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Developing new metrics to evaluate the performance of capacity planning towards sustainable construction

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ABSTRACT

A Since construction is considered a high waste-generating industry, research and business strategies in this field are continuously expending efforts to reduce tangible material wastes and emissions. Yet, these efforts have neglected intangible resource wastes which are equally important and critical such as those produced by improper capacity planning. Capacity planning is a vital process within construction planning that aims at matching capacity (available resources) with demand (forecasted workload) to achieve planning reliability and prevent unnecessary resource waste. However, existing construction studies and practices do not emphasize capacity planning nor do they provide clear measurement frameworks for assessing its impacts on workflow and waste generation. Therefore, the purpose of this study is to highlight the importance of capacity planning by developing new metrics that help provide a holistic understanding and visualization of capacity planning performance and provide feedback for future capacity planning adjustments. The developed metrics were then empirically applied on two well managed projects in the United States. The resulting trends reveal a mismatch problem between load and capacity resulting in wasted resources due to poor allocation strategies that negatively impacted project performance. Moreover, the findings emphasize the need for dynamic evaluation and control of capacity planning performance within project teams. This research contributes novel metrics aimed towards comprehending the underlying mechanisms that shape capacity planning and aims at guiding project teams to achieve more sustainable production flows through quantitative evaluations and adjustments.

1. Introduction

Waste generated during construction is manifested by the overconsumption of materials and polluting emissions where, for instance, about 30% of materials delivered to a typical construction site eventually end up as waste (Osmani, 2011). While most of the research on green building design and construction is directed towards the reduction of environmental impacts and tangible wastes, a major part of these generated wastes remains neglected in the form of intangible resources. Such hidden and intangible resources related to time, cost, and human resources are as scarce and valuable as the tangible ones (Yong et al., 2019; Le Hesran et al., 2019). In fact, around 50% of the construction design process waste is in the intangible form of rework resulting in time, cost, and human capital waste (Ballard, 2000a). Additionally, rework in construction and manufacturing, resulting from the lack of proper planning and scheduling strategies, yields both tangible and intangible wastes (Le Hesran et al., 2019). Therefore, investigating these types of hidden wastes is equally important and is worth studying to render construction processes more sustainable. These wastes result primarily from improperly planning workload and resources as well as inefficiently managing the production flow process.

In this regard, managing production flow is an essential process of construction planning on a project. The adequate allocation of time and resources to production activities can notably increase the probability of a project's success while reducing resulting wastes. Moreover, proper planning can reduce the number of inherent project risks that may otherwise remain unforeseen or not accounted for (Aziz and Hafez, 2013). Adequate development of project's scope, requirements, and technical specifications yields

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short and long term positive impacts on the project (Dvir et al., 2003). Although planning at the project's onset is crucial for developing the objectives and the potential course to achieve them, control is as instrumental to re-aligning the project towards its targets (Kerzner, 1998). In fact, project control minimizes the gap between the long-term project planning and project execution to achieve the project objectives of cost, time, and content (Rozenes et al., 2006). In this context, production planning which includes capacity planning is indispensable in enabling dynamic corrective actions.

Alarcón et al. (2014) analyzed traditional production control mechanisms and found that reliable planning is the key stone for successful performance. To improve construction planning reliability, several tools and systems have been developed. One of the leading systems that is founded on lean principles is the Last Planner System (LPS) that focuses on planning reliability throughout the project. By developing collaborative plans resulting from the participation and commitment of involved stakeholders, both short term and long term plans can be better aligned (Ballard, 2000b). Consequently, maintaining a reliable workflow while producing at minimal process waste becomes an attainable objective. Percent Planned Complete (PPC) is a commonly used metric to measure planning reliability on projects, and projects have shown some improvement in performance when their PPC is high. However, PPC and other current metrics do not express all aspects of production planning (Emdanat and Azambuja, 2016; El Samad et al., 2017).

Reliable plans should not be merely concerned with achieving proper workflow and adhering to set plans, but should also consider the proper assignment of activities and tasks (the workload) to the available labor, equipment, and other resources (the available capacity). This aspect of short-term production planning is known in the world of lean construction as 'capacity planning' which differs from the definitions given in other engineering fields where capacity planning is concerned with long-term expansion or contraction decisions. Capacity planning, in this context, sheds light on another dimension of planning and scheduling concerned with matching load to capacity, thus raising multiple questions: How much of the activities should be allocated to labor? How much work can the labor force accommodate at a time? And is there an optimum ratio between load and capacity? In practice, some construction companies tend to either overload or underutilize their resources, resulting in an inefficient resource utilization and an imbalance between load and capacity (Gonzalez et al., 2010). This may lead to schedule delays, increased costs, and wasted resources if not promptly managed (Shehata and El Gohary, 2011). Therefore, it is vital to examine load and capacity matching and resource allocation dynamics on construction projects.

In this regard, this study introduces new capacity planning metrics as a fundamental stride towards achieving more reliable plans and reducing resource wastes. The derived metrics measure the matching of load to capacity by teams, investigate resource allocation patterns across different types of activities, and correlate capacity planning to project performance. Since mismatches in capacity planning are considered as waste, this research provides quantitative metrics that allow planners and teams to track their performance, identify hidden problems, tackle issues that arise, and provide a benchmark for improving their planning techniques. Moreover, this study extends the knowledge of existing research on construction planning, production control, and process waste.

1.1. Project planning and variability

When comparing the ability of projects to meet their goals, projects with higher pre-planning efforts had an 82% chance of meeting their targets compared to a 66% chance for those with lower invested efforts (Hamilton and Gibson, 1996). When the level of effort during the planning phase is reduced, the final value to customers and stakeholders is subsequently reduced. However, excessively long planning phases had similar low success ratings to those with short planning durations and inadequate planning efforts (Serrador and Turner, 2015). These observations lead to the question as to which planning types and efforts are considered adequate. Accordingly, Ballard (2000a,b) indicated that each project stage requires a different level of planning effort and control. Early project stages undergo long-term perspective planning followed by short-term perspective planning as the project progresses forward and new information becomes available. The long-term planning phase is where major project milestones are set, after which these milestones are broken down into phases. As the project progresses, short-term planning starts where 6-week look-ahead plans are set and are then broken down to weekly work plans (Ballard, 2000b). Therefore, planning is performed in greater detail the closer it gets to the start of an activity (Hamzeh and Langerud, 2011).

While planning considers several factors such as cost, schedule, quality, and the proper definition and availability of a task's prerequisites (Hamzeh et al., 2015), an equally important factor is the proactive analysis of potential problems that might arise (Junnonen and Seppanen, 2004). The emergence of problems is largely due to unforeseen circumstances and inherent variability that are not accounted for earlier. Some research efforts in construction addressed the problem of variability in an attempt to understand its consequences so its impacts can be mitigated. Tommelein et al. (1999) presented the "Parade of Trades" game to illustrate how variability impacts the performance of production. The results of the game demonstrate that variability and unreliable workflow cause a decrease in throughput, a delayed completion date for the project, and an increase in waste resulting from some production phases that do not use their full output capacity because they starve for resources.

Accordingly, the LPS has been developed to increase planning reliability, improve production performance, and create predictable workflows (Ballard et al., 2007). LPS involves the following planning practices: (1) plan in greater detail when getting closer to performing the task, (2) develop the work plan with those who are going to execute the work, (3) identify and remove work constraints ahead of time to make work ready and increase reliability of work plans, (4) make reliable promises and drive work execution based on coordination and active negotiation with trade partners and project participants, and (5) learn from planning failures by detecting root causes and taking preventive measures (Ballard, 2000b; Hamzeh et al., 2008, 2015).

Several metrics have been developed to measure the planning performance under the LPS. The Planned Work Ready (PWR) metric was derived to indicate the portion of the look-ahead planned tasks that where not only made ready for execution, but that are confidently expected to be ready by the time of execution (Mitropoulos, 2005). Similarly, Hamzeh et al. (2012) introduced an updated version of the Tasks Anticipated (TA) and Tasks Made Ready (TMR) metrics that measure the success of anticipating tasks and removing constraints. Such metrics can serve in improving the association between near and long term planning (Hamzeh et al., 2015). Moreover, Gonzalez et al. (2008) developed the Process Reliability Index (PRI) and the Project Productivity Index (PPI) metrics to quantify productivity and progress at the project and weekly work plan level. Results from the application of these metrics showed positive and strong correlations between planning reliability and performance at activity and project levels. Additional metrics have also been proposed to align long-term and short-term plans, such as the Commitment Level (CL), Percent Required Complete and Ongoing (PRCO), and Milestone Variance (MV) developed by Emdanat and Azambuja (2016). Results show that these metrics can serve as good indicators of near-term reliability planning. Although these metrics have provided beneficial assessments of certain planning aspects, they do not address the area of capacity planning which is indispensable for production planning.

1.2. Capacity planning and research gap

Capacity and productivity are two related concepts. Hopp and Spearman (2001) recognize that in a "steady state, all plants will release work at an average rate that is strictly less than the average capacity" and that when work released into system exceeds capacity the system becomes unstable. This means that the capacity of a process is the largest output possible before rendering the system unstable (Antunes et al., 2018). At this threshold capacity, the process can function at maximum productivity. Hence, an accurate estimate of maximum productivity is crucial to understanding the efficiency of construction operations (Kisi et al., 2017). However, optimism bias in estimating seems to be common on construction projects and an unbiased attitude is difficult to be found in practice (Son and Rojas, 2011). In fact, despite the extensive studies in the area of production management, there is a need for more research to understand production on construction projects (Antunes et al., 2018).

'Capacity planning' is understood differently in various fields. On one hand, in the field of production management, 'capacity planning' is long-term strategic thinking focusing on investing productive resources for expansion or contraction (Chein et al., 2018). This decision making process addresses important questions such as when, where, and how much to expand or contract (Sudarto et al., 2016). On the other hand, in the world of lean construction, 'capacity planning' is concerned with matching the chosen workload to available capacity. Workload is the quantity of work needed to be done in a specific time allotted by planners, and capacity is the quantity of work a crew can complete using their available resources (Ballard, 2000b).

Kim et al. (2008) have developed a workforce information database (level of skill, history of accidents, etc.) to help solve the conflict of matching load with capacity. This database system allows the user to consider workforce capacity and access the needed information during production planning to develop proper strategies. Under utopic conditions, this endeavor can be directly achieved without any complications. However, two hurdles prevent planners from achieving proper capacity planning. The first hurdle pertains to forecasting the workload where variability reduces the accuracy in predicting what tasks will be ready for execution; these tasks are dependent on other prerequisite tasks that might not be complete by their planned time (Tommelein et al., 1999). The LPS, while it enhances reliable commitment to ultimately achieve better workload forecasts, can be shadowed by the second hurdle: improper resource estimation and utilization.

Estimating resource requirements in the presence of uncertainties and unreliable forecasts render such estimations inaccurate. Resource variations are impractical, inefficient, and costly when they occur during construction (El-Rayes and Jun 2009; Koulinas and Anagnostopoulos, 2013). In reality, resources are rarely sufficient, and more often than not, are limited and sparse. Therefore, planners allocate their resources using a priority rule, which per Khattab and Soyland (1996), performs better than a CPM-based rule. CPM assumes an unlimited amount of resources for executing tasks and is therefore considered when a project is task-constrained or activity-critical (Kastor and Sirakoulis, 2009). Furthermore, limited resource allocation is used when the project is resource-constrained or resource-critical to keep the exceeded project duration to a minimum (Khattab and Soyland, 1996). On the other hand, Damci et al. (2013) suggested that an increase in project sequencing efficiency can achieve project goals and can aid in resolving the resource leveling problem. Ponz-Tienda et al. (2017) proposed an algorithm to resolve the problem using several resources aiming to decrease variations. Objective functions were studied by Damci and Polat (2014) to understand and measure project sequence efficiency, but no metrics were suggested to show that there are in fact fluctuations and mismatch issues between resource levels and tasks to be completed. Thus, variability present in both capacity and load planning hinders attempts to balance workload and resources. In this respect, a reliable commitment model, at the level of capacity planning, that enhances short term prediction of work progress based on factors related to labor, buffers, and workplans was progressively developed by Mundaca (2006) and Bustamante (2007), then later elaborated by González et al. (2008) and González et al. (2010). However, similar to earlier research, this model does not explicitly incorporate a specific method to directly measure capacity planning.

While the aforementioned studies aim at improving planning trends, their suggested methods do not explicitly present strategies for assessing capacity planning or reducing resource waste. In addition, no clear metrics or applicable frameworks were established to measure capacity planning and evaluate its role in conjunction with the LPS. In this regard, the novelty of this research lies in putting forth a clear quantitative framework that directly evaluates capacity planning performance on construction projects. Therefore, the main goal of this study is to introduce new metrics to measure capacity planning performance on construction projects with the overall aim of improving the control of production workflow and reducing resource wastes upon their application. Without a comprehensive quantitative assessment, performance cannot be tracked nor improved, which in turn hinders actions towards the prevention of unnecessary wasted resources that are valuable for a sustainable construction industry. The study's contributions to science comprise the following: introducing new capacity planning metrics to track and measure various aspects of capacity planning; applying the metrics to actual construction projects to assess load-to-capacity matching patterns and reduce resource wastes; evaluating, empirically, resource allocation and utilization trends; formulating an understanding of the underlying factors shaping capacity planning; and highlighting underlying problems in planning performance.

2. Methodology

Design Science Research (DSR) is the adopted research methodology because it fits the study's nature of introducing and testing an artefact, and because of DSR's ability to align the academic and industrial side of a given field (Smith, 2015). DSR aims to develop knowledge to describe, understand, and improve the system under study by following a set of defined guidelines, namely: designing, building, and applying designed artefacts through rigorous researching and evaluation methods (Van Aken, 2005; Hevner et al., 2004). Such artefacts can be in the form of models, methods, tools, or constructs. Additionally, DSR is deemed an adequate approach for construction management research when devising and implementing solution artefacts in construction due to the field's "applied" nature (Smith, 2015; Rocha et al., 2012). In this research, the newly introduced metrics represent the artefact under study and need to be assessed and tested. The research team was divided into two groups to avoid bias and maintain objectivity throughout the study. The first group handled the scientific process of deriving the metrics (the artefact) and hypothesis, while the second group was responsible for the empirical study and monitoring project related operations.

The study comprises three stages adhering to DSR's guidelines as depicted in Fig. 1: (1) developing new metrics for evaluating capacity planning, (2) conducting an empirical study, on two construction projects for a combined 222 weeks or data points, to test and apply the derived metrics, and (3) evaluating and discussing the obtained results.

The first stage consisted of a comprehensive review of previous research regarding capacity planning and resource allocation. This stage was conducted to explore existing metrics and their limitations in providing a comprehensive understanding of capacity planning. This review also helped in determining the missing metrics that are needed to better evaluate capacity planning. The results of the literature review then guided the derivation of the new metrics to assess the current state of capacity planning on construction projects. The development of metrics is detailed in subsection 3.1.

After developing the metrics, the second stage included the application of the metrics to two actual projects to assess capacity planning performance and how these metrics can depict patterns of planning and its reliability. The metrics were measured on these projects and the resulting values were plotted in Section 4.

The final stage evaluated the ensuing patterns and discussed them to understand the relationship between the different metrics as well as to highlight trends and any issues in planning.

2.1. Derivation of metrics

Metrics are fundamental tools in measuring, tracking, and evaluating performance to help improve the systems or any aspects under study. However, not all metrics are useful or convey a complete and unbiased depiction of the actual conditions occurring. Some metrics, when considered in isolation, fail to provide a holistic understanding of certain mechanisms and may yield biased results. Although existing metrics have contributed to better planning efforts and outcomes in the construction industry, they suffer from the aforementioned issues and come short in capturing the full reality. Therefore, the metrics identified in this study aim to more comprehensively and objectively evaluate capacity planning by complementing existing ones.

Since capacity planning is concerned with allocating resources to task workload demand, it is important to highlight the different types of activity clusters. Fig. 2 distinguishes between three types of clusters. Each comprises two types of activities: normal (non-critical) activities represented by green pebbles and required (critical) activities represented by red pebbles. Required and critical activities are the same and will be used interchangeably throughout the paper. Critical activities, as defined in this study, are activities that will delay the entire work-stream to which they belong if they are late. On the other hand, normal (non-critical) activities are activities that have some leeway that if they take longer to execute will not delay their respective work-stream. Note that criticality is related to the work stream deadline/milestone and not to the whole project's deadline.

The first cluster depicted in Fig. 2, is the *Weekly Work Plan (WWP)* cluster. This group of activities consists of all the tasks that have been committed to be completed during a given week, where some can be critical or normal. Determining whether a task on the WWP is critical or normal depends on the nature of the task itself and this is reflected by the amount of float specific to each task on the schedule; a task with zero days of float is considered critical as opposed to a normal task that has several days of leeway before it can impact subsequent tasks and the overall work-stream. The second cluster is called *New* and comprises tasks that emerge during the review period, in this case-a week, and have not been initially included in the weekly work plan of the given week. These *New* tasks must then be completed during the same week of their

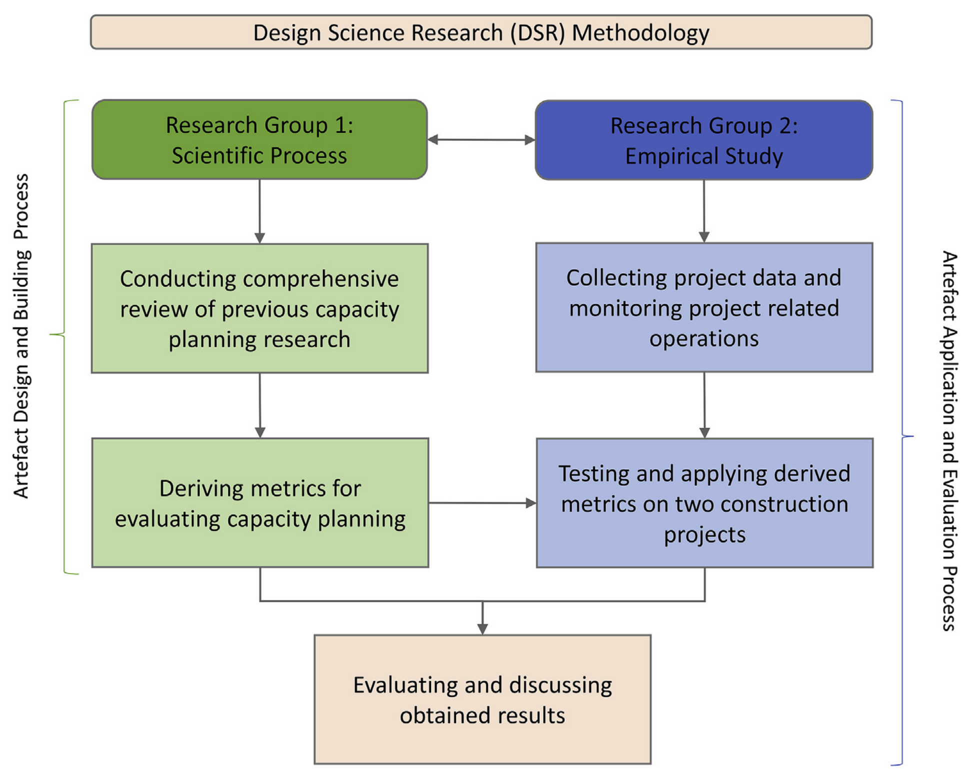

Fig. 1. Research methodology.

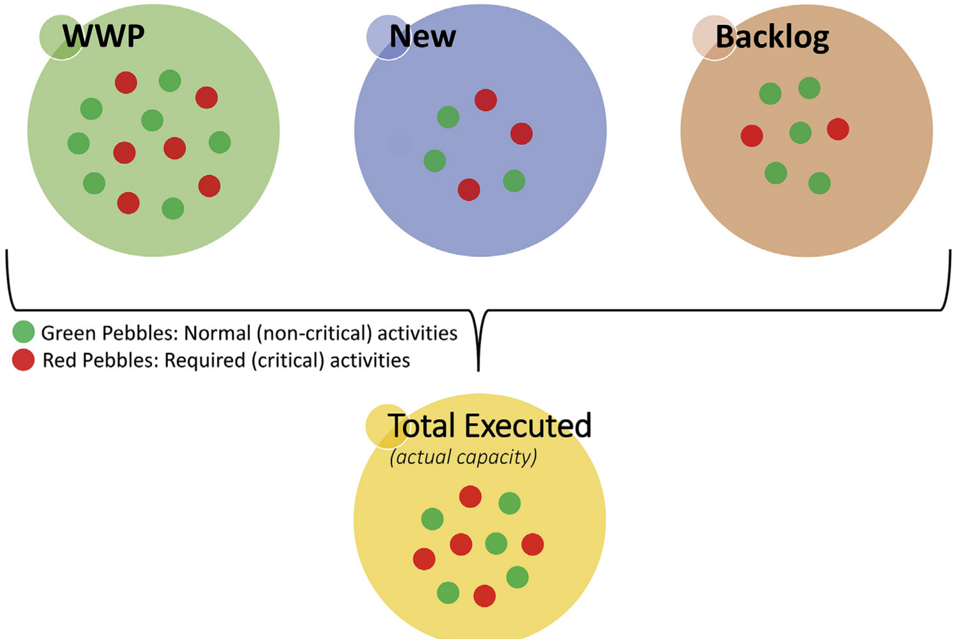

Fig. 2. Activity clusters.

emergence (Rouhana and Hamzeh, 2016). Although the emergence of *New* tasks impacts the performance of teams and the completion of already committed planned tasks, the calculation of PPC in this study still follows the common procedure of 'tasks completed from those committed' on the weekly work plan. In another ongoing research, further metrics are being developed to include the impact of New tasks in their calculation. The third cluster, *Backlog*, comprises excess activities that are ready for execution but are not a priority and can be completed if there is available capacity. For example, if there are extra resources available or there are pending or halted works, backlog activities can be completed to prevent resources from being idle and unutilized. The fourth cluster of activities, *Total Completed*, consists of the actual activities that have been completed during a given week and represents the actual capacity. The tasks that have been completed in each of the three presented clusters contribute to the *Total Completed* cluster.

Four new primary metrics and three secondary metrics are derived to complement existing planning metrics. The seven metrics are defined hereafter along with the developed equations. Note that these metrics are measured on a weekly basis when applying the LPS. Table 1 defines the parameters included in calculating the derived metrics.

2.1.1. Primary metrics

2.1.1.1. Capacity to Load Ratio. The first derived metric is the Capacity to Load Ratio (CLR). This metric compares the actual available capacity (tasks that were Completed) to the chosen load (tasks that were committed to on a given week). It is worth noting that this study is concerned with capacity planning, and it does not address the number of people assigned to activities on the plan but only compares tasks on the plan. The CLR is calculated by dividing the total number of activities completed during a given week (Total Completed Cluster) by the number of activities the team has committed to completing during a given week (WWP Cluster). It is a retrospective metric which aids in tracking how close the team was in adequately employing resources. CLR is calculated using Equation (1):

$$CLR = \frac{Total\ Completed}{WWP} \tag{1}$$

2.1.1.2. Required Capacity Ratio. The second metric is the Required Capacity Ratio (RCR) and represents, on a given week, the ratio of Completed activities that are required. RCR is calculated by dividing the number of required or critical activities that were completed by the total number of activities that were Completed (Total Completed Cluster) as shown in Equation (2):

$$RCR = \frac{Required\ Completed}{Total\ Completed} * 100 \tag{2}$$

Table 1

Parameter	Description
WWP	Represents all the activities on the weekly work plan that have been committed to be completed for the given week
WWP Completed	Represents all activities on the weekly work plan that have been completed for the given week
Total Completed	Represents all the activities from the WWP, New, and Backlog Clusters that were actually Completed on the given week (indicated by all the pebbles in the Total Completed Cluster in Fig. 2)
Total Required	Represents all the critical activities that are in the WWP, the Backlog, and the New Clusters for the given week (indicated by all red pebbles in the WWP, Backlog, and New Clusters in Fig. 2)
Required Completed	Represents all the critical activities that were Completed on the given week (indicated by all red pebbles in the Total Completed Cluster in Fig. 2)

2.1.1.3. Required Percent Complete. The third metric derived is the Required Percent Complete (RPC). RPC indicates how many required tasks have been completed out of the total required tasks during a given week. It is calculated by dividing Completed required activities by the total required activities during a given week, as shown in Equation (3):

$$RPC = \frac{Required\ Completed}{Total\ Required}*100 \quad (3)$$

2.1.1.4. Weekly Deviation. The fourth metric is the Weekly Deviation (WD) which assesses the deviation from the WWP. WD gives us an indication of how far the team has deviated from its weekly work plan. If the direction of the deviation is less than zero ($WD < 0$), then the team is overloading its resources. Otherwise, if $WD > 0$, then the team is under-loading its resources. If $WD = 0$, then the team has matched the load to capacity. The WD metric is calculated by subtracting the number of committed activities (WWP Cluster) from the number of total Completed activities (Total Completed Cluster) as shown in Equation (4):

$$WD = Total\ Completed - WWP \quad (4)$$

2.1.2. Secondary metrics

In addition to the four primary metrics derived, three secondary metrics are developed to show further the misallocation of resources that takes place on projects. These are the Glut, the Starvation, and the Misallocation Factor. Each metric is defined respectively.

2.1.2.1. Glut. If RCR represents the ratio of completed activities that are critical, consequently, the value of 1-RCR represents the ratio of non-critical activities that are completed. Glut reflects the number of non-critical activities which have been Completed and obviously have taken available resources away from critical activities. It is calculated using Equation (5):

$$Glut = Total\ Completed - Required\ Completed \quad (5)$$

2.1.2.2. Starvation. Similarly, if RPC represents the fraction of critical activities that have been Completed, then 1-RPC represents the fraction of required (critical) activities that have not been completed. Hence, Starvation reflects the number of critical activities that are starving for resources and is calculated using Equation (6):

$$Starvation = Total\ Required - Required\ Completed \quad (6)$$

2.1.2.3. Misallocation Factor (MF). A Misallocation Factor can be then deduced as being the sum of the Glut and Starvation metrics, where this sum reflects the resulting waste in capacity planning. MF is calculated using Equation (7):

$$MF = Glut + Starvation \quad (7)$$

In addition to these metrics, two metrics developed in earlier research are tracked on the two case study projects. The first metric is the PPC which is the most commonly used in the industry. Developed by Ballard (2000a,b), PPC measures the effectiveness and reliability of planning by dividing the work performed by the work committed on that weekly work plan. The consistent measurement of PPC, calculated using Equation (8), provides an effective way to monitor variability in project planning (Bhaidani et al., 2016). Using PPC in this study enables a complete analysis of these metrics and measure the reliability of planning.

$$PPC = \frac{WWP\ Completed}{WWP}*100 \quad (8)$$

The second metric derived by Emdanat and Azambuja (2016) is the Milestone Variance (MV). MV is the difference in days between the forecasted date to complete all remaining activities and the required date of the milestone (Emdanat and Azambuja, 2016). MV can relate the developed capacity metrics to the project or workflow stream schedule performance and ensure that the remaining work is in alignment with the milestone targets.

2.2. Description of the empirical study

The detailed planning data used to test the metrics was acquired from a global engineering and construction firm. The data was collected over an approximate 2-year duration from two projects in the United States. Additional case studies would have been more favorable, but the selection was limited to these two case studies on which high level of LPS was implemented and the needed detailed planning data was being collected. Moreover, the application on two cases allows results to be compared and cross-analyzed for a better validation of the metrics and for drawing solid insights. However, these metrics are applicable to any construction project applying the LPS anywhere in the world.

The projects were also selected because they adhered to the general guiding principles of the LPS in their planning process such as: sharing the schedules publicly; planning in greater detail as tasks get closer to execution; producing collaboratively with those who will perform the work; re-planning when necessary as more information becomes available, identifying and removing constraints as a team; committing to tasks that are adequately defined, free from constraints, well sequenced, and properly sized; respecting the process of reliable promising and speaking up in case of an issue in honoring a promise; learning from past planning failures; and keeping a workable backlog of constraint-free tasks to be completed in case of extra capacity or constraints to other committed tasks (Ballard 2000a,b; Ballard et al., 2007; Ballard and Tommelein, 2016).

The choice of these projects was contingent on the presence of a substantial database of detailed planning data and proper implementation of the LPS. Each project comprises multiple teams that are divided based on the phase of the project and work stream. The teams track milestones, adjust the schedule, and apply advanced LPS assisted by a planning and scheduling software called vPlanner, which is targeted for production planning and LPS.

The software addresses two vital matters when applying the LPS that call for substantial effort from the project teams. The first is the alignment between near-term and long-term project plans, and the second is the constant management of the near-term plans to identify and remove constraints that may impact workflow reliability. Furthermore, Hamzeh et al. (2012) showed a gap between the master schedule and WWP due to the use of disjointed tracking tools. In other words, the activities that are placed on the WWP cannot be distinguished as being either critical or non-critical activities. However, in the selected projects, there is no such a gap in which the required (critical) tasks on the WWP are known and are easily distinguishable from the backlog. These features and the information richness of these projects make them highly compatible for use in this study. The data includes details on multiple tasks and activities required to execute the project. Each task has multiple parameters such as task ID, weekly workplan ID, team ID, task status, date created, workplan start date, and others.

Data was collected in vPlanner on weekly basis at the level of the master schedule, phase schedule, lookahead stage and weekly work plan. Since this is a retrospective study, all the weekly-based data was extracted from vPlanner at the end of each week. Once the collected data from the case studies was pre-processed, and the required parameters were calculated, the metrics, which were introduced in Subsection 3.1, were applied to the two project case studies to visualize the capacity planning performance and highlight any existing issues. The results from applying the metrics to the data were analyzed, and correlations were made to understand the resulting patterns and relationships between the different metrics.

3. Results and analysis

The unit of analysis on both case studies are the tasks on the weekly work plans, New tasks, Backlog tasks, and the Total Completed tasks. Analyzing these entities and using them to calculate the metrics enables a comprehensive evaluation of capacity planning performance on the projects. The results of the derived metrics for each case study project are presented and analyzed in the following subsections.

3.1. Project 1 analysis

3.1.1. Overview of tasks committed and completed

Data collected from Project 1 over a 2-year period addressing the number of tasks on the WWP, the number of New tasks added, the number of Backlog tasks, as well as the total number of Completed tasks is plotted in Fig. 3. The trends reveal a change in the number of tasks throughout the project. At the early pre-construction stages, the number of weekly committed tasks was relatively low, averaging an approximate 150 tasks a week. This low number of tasks is due to construction being at its preliminary stages were only limited activities have kicked off and teams primarily had to merely plan design and excavation works. In addition, this limited action at the early stages maintained a low number of New tasks and Backlog tasks during this first year. Consequently, teams were performing well initially and fairly completed tasks on the WWP were the low number of tasks was manageable by the teams. This matter is reflected through the number of Total Completed tasks being aligned with WWP tasks in the early project stages.

By the end of week 44, a notable increase in the number of committed tasks is denoted by the project's progress and new phases kicking off such as structural and MEP works followed by interior finishing works towards week 95. Not only is there a peak in the number of WWP tasks, but also the number of emerging New tasks and added Backlog tasks increased as well. However, the resulting trend of the number of Total Completed tasks shows that teams were falling behind in completing the work they have committed to on the weekly work plan. This matter can be attributed to the emergence of unanticipated New tasks and overcommitting tasks to the WWP that kept the teams short of fulfilling the assigned workload.

3.1.2. Analysis of capacity to load matching through CLR and WD metrics

The CLR and WD metrics are measured throughout Project 1's duration to better understand the teams' capacity planning patterns. Results are plotted in Fig. 4.

In ideal cases, a CLR value of one indicates that teams are matching their selected workload with their actual capacity. When the CLR ratio is higher than one, it means that teams are underloading their resources by selecting a lower workload than their actual capacity. On the other hand, a CLR ratio less than one indicates that teams are overloading their resources by choosing a workload higher than their actual capacity. Fig. 4 reveals that the teams, on average, were matching their chosen load to capacity from the start of the project till week 53 where the associated CLR value fluctuated around 1. After this period, the CLR value decreased beyond the favored value of 1, indicating that teams were overloading their resources. The decrease in the CLR value can be linked to the observed increase in the number of New emerging tasks, where the emergence of unanticipated new tasks overwhelmed existing resources and applied more pressure on the planning processes.

This decrease is also reflected in the Weekly Deviation patterns throughout the project. A positive WD value indicates that teams

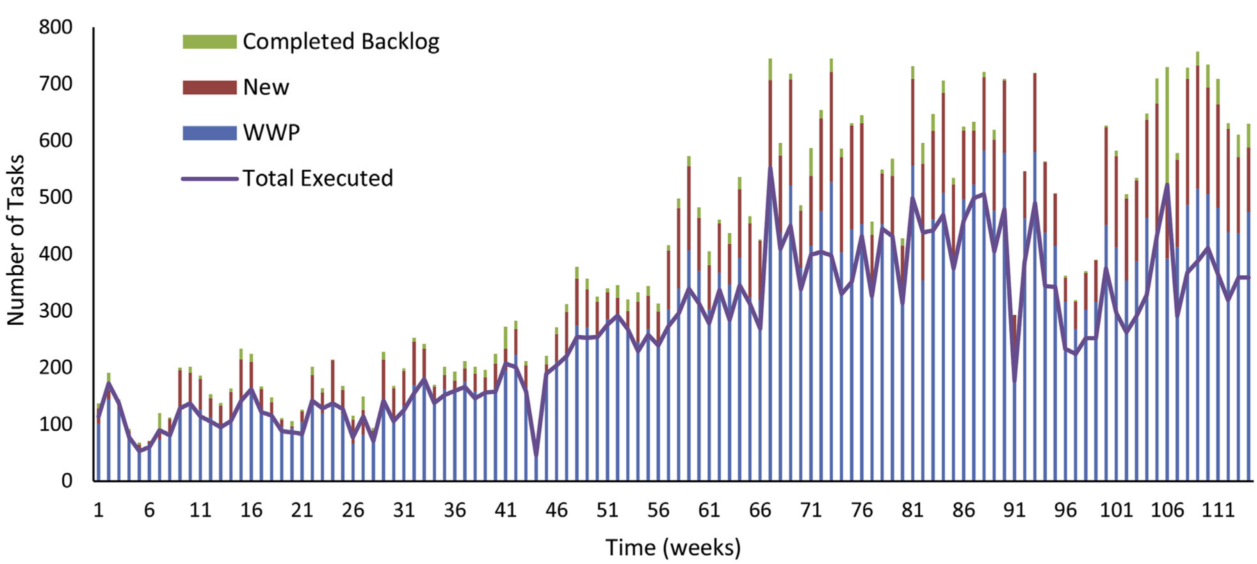

Fig. 3. Number of WWP, New, Backlog, and Total Executed tasks.

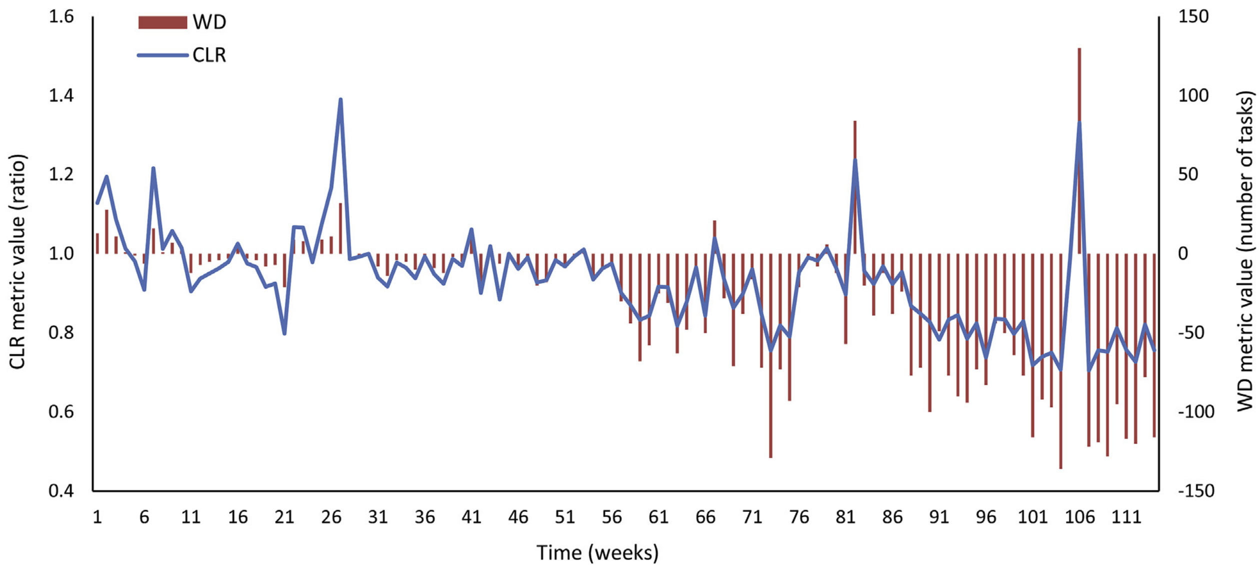

Fig. 4. CLR and WD metric values of Project 1.

are executing more tasks than their actual capacity, whereas a negative WD value indicates that the teams are under-executing and overloading their resources. Preferably, a WD value of zero indicates a proper matching of capacity with planned load. Fig. 4 displays how initially the WD values were fluctuating around a positive value closer to zero, reflecting proper capacity to load matching. However, the WD metric values gradually started to negatively fluctuate drastically beyond week 53 where WD reached a value of −100 tasks. This value indicates that the teams were falling an average of 100 weekly tasks behind their capacity.

The combined results of the CLR and WD metrics uncover a problem of matching load to capacity as the project progresses. The emergence of new unanticipated tasks and the natural increase in the number of tasks on the WWP, resulting from the initiation of different work packages, have overwhelmed the existing capacity of teams beyond a manageable threshold.

3.1.3. *Analysis of task execution through PPC, RPC, and RCR metrics*

The presence of a capacity to load matching problem necessitates a further investigation into the extent of the issue. Therefore, examining the type and amount of work Completed in relation to what has been committed for each week can better help underline the matter. In this respect, the PPC, RCR, and RPC are calculated and plotted in Fig. 5.

Since the start of the project until week 103, the teams maintained average values of 85%, 86%, and 85% of PPC, RCR, and RPC respectively. The PPC value indicates that teams were capable of executing 85% of the committed tasks on the WWP, and that tasks on the WWP were mainly critical as indicated by RPC. Moreover, PPC and RCR values for that period are in alignment reflecting that the Completed tasks were mainly required ones.

Beyond week 103, the three metrics displayed a notable decline in task execution performance by the teams. PPC values decreased by an average of 18%, whereas RCR and RPC decreased by 50% and

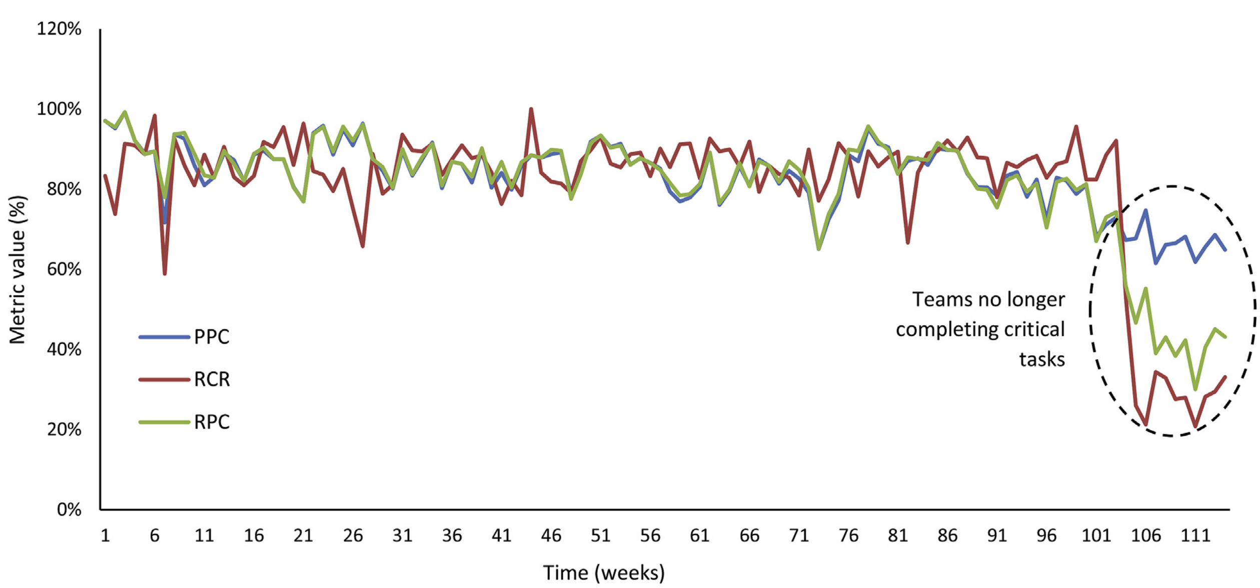

Fig. 5. PPC, RCR, and RPC metric values of Project 1.

39% respectively. This sharp decrease in the RCR metric to an approximate average of 30% shows that most critical tasks on the WWP were not completed. In addition, the RPC value being constantly less than the PPC value reflects that teams were executing non-critical tasks instead of critical ones. By favoring non-critical tasks over critical ones, valuable resources are being wasted and not used efficiently. This depletes the pool of resources that will remain available for executing critical tasks and place additional burdens on existing ones. The trends of these metrics show that the planning system, beyond week 103, is no longer stable or sustainable for proper capacity planning.

3.1.4. Analysis of resource allocation patterns through Glut, Starvation, and MF metrics

Further analysis of the observed task execution trends is achieved by examining how resources were utilized and allocated among different types of tasks. Accordingly, Fig. 6 demonstrates the changes in the calculated Glut, Starvation, and MF metric values throughout the project's duration. A high positive Glut metric value indicates that teams are allocating resources to non-critical activities and completing them on the expense of the critical ones. On the other hand, a high positive Starvation value means that more critical tasks are starving for resources. As a result, a high positive Misallocation Factor indicates a sub-optimal allocation and utilization of resources.

The project's first year recorded values of the Glut, Starvation, and MF metrics that ranked a low average of 19, 15, and 33 tasks respectively up until week 54. These results signify that teams were properly assigning and utilizing resources among critical and non-critical activities. This can be related to the manageable number of committed tasks on the WWP at the project's onset where the demand on resources is relatively still low.

Between week 54 and the end of the project, a prominent increase in Glut, Starvation, and MF metrics is clear. The average value of Glut increased from 19 to 240 (221 tasks) meaning that by the end of the project 240 of the Completed tasks on the WWP were non-critical. Similarly, Starvation also increased by an average value of 157 tasks. In other words, 157 critical tasks were starving for resources and not being completed. Thus, the Misallocation Factor average value increased to 397 tasks. The recorded rise in these values is a direct implication of resource misallocation. As the project progressed, construction works of new disciplines were gradually added to the WWP. In fact, multiple trades occur simultaneously and demand resources, thus placing pressure on how these resources will be assigned. Moreover, the emergence of New tasks as a result of variability and uncertainty, adds more burden on the limited availability of resources. In the absence of priority ruling to optimize the allocation of resources, non-critical tasks will be executed haphazardly on the expense of critical tasks starving and failing to be completed timely. Consequently, the delay in completing critical tasks can result in milestone delays and overall project delays.

3.1.5. Analysis of critical resource allocation and schedule performance through Starvation and MV metrics

Understanding the impact of capacity planning and resource allocation on schedule performance is important and can be achieved by calculating the Milestone Variance metric. For the sake of demonstration and comparison, Starvation is displayed as a negative value in Fig. 7. Analyzing MV from the beginning of the project until week 75, it is clear that teams managed to adhere to the schedule. Despite some dips in milestone dates for some workflow streams, the teams were able to compensate for that and get back on schedule. Starvation metric values during the first 52 weeks of the project were considerably low compared to the rest of the project as examined previously, which is in alignment with the teams' ability to adhere to the schedule. The initial low number of committed tasks on the WWPs and low demand on available resources enabled the teams to properly allocate the required resources to complete the critical tasks.

Between week 75 and the end of the project, the milestone variance started decreasing sharply reflecting a fall back in the set schedule. This can be correlated with the observed negative increase in Starvation values where teams were starving required activities that, as a result, were not completed. By definition, required activities are activities on a project, which if delayed, will delay the entire work-stream to which they belong. The increasing number of tasks committed to the WWP and the emergence of New tasks, coupled with a misallocation of resources, became overwhelming beyond a manageable point. Consequently, required

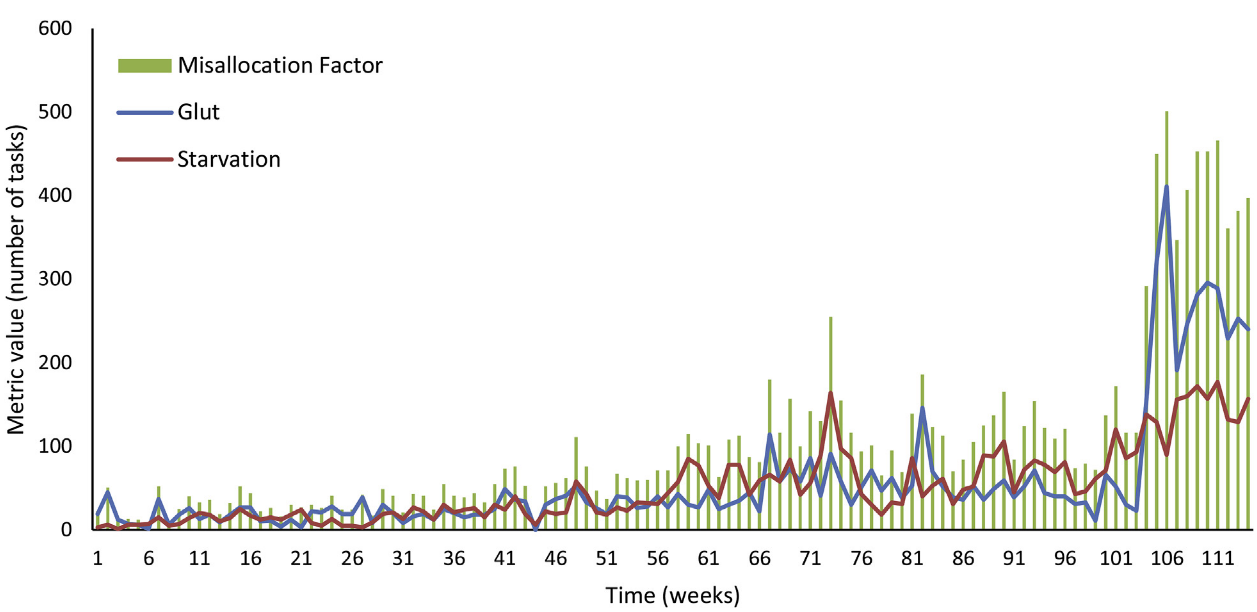

Fig. 6. Glut, Starvation, and Misallocation metric values of Project 1.

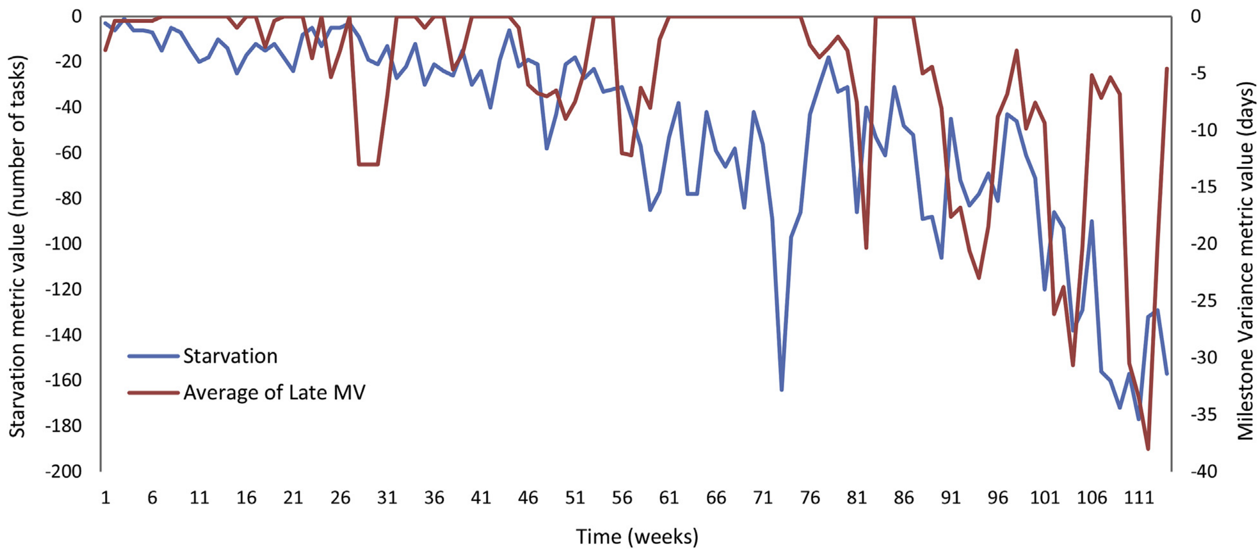

Fig. 7. Starvation and Milestone Variance metric values of Project 1.

activities were starved and negatively impacted the set milestone dates of project workflow streams.

3.2. Project 2 analysis

3.2.1. Overview of tasks committed and completed

The number of WWP, New, Backlog, and Total Completed tasks were collected on Project 2 and displayed in Fig. 8. Project 2 is independent of Project 1 although it has a similar schedule. During the early project stages, the average number of tasks on the WWP was 150. Moreover, New tasks were emerging but at a lower rate than the further stages of the project. In these early stages, teams were able to complete all tasks including the New and Backlog tasks which is reflected by the Total Completed trend line aligning with the committed WWP tasks.

As the project moved forward after week 46, the number of committed tasks on the WWP was on the rise with notable peaks in the number of New emerging tasks. These peaks present a clear sign of an unstable planning process as new workflow streams joined the project. The trend of the number of Total Completed tasks also reveals the inability of teams to complete all committed tasks on the WWP. The addition of more project packages and the joining of new teams created a burden on the project's schedule and set plans. As a result, teams failed to fully execute planned and committed tasks with the onset of new tasks.

3.2.2. Analysis of capacity to load matching through CLR and WD metrics

Assessing the teams' capacity to load matching efforts can help in better visualizing the issues occurring when failing to execute as per the WWPs. Fig. 9 demonstrates the calculated CLR and WD metrics. Unlike Project 1, the average CLR metric value fluctuated

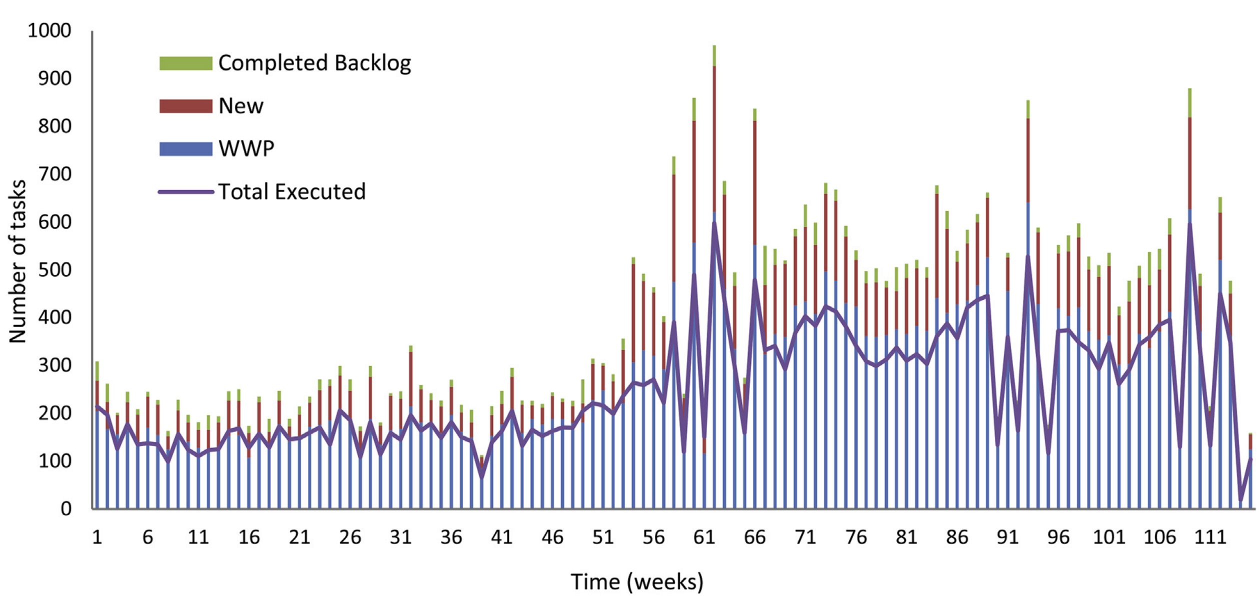

Fig. 8. Number of WWP, New, Backlog, and Total Executed tasks Project 2.

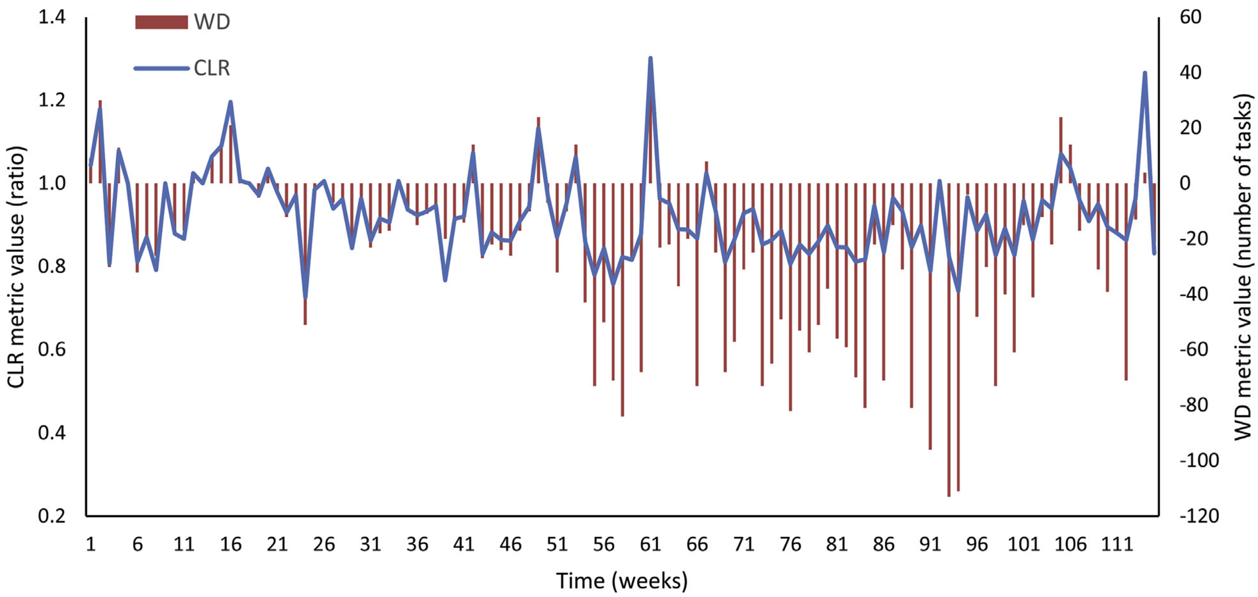

Fig. 9. CLR and WD metric values of Project 2.

more in the preliminary stages of the project reflecting that teams were not consistently managing their resources to match their capacity to the chosen load. After week 66, a continuous decline in CLR was maintained below 1 towards the end of the studied duration. This indicates that teams were overloading their available resources as new tasks were emerging and the chosen workload was increasing.

Consistent with these findings are the patterns of the Weekly Deviation metric. Except for a limited number of weeks at the start of the project, the WD metric constantly ranked below zero, at an average of −40 tasks, indicating that teams were executing less tasks than their actual capacity while overloading their resources. Such a trend is an indication of improper capacity to load matching techniques. The teams did however try to better pair their capacity with the chosen load towards the end of the project to counteract the declining trend in earlier months.

3.2.3. Analysis of task execution through PPC, RPC, and RCR metrics

The observed trends of PPC, RPC, and RCR metrics on Project 2 presented in Fig. 10 show that the teams achieved average values of 78%, 79%, and 81%, respectively, from the start till week 101. Less than those of Project 1, the teams of Project 2 completed only 78% of the committed tasks on the WWP. The RPC and RCR values indicate that the majority of committed tasks on the WWP were critical.

Unlike the observed decline in PPC, RPC, and RCR values on Project 1, the PPC metric on Project 2 recorded an increase to 84% beyond week 101. Although an increase in PPC would normally reflect better execution performance if assessed alone, this increase is actually misleading. Underlying problems are revealed by the decrease in the RPC and RCR values. The significant dip registered by the RCR metric to an average low of 37% indicates that critical tasks on the WWP were not being completed by the teams. Moreover, the RPC average of 71% ranking less than that of PPC is a

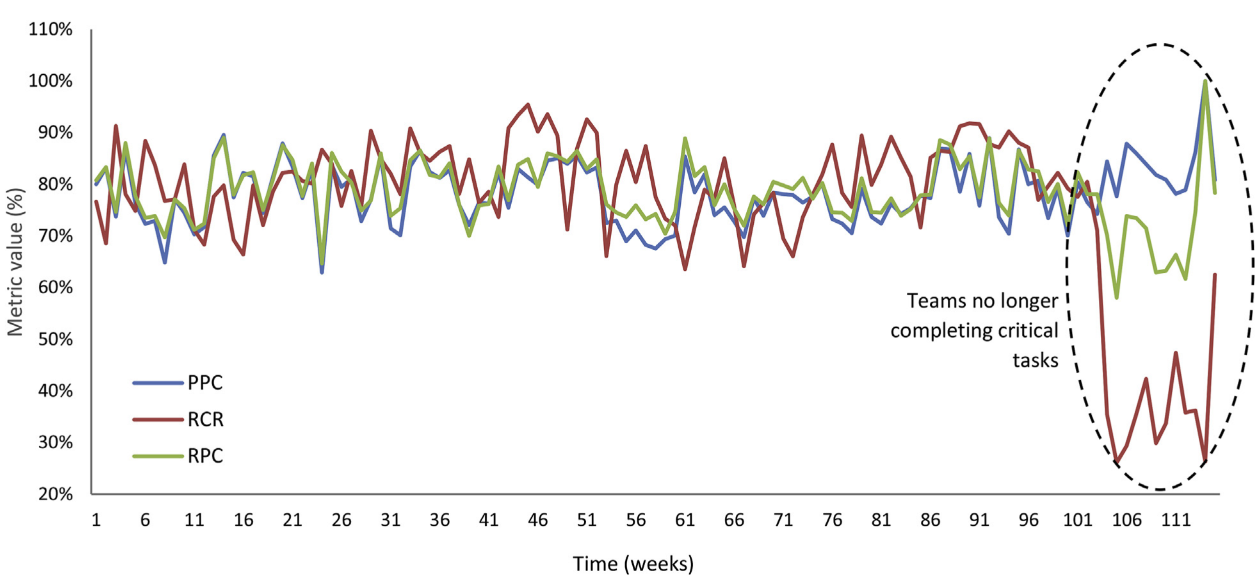

Fig. 10. PPC, RCR, and RPC metric values of Project 2.

direct indication that teams were executing non-critical tasks instead of critical ones. The resulting PPC increase, therefore, does not necessarily indicate a positive outcome and can skew the reality of things if analyzed solely. Moreover, the fact that teams were executing non-critical tasks on the expense of critical tasks further indicates, as in Project 1, a problem in resource allocation and utilization and an unnecessary generation of waste.

3.2.4. Analysis of resource allocation patterns through Glut, Starvation, and MF metrics

The Glut, Starvation, and MF metric values were measured on Project 2 and depicted in Fig. 11. Results show that up to week 53, these metrics had average values of 30 tasks (19% of total Completed), 33 tasks (20% of total required), and 63 tasks (39%) respectively. Compared to Project 1, Project 2 had a higher number of non-critical tasks being overindulged by resources as well as a higher number of critical tasks starving for these resources and not being completed. The MF is consequently higher indicating a clear issue with resource utilization from the beginning.

The situation worsened beyond this time period where the calculated metrics increased to an average Glut value of 96 tasks (29% of total Completed) and a Starvation value of 69 tasks (23% of total required) resulting in a Misallocation Factor of 163 tasks. Moreover, high peaks in the MF metric was recorded towards the last weeks reaching a high 523 tasks. This peak is attributed to teams completing non-critical tasks and allocating needed resources to them instead of critical activities. This is reflected by the high 70% of Total Completed Tasks being non-critical on the final weeks. As observed in Project 1, the recorded results can be due to the emergence of New tasks and the increase in the number of committed tasks on the WWP in the absence of proper prioritizing of resource allocation.

3.2.5. Analysis of critical resource allocation and schedule performance through Starvation and MV metrics

The resulting Starvation trend over the duration of Project 2 showed that almost one quarter of the required tasks on the WWP were not completed as they were starving for resources. As discussed in Project 1, failing to execute critical tasks would result in schedule delays. While Project 1 displayed adherence to the schedule in its early stages, Project 2 consistently showed delays in schedules, except for a few weeks in the project's early stages, as indicated by the Milestone Variance pattern shown in Fig. 12. This is consistent with the higher values of Starvation and Glut metrics that Project 2 registered from the early stages as opposed to Project 1. On average, workflow streams in Project 2 were behind schedule and the situation gradually worsened as the project progressed where more critical tasks starved for resources that were instead allocated to non-critical ones.

The results of Project 2 are consistent with the observed findings of Project 1, indicating that the uncompleted critical tasks result in schedule delays reflected by the Milestone Variance metric.

4. Discussion of findings

The analysis of the calculated metrics on Project 1 and Project 2 reveals several underlying issues. First, teams displayed problems in matching the chosen load with available capacity as the project progressed. This was detected by measuring the CLR and WD metrics showing, beyond the initial stages of the project, that teams were over-utilizing their available capacity while executing less than the committed tasks. Second, the value of PPC on Project 1 decreased slightly while it increased on Project 2. Such PPC results would normally indicate that teams are properly executing tasks as per the WWP. However, assessing the resulting RPC and RCR metrics as the work streams increased proves otherwise. In fact, RCR and RPC on both projects indicated that only a portion of the critical tasks was being completed at the expense of completing non-critical ones.

These trends can be further attributed to a third issue pertaining to resource allocation. In this regard, the Glut, Starvation, and Misallocation Factor metrics were measured on Project 1 and Project 2. As mentioned earlier, the high Glut metric values recorded in the later stages of both projects indicate that teams are completing non-critical activities and hence committing resources towards them. While such a situation does not necessarily have to be a concern when critical tasks are on schedule, it becomes alarming when Starvation metric values are equally high as observed on the projects. The increase in the Starvation values as well as the MF values towards the end of the projects is a direct sign

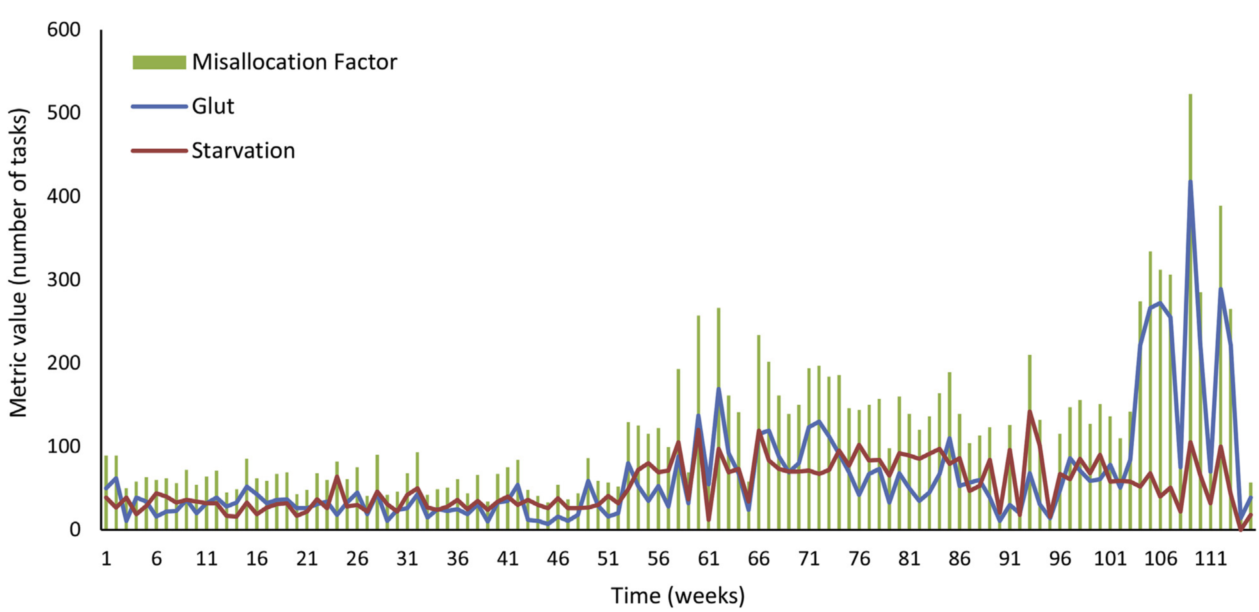

Fig. 11. Glut, Starvation, and Misallocation metric values of Project 2.

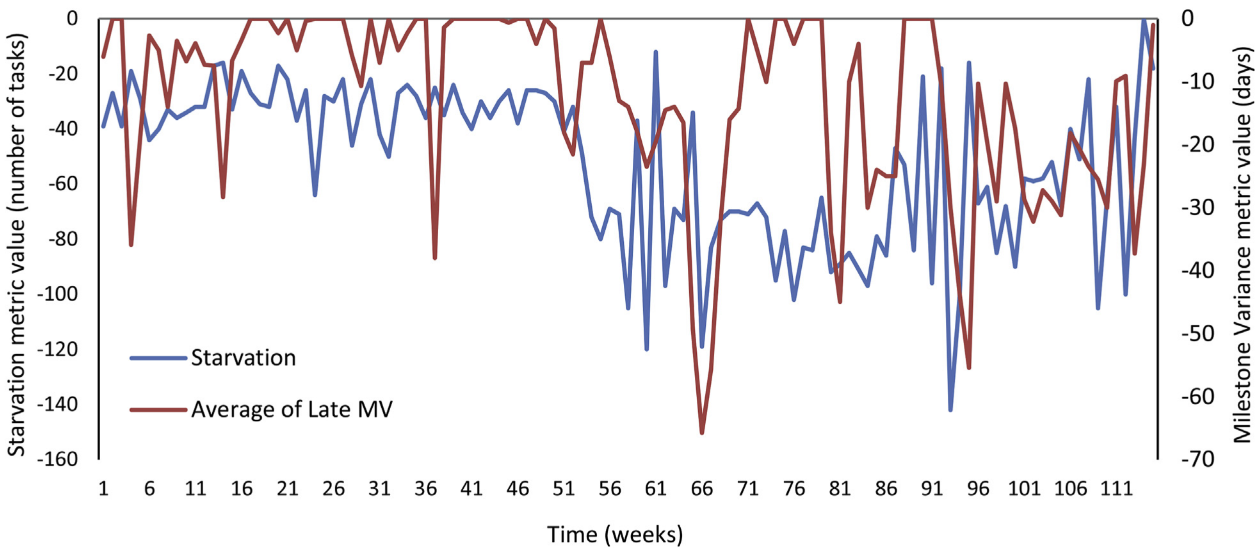

Fig. 12. Starvation and Milestone Variance metric values of Project 2.

that teams were starving critical tasks, that, as a result, were not completed. Given the limited number of resources on construction projects, prioritizing their allocation among critical and non-critical tasks plays a crucial factor in capacity planning. The sub-optimal assignment and utilization of resources are considered major wastes on projects and reflect unsustainable planning trends.

Fourth, beyond wrong resource allocation and prioritization, failing to execute critical activities leads to delays in workflow streams. The measurement of the Milestone Variance metric, which is an indicator of schedule performance, revealed setbacks in the teams' ability to adhere to the required milestone deadlines. Not allocating the required resources resulted in critical tasks not being completed, which, consequently, resulted in delaying the schedules on both projects.

Finally, the observed decline in the teams' performance was analyzed in light of the type and number of tasks committed. As the project moved forward, different work packages kicked off and new teams joined the project. Multiple trades were working in parallel. As a result, New emerging tasks were added to the weekly work plan creating more burden and pressure on the limited resources and on the execution of already committed tasks. Moreover, the works of different teams are interrelated where the works of some teams can be prerequisites to those of other teams. Consequently, if one team fails to complete required tasks that are necessary for other teams to proceed, a ripple wave effect will ensue. The main culprit behind the emergence of New tasks in first place is the inherent uncertainty and deficiencies in the lookahead planning process. Moreover, New tasks can emerge due to an inadequate make-ready planning process where tasks that are expected to be ready by the time of execution are not identified nor planned for in the weekly work plans. Although these matters cannot be completely eliminated, their impacts can be alleviated by proper planning techniques, making tasks ready, as well as the early acquisition and sharing of necessary information.

The culmination of the observed problems can provide a set of important insights. Teams on these projects used the vPlanner software and applied the LPS to better align near-term and long-term plans while removing constraints and reducing wastes. However, since the data was obtained retrospectively, teams were not aware of the capacity planning metrics that were derived in this study. Not being aware of their capacity planning performance deprived the teams of their ability to improve their techniques or pinpoint issues that need to be tackled. However, this fact helped show the need for the proposed metrics and the extent of the capacity planning issues in hindsight of the proposed metrics. In addition, existing metrics such as PPC, MV, and other planning metrics currently utilized in the industry are not alone sufficient to fully understand and improve planning performance. Similarly, the suggested metrics alone would come short in the absence of the existing metrics.

Therefore, the suggested capacity planning metrics are meant to complement existing ones so teams and managers can better align forecasted and actual performance. It is important that a metric not be assessed as a standalone measure as this will result in a biased and incomplete depiction of reality. A collective analysis is thus a cornerstone in bringing about an objective and wholesome evaluation of performance. This enables a successful and more effective achievement of planned targets without wasting resources which are usually limited and costly. Although these results were observed on two high-performing projects in the US, several capacity planning issues were observed. Further studies in other parts of the world should be conducted for further validation.

5. Conclusions

5.1. Summary of the study

Reliable planning and control are main drivers in steering a project towards its objectives by ensuring its timely execution and adherence to quality, cost, and safety considerations without generating waste. Since it is hard to improve what cannot be measured, several metrics have been developed in earlier research to improve on the planning efforts. Although the use of these metrics in the industry has shown positive outcomes, there is lack of metrics that assess the performance of capacity planning at the weekly work planning level. Therefore, this study presents new capacity planning metrics to provide a deeper analysis of the current state of planning on construction projects. These suggested metrics help assess the performance of teams on projects in regards to load and capacity matching, resource allocation, and work stream schedule performance.

Seven metrics related to capacity planning are introduced in this study: (1) CLR metric compares the available capacity to the chosen load, (2) RCR metric indicates how many tasks were required (critical) out of all those Completed during a given week, (3) RPC metric depicts the percentage of critical tasks completed out of the committed critical tasks, (4) WD metric assesses the deviation from the weekly work plan by measuring how many tasks failed to be Completed, (5) Glut metric measures how many non-critical tasks are being indulged by resources, (6) Starvation metric measures how many critical tasks are starving for resources, and (7) Misallocation Factor which sums the Glut and Starvation and gives an indication of the extent of the misallocation of resources. All these metrics employ the actual completed tasks on the weekly work plan to estimate where resources have been allocated. Thus this assessment gives an estimate of actual resource allocation as the real numbers are very difficult to track on construction projects.

5.2. Summary of results

The calculation of the proposed metrics on two projects in the US revealed several issues such as load and capacity mismatching, improper allocation and utilization of resources among critical and non-critical activities, and deviating from the set weekly work plans by not executing all committed tasks. Moreover, the resulting metrics show that analyzing a metric individually can yield misleading interpretations and biases in the outcomes. Therefore, the developed metrics are meant to complement existing metrics and should be analyzed collectively to achieve a comprehensive and objective assessment. The metrics are applicable in a universal context on any project properly applying the LPS and can be readily used by the construction industry to uncover the implicit pathologies in current capacity planning practices.

5.3. Contributions and further research

The research presented contributes to practice by aiding last planners and responsible parties in identifying problems in capacity planning so they can undertake the necessary measures to improve their performance and prevent the unnecessary wasting of valuable resources. Moreover, this study extends the knowledge on existing research regarding construction planning procedures to highlight hurdles in current strategies so that the right steps can be put forth and implemented to counteract prevailing problems. Ultimately, by properly utilizing resources, prioritizing activities, and avoiding time and cost overruns, production wastes generated can be diminished. The latter is achieved by proper quantitative tools for effective planning and management strategies.

Further research can extend this study to include facets such as cost analysis and productivity in evaluating capacity planning and project performance. Additionally, applying the derived metrics on more case study projects can increase the validity and robustness of the obtained results and provide further insights into the dynamics of capacity planning on projects. Moreover, adopting action research in future case studies can enable real-time monitoring, feedback, and adjustment of analyzed performance.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.04.021.

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