number of total responses obtained (532).

Insert Table 2 about here

A large number of respondents (67%) work in residential or commercial buildings, followed by smaller percentages in industries such as infrastructure (8%) and Oil and gas (6%). For the other industries indicated in the survey, less than 5% of respondents work in each industry. For the most part, respondents work in organizations that represent construction contractors or subcontractors (32%), whereas 19% are self-identified as belonging to engineering organizations, owner (17%), and construction management (16%). Most respondents (21%) belong to organizations that have between 101-500 employees; however, about 35% of organizations have over 1,000 employees. Most respondents are project managers (17%), followed by project engineers (15%), executive officer (14%), or staff (13%). Schedulers (12%) and superintendents (7%) composed about a fifth of the respondents. Most respondents work in multiple areas related to management (55%), planning and control (52%), budgeting (30%), quality or technology (27%) and production (27%).

Planning and control systems

The survey results show in Table 3 that CPM is used by close to three fourths of respondents (71%), followed by LB (40%) and LPS (28%). The use of the planning and control systems distributed by topic is shown in Table 2, where the percentage indicates the number of responses by topic divided by the number of responses by system. Please note that a respondent may be using multiple systems, so the percentages across rows in Table 2 may add to be greater than 100%. CPM is the dominant system used in all types of primary industry, where responses were obtained. Although LB is not the most used system in residential and commercial buildings, even though the projects usually present characteristics of repetition, a high percentage (46%) of the responses indicates LB use. On the other hand, in addition to buildings (32%), LPS is commonly used in healthcare projects (56%) and other projects (28%), such as datacentres and schools.

CPM is the dominant system in all types of organizations, especially construction management (82%), supplier (75%), construction contractor or subcontractor (74%), and engineering (73%) companies. Surprisingly, LB is highly used by designers (48%), besides construction contractors or subcontractors and suppliers (50% each). CPM use is expressively cited by government organizations (69%). In terms of organization size, CPM is the most representative system of all. However, despite the evident dominance of CPM, LB is well used in organizations with less than 50 employees (49%) and between 1001 and 5000 employees (45%). LPS use is expressive in companies that have between 501 and 1000 employees (34%) and between 1001 and 5000 employees (40%).

All kinds of professionals have indicated CPM as the dominant system, including schedulers (81%), department heads (80%), project managers (74%) and project engineers (71%), which indicates that CPM is widely used in different levels of management. On the other hand, LB is highly used by superintendents (54%) and those in staff positions (55%), LPS is well referred by department heads (39%) as well. When analysing by area, CPM is the most representative system of all, especially in quality or technology (78%), in management (75%), planning and control (75%), budgeting (75%), and supply chain (75%). LB and LPS systems are highly used in production (60% and 40%, respectively), planning and control (52% an 36%, respectively), and consultancy (47% and 38%, respectively) areas.

Table 3 shows the number of users in each country who indicated use of the systems, working alone or combined with other systems.

Insert Table 3 about here

CPM is the most used system (71%), followed by LB (40%) and LPS (28%). Furthermore, CPM is the most used system in all the countries.

Project management and production management

Topics and data from hypotheses listed in Table 1 were evaluated by non-parametric Chi-squared tests. The results are shown in Table 4. The number of people who answered each question related to a hypothesis is shown by system. Those numbers are used to calculate percentages by system as well as both the Chi-squared test statistics and *p*-value for each question. The *p*-value is based on the comparison of all three systems. If a significant result was found, post-hoc tests were done on each pair of systems to detect individual differences. Significant findings are reported with asterisks in the table: three asterisks denote significance at 0.001; two asterisks denote significance at 0.01, and one asterisk denotes significance at 0.05.

Insert Table 4 about here

Survey results show that while CPM was indicated by 20% of the respondents as a contractual requirement, LB and LPS systems were indicated only by 8% and 2% of the respondents respectively. In a comparison between the systems, CPM users selected this option statistically significantly more often than LB and LPS users. Additionally, 79% of the CPM users frequently use the critical path analysis, which is statistically significant when compared to performing critical path analysis in a LB or LPS system.

Data from four survey questions were evaluated when analysing the topic ‘managing contracts’. CPM, LB and LPS systems were compared in terms of 1) improves scheduling, 2) improves planning before work starts, 3) improves estimating and bidding, and 4) improves understanding of the project. The results show no statistical difference for these topics, except for improving planning before the work starts where both CPM and LPS users selected that benefit statistically significantly more often than LB users. On the other hand, results from the questions related to management of delay and change showed statistically significant differences only related to the benefits of reducing delays and minimizing disputes between the contractor and owner. With respect to disputes, LPS had a statistically significant difference compared to LB users. For other questions, no statistically significant differences existed between the perceived benefits identified by the users of each system.

Two questions were analysed when evaluating continuous flow and continuous use of resources. In terms of workflow improvement and evaluation of workflow, LB and LPS users indicated benefit of improved workflow or evaluated that workflow works well or very well when using LB or LPS compared to CPM. When evaluating the perceived benefits in the context of improving constraints analysis and how this analysis works, LPS users expressed the benefit of improving constraint analysis statistically significantly more often than CPM or LB users; those users also favourably evaluated constraint analysis statistically significantly more often than CPM users. LPS is considered a well-known system used for the treatment of interferences between activities as well as reduction of uncertainty and constraints. In terms of improving production control, LB and LPS users both have statistically significant perceived benefits when compared to CPM users for the questions related to production control. Similarly, both LB and LPS have perceived benefits associated with faster response to problems. On the other hand, CPM, LB and LPS systems have no statistically significant differences when comparing the evaluation of root cause of delays. However, the benefit of root cause analysis was statistically significant for LPS users when compared to both LB and CPM users.

Because CPM is the dominant scheduling system in the survey, it is possible that respondents who selected just CPM are not fully aware of the strengths and drawbacks of the system compared to other tools. To evaluate this, we analysed separately those CPM users who also used either LPS or LB. These results are shown in Table 5. Overall, these results are in line with the results of the full sample (Table 4). However, there are some ~~minor~~ differences in the patterns of statistically significant results. The discussion below focuses on the differences.

CPM was still dominant as a contractual requirement, but surprisingly it was no longer chosen the tool of choice for critical path analysis with statistically significant results. CPM was also credited with improving planning before work starts alongside the LPS when compared to LB methods. Additionally, the benefit of CPM improving estimating and bidding was emphasized in the partial sample that used multiple systems. CPM and LPS both were seen to increase understanding of the project when compared to LB methods, while there was no statistical significance on this aspect with the full sample. With respect to delay management, the perceived advantage of LPS for the benefit of minimizing disputes between contractor and owner does not exist in the partial sample.

Differences arose when evaluating continuous flow and continuous use of resources. With the full sample, users of both LB and LPS indicated statistically significantly more often benefit of improved workflow over CPM users. With the partial sample, this result was no longer statistically significant, and the benefit of LPS compared to CPM decreased. With the partial sample, LPS users selecting well to very well workflow rose from 69% of respondents to 74% of respondents, and LPS and LB both statistically significantly overperformed CPM. This is significant because the subset sample is certainly comparing the performance of LPS and/or LB to CPM. In a similar fashion, the statistical significance was consistent for the constraint analysis function of LPS (Hypothesis 6).

In terms of improving production control as a benefit, the systems do not show statistically significant differences within the limited sample (the full sample had a statistically significant effect for LB and LPS methods), indicating that the respondents who use CPM with LB and/or LPS think that each system has a role to play in production control. However, for evaluation of production control, LB and LPS were statistically significant in the full sample and in the partial sample. For root cause working well to very well, LB and LPS are statistically significant when compared to CPM.

Insert Table 5 about here

Discussion

A comparison between the findings of literature review and survey results is presented in this section alongside Table 6, which presents a summary of results.

Hypothesis 1 considers the use of CPM as a contractual requirement. Galloway (2006) applied a survey in the United States where 63% of the respondents indicated contract requirement as the main reason for using CPM scheduling. Furthermore, 72.5% of the owners who answered the same survey specify CPM schedule in their contracts. Thus, it is expected that CPM is largely used within the construction sector due to its contractual requirements. Findings from this current survey indicates that CPM is used by 71% of the respondents, and 20% of those indicated contractual requirement as the main reason for using CPM, which is statistically significantly higher compared with other systems. Hence, this hypothesis is supported by survey results. In contrast to Galloway (2006), we were not asking respondents if CPM was indeed a contractual requirement, but instead we inserted contractual requirement as one of the options for the main reason for using CPM. This might explain the differences between percentages presented by Galloway (2006) and these results. However, given the contractual requirement of CPM, professionals do not seem to view using the method begrudgingly; as previously discussed, CPM is viewed favourably and **hypothesis 1 is supported**.

Hypothesis 2 refers to the associated use of critical path analysis and CPM. The critical path analysis is a fundamental basis of CPM (Kelley and Walker 1959). Accordingly, it is expected that the use of CPM is associated with critical path analysis. A statistically significant higher share of CPM users compared to LB and LPS users indicated frequent or moderate use of this analysis when managing schedules (79%); survey results support this hypothesis. This result was no longer statistically significant when a limited sample including those respondents who used CPM together with LB or LPS was considered; however, CPM still achieved the highest share of responses (CPM: 75%, LB: 68%, LPS: 61%). This continues to support the literature and established industry trends and **supports hypothesis 2**.

Hypothesis 3 explores the use of CPM with managing contracts, which is indicated by findings from the literature review. Furthermore, due to the fact that CPM is usually a contractual requirement, it is expected that CPM supports the management of contracts. Results from the questions associated with this topic show that all systems have perceived benefits associated with improving schedules (CPM 70%, LB 63%, LPS 76%), planning before work starts (CPM 52%, LB 36%, LPS 49%), estimating/bidding (CPM 30%, LB 27%, LPS 20%) and understanding of the project (CPM 52%, LB 42%, CPM 49%). The differences were statistically significant only with improving planning before the work starts, where CPM and LPS both had statistically significant higher perceived benefits than LB. Additionally, with the limited sample of CPM users who also used also another system, improving the estimating and bidding phase was significantly perceived as a benefit related to CPM. In the limited sample, understanding the project was statistically significant for CPM and LPS when compared to LB. Thus, although CPM has been used for managing contracts in terms of scheduling, other systems also have a role to play related to this category. Considering the results of the full sample, **hypothesis 3 is not supported**.

Hypothesis 4 refers to the use of CPM for delay and claim management. CPM has historically been used for contract claims and analysis of delays (e.g. Wickwire and Smith 1974, Hegazy and Menesi 2010). On the other hand, literature exploring the use of LB and LPS systems associated with claim and delays analysis is scarce. However, when analysing questions in this survey related to reducing delays and reduction of disputes between contractor and owner, LPS, and not CPM, was statistically significantly perceived to reduce delays and minimize disputes. Thus, because delays and claims are managed with all the systems, and LPS outperformed CPM twice, **hypothesis 4 is not supported**. This approach might be justified due to the social characteristic aspects of LB and LPS, which aims for collaborative definition and discussion involving the project team and subcontractors (e.g. Ballard 2000, Kenley and Seppänen 2010), which increases the level of trust and reflects in reduction of delays, for example. The respondents could have thought about the role of LB and LPS in preventing claims rather than analysing a claim in dispute.

Hypothesis 5 explores the ability of the systems for generating continuous flow and continuous use of resources. As expected, LB and LPS users reported improved workflow as a benefit statistically significantly more often than CPM users (CPM: 44%, LB 54%, LPS 64%). Additionally, a significantly higher share of LB and LPS users were satisfied with the workflow functions of their system than CPM users. **Therefore, hypothesis 5 is supported**.

Due to its social aspects and findings from literature review, LPS is usually well associated with the reduction of interferences between activities, uncertainty, and constraints, as explored by **Hypothesis 6**. Indeed, 49% of LPS users indicated improving constraints analysis is a benefit of this system, which is a statistically significant difference compared with CPM users (23%) and LB users (27%). Similarly, when constraint analysis was evaluated, 65% of LPS users reported that it works well or very well which was a statistically significant difference compared with CPM users, where just 46% of the users evaluated this topic favourably. With the partial sample, the differences hold and also include LB overperforming CPM in constraint analysis evaluation. Therefore, **hypothesis 6 is supported**.

Hypotheses 7A and 7B refer to the support and improvement of production control. These hypotheses received full support from the survey results. Both LB and LPS systems had perceived benefits associated with production control. Both LPS and LB had statistically significant benefits with improvement of production control (64% and 58% of users, respectively), good evaluation of how the production control process works (76%% and 73% of users, respectively), and higher benefits associated with faster response to problems (53% and 29% of users, respectively), which all contribute to the improvement of production processes. The significance of the p-value was stronger with the partial sample for evaluation of production control process and response time for problems. However, in the partial sample, overall improvement of production control was not statistically significant. This indicates that while users of LB and LPS saw these systems stronger with respect to production control functions, they considered that CPM also had a role to play in improving production control. Considering the results of the full sample, **hypotheses 7A and 7B are supported**.

Hypotheses 8A and 8B refer to the identification of root causes of delays. A statistically significantly higher share of LPS users selected this benefit when comparing with CPM and LB users (CPM: 23%, LB: 22%, LPS: 36%). However, the evaluation about working well or very well had no statistically significant differences across the systems (CPM: 38%, LB: 50%, LPS: 45%). However, when the partial sample was considered, both LB and LPS were statistically significantly evaluated better than CPM (CPM: 29%, LB 44%, LPS 50%) in evaluation of root causes. Considering the full sample, **hypothesis 8 is partially supported**. In the full sample, 38% of CPM indicated that root cause evaluation works very well or well; this was not statistically significantly lower than the result for LB and LPS. This finding might be associated with the expressive use of CPM for managing contracts (Galloway 2006) and delays (e.g. Hegazy and Menesi 2010). For example, if CPM is mandated to be used, and a delay occurs, personnel will find a root cause regardless if the planning method facilitates a quick identification of such. A limitation of this topic could be respondents' understandings of root cause analysis, which may impact the results.

Hypothesis 9 refers to CPM perceived benefits being mostly related to the PM approach, including the topics illustrated in Figure 1: 1) contractual requirement; 2) critical path analysis; 3) managing contracts; and 4) management of delay and change. In general, the survey results support topics 1 and 2, showing that CPM users selected these benefits significantly more often than the users of LB and LPS systems. On the other hand, there was not strong support for management of contracts and delay and change management. The differences related to improving scheduling, estimating or bidding, improving understanding of the project had no significant perceived differences between the systems. Very few users of any system selected claims documentation as their primary goal of scheduling systems, and LPS users selected the benefits related to delay reduction and minimizing disputes significantly more often than CPM users. Because contract management and delays are an important part of PM functions, it seems that all systems could have a role to play within the scope of PM. Thus, **hypothesis 9 is not supported**.

Hypothesis 10 discusses that LB and LPS perceived benefits are mostly related to PPM, including the topics illustrated in Figure 1: 1) continuous flow and resources; 2) interferences, uncertainty and constraints; 3) improving production control; and 4) identification of the root cause of delays. In general, the survey results for the full sample support most topics, except for the evaluation of root causes. Thus, the results of the full sample **support hypothesis 10**.

Insert Table 6 about here

Support to hypotheses 6 and 10 depends on whether the full or partial sample was used. It can be argued that the respondents who are familiar with multiple approaches are able to differentiate between the benefits of the systems better. Based on these differences it seems that CPM users who are not familiar with the other systems may not even be aware of the relative strengths and limitations of CPM.

Conclusion

This research explores the differences between CPM, LB and LPS in terms of PM, PPM, and related topics. First, the results show that CPM is the most dominant system when the following characteristics are considered: primary industry types, type of organization, size of organization, and professional position within the organization and area of work. Secondly, while CPM is a contract requirement and has perceived benefits associated with critical path analysis, LB and LPS have perceived benefits related to continuous flow and continuous use of resources, treatment of interferences, reduction of uncertainty and constraints, and improving production control. All systems were found to have a similar level of benefits in terms of management of contracts, and management of delay and change, and evaluation of the root causes of delays. Finally, LB and LPS have particular topics associated with both PM and PPM as the analyses conducted for hypotheses 1 through 4 have shown. Conversely, CPM was not found to support project production management as observed in the analyses regarding hypotheses 5 through 8, which were strongly supported by the data favouring LPS and LB as better suited to support PPM.

Theoretical implications of this study contribute to supporting well-established notions, especially in the Lean literature, that LPS and LB offer more support to project production management with generation and maintenance of continuous flow. Additionally, as identified in the literature, a growing body of research has been focusing on the integration of the systems, and this study offers insights in terms of how practitioners might use these systems. Specifically, our results show that CPM is used for critical path analysis, LB and LPS are used for improving production control and workflow functions, and support faster response and reduction of interferences between activities, uncertainty, and constraints. There is no difference between the systems for the management of contracts, delay and claim management, and evaluation of root causes of delays. However, for projects that require production control and faster response to problems, LB and LPS may be preferred methods, respectively. Furthermore, the popularity of CPM may be masking the benefits of the other methods; if more professionals used LB and LPS, they may find more success with those methods.

Clearly, the needs of the project may drive the best management technique to be used for planning and scheduling. These trends exist internationally, and across the industry, regardless of country. Industry norms are challenged as no statistical difference exists among the three systems in most of the topics associated with managing contracts (i.e., improves scheduling, bidding, and estimating; improves understanding of the project), and some of the delay and claim management benefits (i.e., evaluation of delays). It is clear that these findings can help to eliminate misunderstanding about the benefits of these systems to the industry. Future development of case studies may help address questions related to improving the performance of projects in terms of efficient contract management, value generation, and flow creation. Future research by the authors will compare CPM, LB, and LPS from the perspective of countries, exploring underlying differences among the systems and countries.

Practical implications include identifying areas of interest to further integrate these systems into a single platform or to develop systems that are able to address all relevant features that any of these systems might address individually. CPM has an enormous advantage in terms of use in the construction industry due to the familiarity of practitioners with this approach, the existence of well-established software platforms to operationalize its use, and its acceptance as a legal document. However, to break through the status quo and incorporate other tools and ideas more suitable to the management of operations, the change might need to start in academia where the new generation of practitioners will be trained and familiarized with the need to more closely manage production as an extension of managing contracts. The insights on the strength and weakness of each method from industry practitioners' first-hand experience sets a foundation of a starting point for further development of scheduling methods. This research identifies the utility and function for each method and identifies potential areas of interest for the integration of the analysed systems by promoting synergies between the methods.

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Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request.

References

Al-Reshaid, K., Kartam, N., Tewari, N., and Al-Bader, H., 2005. A project control process in pre-construction phases: Focus on effective methodology. *Engineering, Construction and Architectural Management*, 12 (4), 351–372.

Alsehaimi, A.O., Fazenda, P.T., and Koslela, L., 2014. Improving construction management practice with the last planner system: A case study. *Engineering, Construction and Architectural Management*, 21 (1), 51–64.

Antill, J.M., and Woodhead, R.W., 1990. *Critical path methods in construction practice*. New York: John Wiley & Sons.

Arditi, D., Tokdemir, O.B., and Suh, K., 2002. Challenges in line-of-balance scheduling. *Journal of Construction Engineering and Management*, 128 (6), 545–556.

Arditi, D., Pattanakitchamroon, T., 2006. Selecting a delay analysis method in resolving construction claims. *International Journal of Project Management*, 24, 145–155.

Ballard, H.G., 1997. Look ahead planning, the missing link to production control. *In: Proc. of 5th Annual Conference of the International Group for Lean Construction*. Gold Coast.

Ballard, H.G., and Howell, A., 1998. Shielding production: Essential step in production control. *Lean Construction Journal*, 1 (1), 38–45.

Ballard, H.G., 2000. *The last planner system of production control*. Thesis (Doctor of Philosophy), School of Civil Engineering, University of Birmingham.

Benjaoran, V., Tabyang, W., and Sooksil, N., 2015. Precedence relationship options for the resource levelling problem using a genetic algorithm. *Construction Management and Economics*, 33 (9), 711–723.

Bragadin, M.A. and Kähkönen, K., 2016. Schedule health assessment of construction projects. *Construction Management and Economics*, 34 (12), 875–897.

Brown, J.W., 1985. Evaluation of projects using critical path analysis and earned value in combination. *Project Management Journal*, 16 (3), 59–63.

Burns, S.A., Liu, L., and Feng, C.W., 1996. The LP/IP hybrid method for construction time-cost trade-off analysis. *Construction Management and Economics*, 14 (3), 265–276.

Edum-Fotwe, F.T. and McCaffer, R., 2000. Developing project management competency: perspectives from the construction industry. *Intnl. J. of Project Management*, 18, 111–124.

Fernandez-Solis, J.L., Porwal, V., Lavy, S., Shafaat, A., Rybkowski, Z.K., Son, K., and Lagoo, N., 2013. Survey of motivations, benefits, and implementation challenges of Last Planner System users. *J. of Construction Engineering and Management*, 139 (4), 354–360.

Fiallo, C.M., and Revelo, P.H.V, 2002. Applying the last planner system to a construction project: Case study in Quito, Ecuador. *In: Proc. of 10th Annual Conference of the International Group for Lean Construction*. Gramado.

Forza, C., 2002. Survey research in operations management: A process-based perspective. *Intnl. J. of Operations & Production Management*, 22 (2), 152–194.

Frandson, A., Berghede, K., and Tommelein, I.D., 2013. Takt time planning for construction of exterior cladding. *In: Proc. of 21th Annual Conference of the International Group for Lean Construction*. Fortaleza.

Galloway, P.D., 2006. Survey of the construction industry relative to the use of CPM scheduling for construction projects. *J. of Construction Engineering and Management*, 132 (7), 697–711.

Hamzeh, F., Ballard, G., and Tommelein, I.D., 2012. Rethinking look ahead planning to optimize construction workflow. *Lean Construction Journal*, 1 (1), 15–34.

Hamzeh, F., Kankoul, E., and Rouhana, C., 2015. How can 'tasks made ready' during lookahead planning impact reliable workflow and project duration? *Construction Management and Economics*, 33 (4), 243–258.

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

Hegazy, T., 2005. Computerized system for efficient scheduling of highway construction. *J. of the Transportation Research Board*, 1907, 8–14.

Hegazy, T. and Menesi, W., 2010. Critical path segments scheduling technique. *J. of Construction Engineering and Management*, 136 (10), 1078–1085.

Howell, G.A., and Ballard, G., 1994. Lean production theory: Moving beyond "Can-Do". *In: Proceeding of International Workshop on Lean Construction*. Santiago de Chile.

Huber, B., and Reiser, P., 2003. The marriage of CPM and lean construction. *In: Proceeding of 11th Annual Conference of the International Group for Lean Construction*. Blacksburg.

IBM, 2018. [online]. Available from: https://www.ibm.com/fi-en/marketplace/spss-statistics [Accessed 19 January 2018].

Johnston, D.W., 1981. Linear scheduling method for highway construction. *J. of the Construction Division,* 107 (2), 247–261.

Kelley, J.E. and Walker, M., 1959. Critical path planning and scheduling. *In: Proceeding of Eastern Joint Computer Conference*.

Kenley, R. and Seppänen, O., 2010. *Location-based management for construction: Planning, scheduling and control*. Abingdon: Spon Press.

Kemmer, S.L., Heineck, L.F.M., and Alves, T.C.L., 2008. Using the line-of-balance for production system design. *In: Proc. of 16th Annual Conference of the International Group for Lean Construction*. Manchester.

Khanh, H.D., and Kim, S.Y., 2016. A survey on production planning system in construction projects based on last planner system. *KSCE Journal of Civil Engineering*, 20 (1), 1–11.

Kim, Y.W., Park, C., and Ballard, G., 2007. A case study on rebar supply chain management by GS E&C. *In: Proc. of 15th Annual Conference of the International Group for Lean Construction*. Michigan.

Kim, W., Ryu, D., Jung, Y., 2014. Application of linear scheduling method (LSM) for nuclear power plant (NPP) construction. *Nuclear Engineering and Design*, 270, 65–75.

Koskela, L., 1999. Management of production in construction: A theoretical view. *In: Proc. of 7th Annual Conference of the International Group for Lean Construction*. Berkeley.

Koskela, L., and Howell, G., 2002. The underlying theory of project management is obsolete. *In: Proceeding of the PMI Research Conference,* PMI, 293–302.

Koskela, L., Startton, R., and Koskenvesa, A., 2010. Last planner and critical chain in construction management: Comparative analysis. *In: Proc. of 18th Annual Conference of the International Group for Lean Construction*. Haifa.

Koskela, L., Howell, G., Pikas, E., and Dave, B., 2014. If CPM is so bad, why have been using it so long. *In: Proc. of 22th Annual Conference of the International Group for Lean Construction*. Oslo.

Laufer, A., and Tucker, R.L., 1987. Is construction project planning really doing its job? A critical examination of focus, role and process. *Construction Management and Economics*, 5 (3), 243–266.

Levin, P., 1998. *Construction contract claims, changes and dispute resolution*. New York: ASCE Press.

Lucko, G., Alves, T.C.L., and Angelim, V.L., 2014. Challenges and opportunities for productivity improvement studies in linear, repetitive, and location-based scheduling. *Construction Management and Economics*, 32 (6), 575–594.

Lumsden, P., 1968. *The line of balance method*. London: Pergamon Press.

Mattila, K.G., and Park, A., 2003. Comparison of linear scheduling model and repetitive scheduling method. *J. of Construction Engineering and Management*, 129 (1), 56–64.

Meredith, J.R., and Mantel, S.J., 2012. *Project management: a managerial approach*. Danvers: John Wiley & Sons.

Olano, R.M., Alarcón, L.F., and Razuri, C., 2009. Understanding the relationship between planning reliability and schedule performance: A case study. *In: Proceeding of 17th Annual Conference of the International Group for Lean Construction*. Taipei.

Olawale, Y., and Sun, M., 2015. Construction project control in the UK: Current practice, existing problems and recommendations for future improvement. *International Journal of Project Management*, 33, 623–637.

Olivieri, H., Seppänen, O., and Granja, A.D., 2016. Integrating LBMS, LPS and CPM: A practical process. *In: Proc. of 24th Annual Conference of the International Group for Lean Construction*. Boston.

Olivieri, H., Seppänen, O., and Granja, A.D., 2018. Improving workflow and resource usage in construction schedules through location-based management system (LBMS). *Construction Management and Economics*, 36 (2), 109–124.

Orouji, H., Haddad, O.B., Fallah-Meddipour, E., and Marino, M.A., 2014. Extraction of decision alternatives in project management: Application of hybrid PSO-SFLA. *J. of Management in Engineering*, 30 (1), 50–59.

Patton, M.Q., 1990. *Qualitative evaluation and research methods*. Thousand Oaks: Sage Publications.

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

Qualtrics, 2017. [online]. Available from: http://www.qualtrics.com/ [Accessed 14/12/2017].

Rossi, P.H., Wright, J.D., and Anderson, A.B., 2013. *Handbook of survey research*. Academic Press.

Russell, A.D. and Wong, W.C.M., 1993. New generation of planning structures. *J. of Construction Engineering and Management*, 119 (2), 196–214.

Sacks, R., 2016. What constitutes good production flow in construction? *Construction Management and Economics*, 34 (9), 641–656.

Schmenner, R.W. (1993). *Production/Operations Management*. Englewood Cliffs, N.J.: Prentice Hall, 825 pp.

Sears, S.K., Sears, G.A., Clough, R.H., Rounds, J.L., and Segner, R.O., 2015. *Construction project management*. New Jersey: John Wiley & Sons.

Shi, Q., and Blomquist, T., 2012. A new approach for project scheduling using fuzzy dependency structure matrix. *International Journal of Project Management*, 30(4), 503–510.

Tavakoli, A., and Riachi, R., 1990. CPM use in ENR top 400 contractors. *J. of Management in Engineering*, 6 (3), 282–295.

Wickwire, J.M., and Smith, R.F., 1974. The use of critical path method techniques in contract claims. *Public Contract Law Journal*, 7 (1), 1–45.

Willis, C, and Friedman, D., 1998. *Building the Empire State Building*. New York: W.W. Norton & Company.

Yang, J.B., and Kao, C.K., 2012. Critical path effect based delay analysis method for construction projects. *Intnl. J. of Project Management*, 30, 385–397.

Figure Caption List:

Figure 1: Systems characteristics and related functions

Table 1: Reported functions fulfilled by each system and related questions

Topics and hypotheses	**Analyzed data**
H9. Project Management	Joint analysis of **H1** through **H4**.
H1. Contractual requirement	Number of "contract requirements," option selected in questions 8, 24 and 38
H2. Critical path analysis	Number of answers for "frequently" and "moderate" in questions 16, 31 and 46
H3. Managing contracts	Number of answers for "improves scheduling", "improves planning before work starts", "improves estimating / bidding" and "improves understanding of the project" in questions 21, 35 and 50
H4. Management of delay and change	Number of answers for "claims documentation" in questions 8, 24 and 38, "reduce delays" and "minimizes disputes between contractor and owner in questions 21, 35 and 50, and "delays analysis – options definitively works very well and works well" in questions 23, 37 and 52
H10. Production Management	Joint analysis of **H5** through **H8A/B**.
H5. Continuous flow and continuous use of resources	Number of answers for "improves workflow" in questions 21, 35 and 50, and "workflow – options definitively works very well and works well" in questions 23, 37 and 52
H6. Treatment of interferences between activities, reduction of uncertainty and constraints	Number of answers for "improves constraints analysis" in questions 21, 35 and 50, and "constraints analysis – options definitively works very well and works well" in questions 23, 37 and 52
H7A and H7B. Improving production control	Number of answers for "improves production control" and "faster response to problems" in questions 21, 35 and 50, and "effective production control – options definitively works very well and works well" in questions 23, 37 and 52
H8A and H8B. Identification of the root causes of delays	Number of answers for "improve root causes analysis of deviations and action plans" in questions 21, 35 and 50, and "root causes analysis of deviations and action plans – options definitively works very well and works well" in questions 23, 37 and 52

Table 2: Profile of the respondents and used planning and control systems

Topic		Total and % of responses	Planning and control system (within system % of responses)		
			CPM	**LB**	**LPS**
Primary Industry	Buildings	356 (67%)	248 (70%)	163 (46%)	114 (32%)
	Infrastructure	43 (8%)	33 (77%)	12 (28%)	2 (5%)
	Oil and gas	34 (6%)	25 (74%)	12 (35%)	9 (26%)
	Other	32 (6%)	18 (56%)	10 (31%)	9 (28%)
	Pharmaceutical	23 (4%)	20 (87%)	3 (13%)	3 (13%)
	Power	20 (4%)	15 (75%)	5 (25%)	3 (15%)
	Healthcare	9 (2%)	8 (89%)	4 (44%)	5 (56%)
	Process	9 (2%)	7 (78%)	3 (33%)	2 (22%)
	Transportation	6 (1%)	6 (100%)	1 (17%)	0 (0%)
	Aerospace	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Type of organization	Contractor or subcontractor	171 (32%)	126 (74%)	86 (50%)	66 (39%)
	Engineering	101 (19%)	74 (73%)	31 (31%)	23 (23%)
	Owner	90 (17%)	61 (68%)	30 (33%)	18 (20%)
	Construction management	87 (16%)	71 (82%)	31 (36%)	27 (31%)
	Other	39 (7%)	19 (49%)	16 (41%)	12 (31%)
	Designers	23 (4%)	14 (61%)	11 (48%)	0 (0%)
	Government	13 (2%)	9 (69%)	4 (31%)	1 (8%)
	Supplier	8 (2%)	6 (75%)	4 (50%)	0 (0%)
Organization size	101-500 employees	113 (21%)	87 (77%)	37 (33%)	36 (32%)
	Under 50 employees	96 (18%)	59 (61%)	47 (49%)	22 (23%)
	1001-5000 employees	97 (18%)	70 (72%)	44 (45%)	39 (40%)
	Over 5000 employees	92 (17%)	72 (78%)	34 (37%)	20 (22%)
	50-100 employees	78 (15%)	53 (68%)	30 (38%)	11 (14%)
	501-1000 employees	56 (11%)	39 (70%)	21 (38%)	19 (34%)
Position within the organization	Project manager	92 (17%)	68 (74%)	39 (42%)	24 (26%)
	Project engineer	82 (15%)	58 (71%)	38 (46%)	22 (27%)
	Executive officer	77 (14%)	54 (70%)	22 (29%)	28 (36%)
	Staff position	67 (13%)	41 (61%)	37 (55%)	14 (21%)
	Scheduler	64 (12%)	52 (81%)	18 (28%)	15 (23%)
	Department head	56 (11%)	45 (80%)	19 (34%)	22 (39%)
	Other	57(11%)	40 (70%)	19 (33%)	15 (26%)
	Superintendent	37 (7%)	22 (59%)	20 (54%)	7 (19%)
Area (respondents were able to select more than one option)	Management	292 (55%)	219 (75%)	110 (38%)	87 (30%)
	Planning and control	277 (52%)	208 (75%)	144 (52%)	100 (36%)
	Budgeting	162 (30%)	121 (75%)	71 (44%)	53 (33%)
	Quality or technology	144 (27%)	112 (78%)	60 (42%)	51 (35%)
	Production	144 (27%)	98 (68%)	86 (60%)	58 (40%)
	Supply chain	100 (19%)	75 (75%)	47 (47%)	36 (36%)
	Consultancy	77 (14%)	50 (65%)	36 (47%)	29 (38%)
	Product development/specification	52 (10%)	35 (67%)	24 (46%)	15 (29%)
	Other	24 (5%)	15 (63%)	8 (33%)	7 (29%)

Table 3: System use by country

System	U.S.	Brazil	Finland	China	Total
a. Only CPM	70 (13%)	76 (14%)	34 (6%)	62 (12%)	**242 (45%)**
b. Only LB	3 (1%)	41 (8%)	28 (5%)	32 (6%)	**104 (20%)**
c. Only LPS	13 (2%)	11 (2%)	6 (1%)	0 (0%)	**30 (6%)**
d. CPM + LB + LPS	12 (2%)	14 (3%)	26 (5%)	0 (0%)	**52 (10%)**
e. CPM + LPS	30 (6%)	9 (2%)	8 (2%)	0 (0%)	**47 (9%)**
f. CPM + LB	1 (0.2%)	14 (3%)	16 (3%)	8 (2%)	**39 (7%)**
g. LB + LPS	1 (0.2%)	3 (1%)	14 (3%)	0 (0%)	**18 (3%)**
Subtotal 1	**130 (24%)**	**168 (32%)**	**132 (25%)**	**102 (19%)**	**532 (100%)**
Total CPM (alone or combined): a+d+e+f	113 (21%)	113 (21%)	84 (16%)	70 (13%)	**380 (71%)**
Total LB (alone or combined): b+d+f+g	17 (3%)	72 (14%)	84 (16%)	40 (8%)	**213 (40%)**
Total LPS (alone or combined): c+d+e+g	56 (11%)	37 (7%)	54 (10%)	0 (0%)	**147 (28%)**

Table 4: Hypotheses – Complete dataset

Topic	Answers	Occurrences / total (percentage)			Analysis		
		CPM[1]	LB[2]	LPS[3]	$\chi 2$	df	p
H9. Project management							
H1. Contractual requirement	Contract requirement	73/357 (20%)***[2,3]	15/178 (8%)	3/125 (2%)	31.26	2	0.000
H2. Critical path analysis	Frequently / moderate	266/336 (79%)***[3] *[2]	111/157 (71%)	68/112 (61%)	15.59	2	0.000
H3. Managing contracts	Benefits: improves scheduling	226/322 (70%)	114/180 (63%)	97/128 (76%)	5.66	2	0.058
	Benefits: improves planning before work starts	168/322 (52%)***[2]	65/180 (36%)	63/128 (49%)***[2]	12.28	2	0.002
	Benefits: improves estimating / bidding	95/322 (30%)	48/180 (27%)	25/128 (20%)	5.99	2	0.097
	Benefits: improves understanding of the project	169/322 (52%)	75/180 (42%)	63/128 (49%)	5.42	2	0.066
H4. Management of delay and change	Main reason: claims documentation	9/357 (3%)	6/178 (3%)	2/125 (2%)	0.93	2	0.629
	Benefits: reduce delays	145/322 (45%)	72/180 (40%)	75/128 (59%)**[1,3]	10.86	2	0.004
	Benefits: Minimize disputes between contractor and owner	85/322 (26%)	34/180 (19%)	40/128 (31%)*[2]	6.53	2	0.038
	Evaluation: delays (works very well / works well)	141/275 (51%)	82/139 (59%)	#	2.21	1	0.137
H10. Project production management							
H5. Continuous flow and continuous use of resources	Benefits: improves workflow	141/322 (44%)	97/180 (54%)*[1]	82/128 (64%)***[1]	16	2	0.000
	Evaluation: workflow (works very well / works well)	112/280 (40%)	103/141 (73%)***[1]	70/102 (69%)***[1]	51.51	2	0.000
H6. Treatment of interferences, reduction of uncertainty and constraints	Benefits: improving constraints analysis	75/322 (23%)	49/180 (27%)	63/128 (49%)***[12]	30.2	2	0.000
	Evaluation: constraints analysis (works very well / works well)	125/273 (46%)	80/139 (58%)	65/100 (65%)***[1]	12.62	2	0.002
H7A and H7B. Improving production control	Benefits: improves production control	133/322 (41%)	105/180 (58%)***[1]	82/128 (64%)***[1]	24.7	2	0.000
	Evaluation: production control (works very well / works well)	121/275 (44%)	102/139 (73%)**[1]	77/101 (76%)***[1]	49.49	2	0.000
	Benefits: faster response to problems	69/322 (21%)	53/180 (29%)	68/128 (53%)***[1,2]	43.75	2	0.000
H8A and H8B. Root causes of delays	Benefits: root causes	73/322 (23%)	40/180 (22%)	46/128 (36%)**[1,2]	9.76	2	0.01
	Evaluation: root causes (works very well / works well)	104/273 (38%)	69/139 (50%)	45/100 (45%)	5.32	2	0.070

Note: ***$p<0.001$; **$p<0.01$; *$p<0.05$; superscript numbers indicate system where comparison is significant (1=CPM, 2=LB 3=LPS); #data is not available

Table 5: Hypotheses: Only data related to use of CPM along with LPS and/or LB

Topic	Answers	Occurrences / total (percentage)			Analysis		
		CPM[1]	LB[2]	LPS[3]	χ2	df	p
H9. Project management							
H1. Contractual requirement	Contract requirement	27/136 (20%)***[2,3]	3/67 (4%)	2/83 (2%)	19.75	2	0.000
H2. Critical path analysis	Frequently / moderate	99/132 (75%)	43/63 (68%)	46/76 (61%)	4.80	2	0.091
H3. Managing contracts	Benefits: improves scheduling	91/128 (71%)	50/83 (60%)	66/91 (73%)	3.71	2	0.156
	Benefits: improves planning before work starts	74/128 (58%)***[2]	28/83 (34%)	45/91 (49%)**[2]	11.72	2	0.003
	Benefits: improves estimating / bidding	42/128 (33%)*[3]	19/83 (23%)	16/91 (18%)	6.90	2	0.032
	Benefits: improves understanding of the project	71/128 (55%)*[2]	32/83 (39%)	52/91 (57%)*[2]	7.53	2	0.023
H4. Management of delay and change	Main reason: claims documentation	4/136 (3%)	3/67 (4%)	1/83 (1%)	1.48	2	0.477
	Benefits: reduce delays	58/128 (45%)	29/83 (35%)	56/91 (62%)***[2] *[1]	12.69	2	0.002
	Benefits: Minimize disputes between contractor and owner	38/128 (30%)	18/83 (22%)	30/91 (33%)	2.87	2	0.238
	Evaluation: delays (works very well / works well)	53/113 (47%)	32/57 (56%)	#	3.84	1	0.255
H10. Project production management							
H5. Continuous flow and continuous use of resources	Benefits: improves workflow	58/128 (45%)	42/83 (51%)	57/91 (63%)*[1]	6.48	1	0.039
	Evaluation: workflow (works very well / works well)	34/112 (30%)	40/56 (71%)***[1]	53/72 (74%)***[1]	42.96	2	0.000
H6. Treatment of interferences, reduction of uncertainty and constraints	Benefits: improving constraints analysis	34/128 (27%)	20/83 (24%)	50/91 (55%)***[12]	24.4	2	0.000
	Evaluation: constraints analysis (works very well / works well)	38/113 (34%)	30/58 (52%)*[1]	50/71 (70%)***[1] *[2]	23.9	2	0.000
H7A and H7B. Improving production control	Benefits: improves production control	65/128 (51%)	46/83 (55%)	59/91 (65%)	4.3	2	0.116
	Evaluation: production control (works very well / works well)	39/112 (35%)	42/58 (72%)***[1]	58/71 (82%)***[1]	45.9	2	0.000
	Benefits: faster response to problems	28/128 (22%)	31/83 (37%)*[1]	53/91 (58%)***[1], **[2]	30.15	2	0.000
H8A and H8B. Root causes of delays	Benefits: root causes	32/128 (25%)	17/83 (20%)	36/91 (40%)**[2] *[1]	8.89	2	0.012
	Evaluation: root causes (works very well / works well)	32/111 (29%)	26/59 (44%)*[1]	35/70 (50%)**[1]	9.04	2	0.011

Note: ***p<0.001; **p<0.01; *p<0.05, superscript numbers indicate system where comparison is significant (1=CPM, 2=LB 3=LPS); #data is not available; respondents/total n

Table 6: Summary of results for the complete dataset

Hypotheses	Support
H1: CPM is frequently used due to contractual requirements.	Supported
H2: CPM is the tool of choice for critical path analysis.	Supported
H3: CPM is used to support the management of contractual requirements (e.g. schedule, preconstruction tasks, estimating/bidding, project understanding).	Not supported
H4: CPM is used to support the management of delays and claims.	Not supported
H5: LB use is credited with generating continuous flow and improving the use of resources.	Supported
H6: LPS is credited with supporting and improving the analysis of constraints.	Supported
H7A: LB is credited with supporting and improving production control.	Supported
H7B: LPS is associated with supporting and improving production control.	Supported
H8A: LB is credited with supporting and improving the identification of the root causes of delays.	Not supported
H8B: LPS is credited with supporting and improving the identification of the root causes of delays.	Partially supported
H9: The perceived benefits of CPM by users are mostly related to the PM approach.	Not supported
H10: The perceived benefits of LB and LPS by users are mostly related to the PPM approach.	Supported

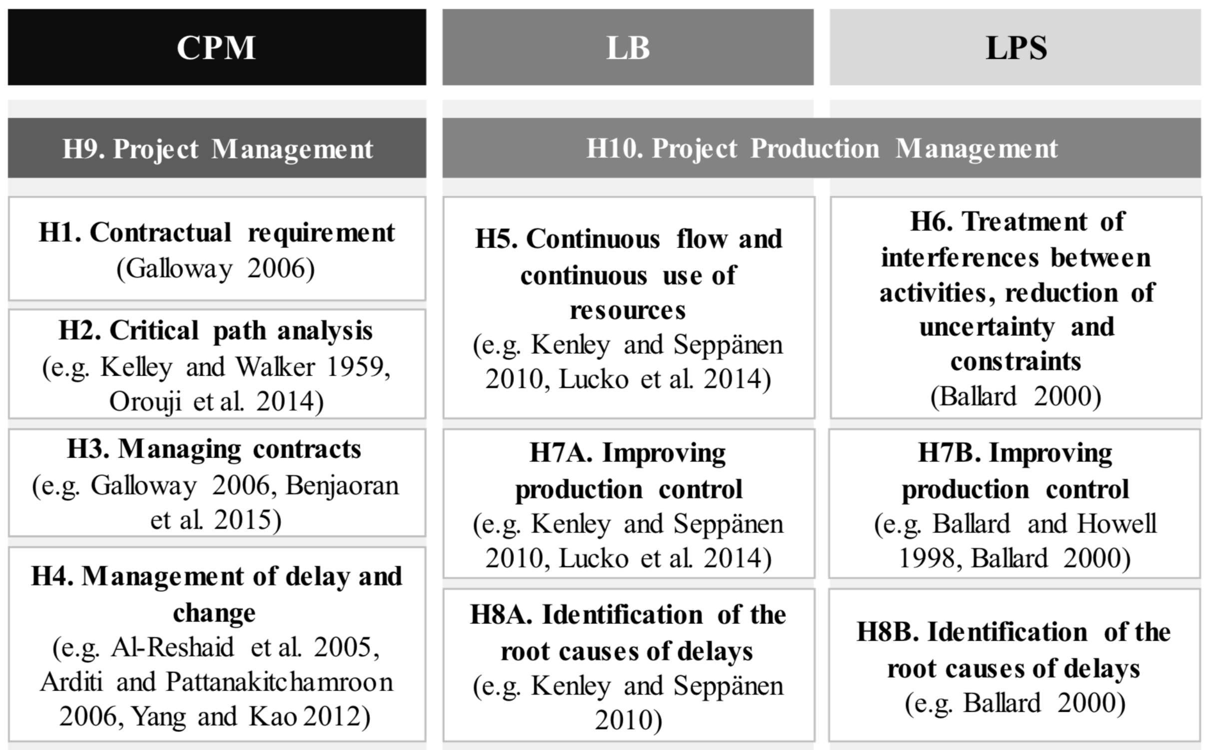

Figure 1: Systems characteristics and related functions

Click here to access/download
Supplemental Data File
Questionnaire-CPM-LPS-LB.docm