ABSTRACT


Due to increasing complexity and inefficiencies in project control system design and implementation, construction projects struggle to achieve initial cost and schedule performance goals. Assessment of project progress and performance is critically important to the successful delivery of capital facility projects. Often, project managers are misled in their perceptions of project performance until the project nears its end. Major challenges are related to the lack of consistent, reliable, and objective metrics and indicators. This research identified several core predictive and diagnostic metrics that can help provide actionable insights into a project’s actual progress, performance, and forecast at completion. It also provides information on ways to improve the reliability of these metrics.

The research methodology included a broad literature review to identify progress, performance assessment, and forecasting metrics. Next, a survey was distributed to collect data on metrics and reliability concepts that were used on completed projects. In total, 44 surveys were completed, representing mostly large, industrial projects. This was followed up by a Delphi session including 16 subject matter experts with more than 360 years of experience in total, who evaluated and validated the findings from the survey and case studies. The Delphi session further refined a list of metrics and determined 20 core (“must have”), 7 validation (metrics that confirm the validity of the core metrics), 7 innovative (metrics that are not currently in wide use, but are considered potentially beneficial), and 14 other significant (other metrics that fall outside the previous categories, but are perceived to have value).

A metric typology and framework defined predictive and diagnostic metrics with the purposes of achieving consistent project control procedures across the industry. Details of various
predictive and diagnostic metrics are visualized using metric maps and a network. Network analysis revealed interrelationships among metrics.

Statistical analysis of survey responses with Spearman’s rank correlation revealed that compared to projects using fewer core metrics, projects that used more core metrics for project controls experienced higher rates of success at meeting their original budgets. A correlation between the use of more core metrics and better project cost outcomes was observed at the 95% confidence level using the Spearman’s rank correlation method. At the same confidence level, utilizing more diagnostic metrics was shown to be correlated with better schedule and cost outcomes as well. Further statistical assessment using Multiple Correspondence Analysis demonstrated that usage of certain metrics are more closely associated with better cost and schedule outcomes.

Core metrics were initially selected based on the following project characteristics: large, industrial, reimbursable cost, balanced cost and schedule goals, moderate complexity, and contractor perspective. However, when considering core metrics for other project characteristics, it was discovered that the core metrics will be the same—the only differences relate to the frequency of data collection and level of effort involved in collecting and analyzing these data.

Additionally, factors for improving metric reliability in several areas such as project scope definition, execution planning, and risk management were also included. Ten projects were selected for case studies, which provided more in-depth analysis on metrics and reliability issues. 15 critical reliability factors and 85 indicators were identified for improving the reliability of project control metrics. An expert panel verified these findings and added phase specific timing details for application of the factors and indicators.
Based on the findings of this research, a Project Controls Improvement (PCI) Tool was created to provide a standardized and systematic tool for project controls. Using the PCI Tool, project stakeholders can identify the gaps in their project control systems and learn more about core metrics and steps they can take to improve metric reliability within a dynamic and interactive software environment.
Metrics That Matter: Improving Project Controls and Analytics in Construction Industry

by
Resulali Emre Orgut

A dissertation submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

Civil Engineering

Raleigh, North Carolina

2017

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________________________________
Edward J. Jaselskis
Committee Chair
DEDICATION

Aşık Veysel, a Turkish poet, once wrote:

“In a mansion with two doors / I walk day and night.”

This dissertation is dedicated to

My late grandfathers, Ibrahim Orgut and Mehmet Ihsan Erlat, who left this mansion by the door at the end and they will be forever missed;

My son, Emre Orgut, who just entered by the first door and brought us all the joy in the world;

and

My wife; Irem Sengul Orgut, for always walking beside me day and night.
BIOGRAPHY

Resulali Emre “Res” Orgut was born in Sakarya, Turkey on May 9th, 1987. After graduating from Kadikoy Anatolian High School in Istanbul, Turkey in 2005, he received his Bachelor of Science in Civil Engineering and Master of Science in Construction Management degrees from Istanbul Technical University in Istanbul, Turkey in 2010 and 2012, respectively. During his undergraduate studies, he was an ERASMUS Exchange Student for Spring semester of 2008 in the Universitá della Calabria in Cosenza, Italy. After finishing his master’s studies, he joined the Department of Civil, Construction, and Environmental Engineering at North Carolina State University (NCSU) in Raleigh, NC, and began pursuing his Ph.D. degree under the guidance of Dr. Edward J. Jaselskis.

His research interests are focused on improving project control systems and performance analytics with the use of qualitative and quantitative analysis tools. His research is motivated by the problems in construction project controls and aims to find proven metrics and develop robust frameworks for systematic, consistent, and reliable assessment of project progress and performance.

During his doctoral studies at NCSU, he held research assistantship positions. He won several awards with his dissertation work, such as the second place in the Engineering Category at the 11th Annual NC State University Graduate Student Research Symposium in 2016 and the second place in the 2nd Annual NC State University Three Minute Thesis Competition in 2016. He was also awarded Johnston Graduate Award in Construction Engineering by the Department of Civil, Construction, and Environmental Engineering (CCEE). During his doctoral studies, he held positions as a Technology Commercialization Analyst for Poole College of Management.
Advanced Commercialization of Technologies program and as a Data Analyst for NCSU Facilities Division Energy Systems. His professional experience also includes a Project Engineer position at Zorlu Center, a multi-use megaproject in Istanbul, Turkey.

He is currently the president of the Civil Engineering Graduate Students Association (CEGSA), president of the National Association of Home Builders (NAHB) and the founding president of newly formed Construction Management Association of America (CMAA) Student Chapters at NCSU. He was also elected for and served as a Graduate Student Senator for the 93rd Session of the NCSU Student Senate for the 2013-14 academic year. During his tenure at NCSU, he served on several university committees and initiatives both as a leader and a member. He is a member of American Society of Civil Engineers (ASCE), CMAA, Professional Engineers of North Carolina (PENC), Institute for Operations Research and Management Science (INFORMS) and Chi Epsilon (Civil Engineering Honor Society).

Upon graduation, he will be joining Fluor Corporation as the Project Controls Specialist II for the Novo Nordisk DAPI-US project in Clayton, NC. He will also stay involved with the CCEE Department as a member of the Student Advisory Board and Zia Lecture Committee.
ACKNOWLEDGEMENTS

I feel overwhelmed with gratitude towards the following people, for I know that none of this would have been possible without them.

First and foremost, I would like to express my deepest appreciation to my advisor Dr. Edward J. Jaselskis for his guidance, support and patience. It was with his motivation and encouragement that I became the researcher and the professional I am now, and I am eternally grateful for all that he has done for me.

My sincere thanks also go to Dr. Ali Mostafavi, for all his help and invaluable guidance. He showed me the best ways to learn and adopt from other domains. I am also grateful to Drs. Jin Zhu and Mostafa Batouli for their support and professionalism but also for their friendship and sharing this journey with me, through thick and thin.

I would also like to thank Drs. Min Liu and Alex Albert for their feedback and support. I would like to specifically thank Dr. Steve Barr for teaching me the value and beauty of entrepreneurial thinking, which completely transformed the way I look at research and business. I also appreciate that he agreed to be my graduate school representative.

I would like to acknowledge the support for this research, which was funded by the Construction Industry Institute under Research Team 322. I would also like to thank NC State CCEE Department, E.I. Clancy Distinguished Professorship fund, and David W. Johnston Graduate Fellowship for their additional financial support. Also many thanks to Charlene Couch and Heather Bowlan for their continuous help and support with the editing process.

I have been very lucky to be a part of the CCEE Department at NC State. I would like to thank all the faculty and staff members for making me feel at home and for keeping their doors
open. Dr. Ranji Ranjithan, Lora Bremer, Lindsay Smith, Barbara Simerson and Toni Pascucci have provided me their support at every opportunity. I would like to specifically thank Renee Howard (a.k.a. “the godmother of all CCEE graduate students), for being the most helpful, understanding and caring Graduate Services Coordinator I could ever ask for.

NC State always offers the best resources for personal, professional and academic development, and I have been lucky enough to be on the receiving end of these opportunities. I am indebted to Dr. Meagan Kittle-Autry for teaching me the intricacies and the beauty of effective writing to convey my ideas in a much clearer and better way. My thanks also go to Dr. Justin Post for teaching me how to use statistics the right way whatever the case is, but also for his understanding through tough times. Dr. Peter Harries, Dr. Laura DeMarse and everybody at the Graduate School for all the invaluable resources they offer. Alison Blaine, Jennifer Garrett and everybody at the NCSU Libraries for all the time and effort they spent on preparing and presenting those amazing workshops and activities.

I owe everything in my life to my loving and caring family. Without the continuous support of my parents, Demet and Melih Orgut, I couldn’t have even imagine of this journey and where I am now. They provided me the best life I could ever ask for. They helped and encouraged me at every stage, showed me how to keep going persistently and pursuing my dreams. None of this would be possible without their unconditional love, and I am lucky to have them as “Annekus” and “Babus”. I am also lucky enough to have the most caring, thoughtful and supporting brother one could ever have. Although I am his senior, sometimes it does not feel that way, I am eternally grateful to have “Memo” on my side, no matter what. I am also deeply grateful to my aunt Bukef Erlat and my grandmother Sebahat “Nana” Erlat for surrounding me with their love, and for always
having my back whatever the endeavor I choose to pursue. I am thankful for my late grandfathers Ibrahim Orgut and Mehmet Ihsan Erlat for being my role models on how to live an honest life. I know they will be protecting me under their wings as angels in the heavens above. My thanks also go to Nadire “Manne” Orgut, Meral Atasoy, Erol Atasoy, and Abdullah “Apo” Atasoy for all they have done for me.

I would like to thank my second family, Fusun Sengul and Mehmet Sengul, for also being my parents, putting a hold on their lives, supporting me when I needed the most, and being the most amazing grandparents. I would also like to thank Ayser Kalipci and late Orhan Kalipci for welcoming me to their family but also for somehow making me feel like I had always been a part of it. I am very lucky to have all of you in my life.

I am very fortunate to call the following people not only my friends, but also my extended family as they have been much more than friends. I would like to thank Memet Candalay, Hatice Cetin, Enis Goktepe, Gulcan Uysalol, Enis Uysalol, Tugce Tokus, Mert Sertoglu, Yetkin Cetin, Selim Suman and Ozan Kirman as I cherish every minute we have spent together and look forward to many more. I would like to specifically thank Erinc Albey for being a mentor, friend, comrade, and the big brother I have never had. My thanks also go to Muge Capan, Carl Pankok, Gokce Akin Aras, Korhan Aras, and Elif Albey for sharing this journey with me and making it more fun.

A very special thanks to my son, Emre Orgut, for bringing joy and happiness to my life to the extent I did not even know possible, for making everything more meaningful and purposeful, and for making me realize I can never love you enough. I am grateful to see your smile every single day and I wake up every morning to make sure that smile always is there.
Lastly, I would like to thank Irem Sengul Orgut, my best friend in the world, my confidant, my sun, my moon, my stars, my wife. Words are never enough to express my gratitude to you for everything you have done for me, for always leading the way for me; for supporting, understanding, and challenging me; for your kindness, caring and compassion; and finally, for being the best mom in the world, every single day. You make everything more fun, more meaningful and more enjoyable. You make me happy, calm and proud with everything you do. I could not have even imagine any of these without you. Knowing that you are always on my side, and you always have my back are the best feelings I could ever ask for. I have always loved sharing every minute of my entire adult life with you, and I am very excited to have many more adventures with you.
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1 Introduction

1.1 Background and Need

Performance and project control system inefficiencies, combined with increasing complexity in project execution, are plaguing construction projects to achieve their cost and schedule performance goals. According to the Construction Industry Institute (CII), only one in every 20 projects meet both its authorized cost and its schedule within an acceptable margin, while almost 14 out of the same 20 projects suffer from more than 10% variation compared to authorized values (CII, 2012). Project managers and control teams are often asked:

- When was the last time one of your projects experienced cost and/or schedule overruns?
- Which metrics and indicators provide you with the greatest insight and predictability for determining project outcomes?
- Are you sure the right assessment tools, metrics, and indicators are in place to reliably assess project progress and performance?
- How effective is your senior management and project team at using and interpreting project control metrics and indicators?

Assessment of project progress and performance is critically important to the successful delivery of capital facility projects. Major challenges related to measuring project progress and performance include the lack of consistent, reliable, and objective metrics and indicators, and the lack of appropriate interpretation of these data for establishing suitable corrective action plans. Often, project managers are misled in their perceptions of project performance until the project nears its end. This lack of accurate project progress and performance information is a major issue that causes performance shortcomings and resource shortfalls.
One major obstacle to understanding the actual conditions of a construction project is the subjective and inconsistent use and interpretation of metrics related to progress measurement, performance assessment, and forecasting. Many companies measure progress and performance during project execution by utilizing a variety of metrics and indicators. Analysis of the current methods reveals that there is no systematic, consistent and efficient approach to identifying and using progress and performance assessment metrics in the construction industry. This results in performance of projects being potentially misrepresented and causes issues since the true project progress and performance is not known. Too many subjective inputs allow for easy manipulation or misrepresentation of project progress and performance within the current matrices and rules of credit. Limitations of existing methods in providing a “true” measure of project progress and performance is a critical issue for construction industry stakeholders.

Some say that the metrics used to assess progress and performance are sound and that the larger issue pertains to conformity across the industry. In other words, if all “players” in the industry used the same or similar methods to track progress and productivity, then there should be little ambiguity in reporting. However, during project setup, a great deal of time is spent between owners and contractors agreeing on what metrics should be monitored and how they should be monitored. This process could be streamlined with a concise set or list of metrics that are proven to correlate with successful project outcomes (e.g., on/under budget; on/earlier schedule, etc.). Establishing a reliable standard might alleviate the need to “reinvent the wheel” for many projects. The industry needs standard, objective ways to assess a project’s progression and performance. Currently, there is no proven, accepted standard for how projects should be properly controlled that accurately conveys timely progress and performance information.
Clearly, there is a growing need to identify true metrics and measures for assessment of project progress and performance. Problems with poor project performance can be solved, in part, with better use and interpretation of project control metrics and indicators. However, it remains unclear which core metrics and indicators are essential to achieving better project cost and schedule performance assessment. This study proposes a systematic approach to identifying key metrics and indicators during the engineering, procurement, construction and start-up and commissioning phases of a project. Results will provide insights for improving future project performance. This research will enable the industry to improve project progress and performance assessment practices by:

• Identifying key (core) metrics and performance indicators;
• Improving the reliability of the key metrics.
• Understanding how better to use and interpret these metrics and indicators; and

In short, this study addresses two essential questions: 1) How can we better assess project progress and performance and provide insight for future project improvement? and, 2) What are the most useful parameters and indicators for assessment?

1.2 Problem Statement

Two problem areas relevant to improving assessment of project progress and performance are addressed in this study:

Problem #1: There is a lack of consistency in the use of metrics for progress measurement and performance indicators. Currently, there is no consistent set of progress metrics and performance indicators being used in the construction industry. Different companies use different metrics and indicators, in different projects. Earned value (EV) metrics and indicators are widely used in the
industry; however, there are companies that use other approaches to assess progress and forecasting performance. Therefore, it is difficult to have a true comparison of one project's performance to another, much less to forecast future performance if the metrics and indicators vary by project. Hence, there is an obvious need for a framework and a typology that identify core metrics that should be used consistently on capital facility projects in order to deliver better progress and performance assessment.

Problem #2: There is a lack of guidance on improving metric reliability. For example, each company might use a slightly different approach for determining the percent complete of design documents. "Approved for Design" drawings are assigned points and credit values differently from one company to another. There is no consistent definition and acceptance criteria for what "Approved for Design" drawings really means. Such inconsistencies increase the potential for misrepresentation of information. Hence, it is essential to develop clear guidelines and procedures for improving the reliability of the project control metrics and indicators.

1.3 Research Objectives and Hypotheses

The overarching objective of this research is to improve the current and future project progress and performance through the improvement of the assessment process. Three specific objectives are identified, as follow:

Objective #1: Identify the gap in the existing body of research with regards to lack of systematic project controls applications, and address it with a new metric categorization framework. This new framework – supported with the relevant typology, metric information (e.g., definition, indicators, use and interpretation), metric maps and network – is a step towards standardization of project controls across the industry.
Objective #2: Identify the core metrics and validate their value for improving the assessment of project progress and performance. Develop a proven, accepted metric classification system that describes how projects should be properly controlled that accurately conveys the progress and performance during the execution phase. Focus on the core metrics that provide actionable insights for improving progress and performance assessment of projects.

Objective #3: Identify critical factors and related indicators for improving the reliability of project control metrics. Remove as much subjectivity as possible so that standardization can be achieved across the industry. Connect these factors and indicators with specific phase based timing throughout the lifecycle of a project for continuous assessment and improvement.

Based on the objectives, three hypotheses were identified for this research study as follow:

**Hypothesis 1:** There are patterns, interrelationships and similarities in terms of the functionality of project control metrics that would allow for a standardized framework and typology. These two components for using and interpreting metrics would improve their capacity for predicting project outcomes and providing actionable insights.

**Hypothesis 2:** There are core metrics and measures that can provide better assessment of progress and performance of projects across different phases. If project decision makers align on a standardized set of metrics for progress and performance assessment, changes in project progress and performance can be addressed earlier during execution and lead to improved project outcomes.

**Hypothesis 3:** There are guidelines and implementation approaches that can improve the reliability of existing progress and performance assessment methods. While various industry methods of project progress and performance assessment exist, the “quality of the assessment” cannot be determined because there is no industry standard that evaluates the reliability of these methods.
1.4 Acknowledgements

This study is a part of a research effort that has been supported by the Construction Industry Institute (CII). CII Research Team 322 (RT-322) focused on improving project progress measurement, performance assessment, and forecasting, through identification of core metrics and reliability improvement measures. Industry members of RT-322 contributed to identification and review of metric lists and categories, development of surveys, analysis of case studies, finalizing most components of the research. The opinions expressed in this research represent those of the authors and not necessarily those of the Construction Industry Institute.

1.5 Organization of the Dissertation

This dissertation follows the “multiple publication” format. Chapter 2, 3, and 4 are planned to be submitted for publication in peer-reviewed journals. Each of these chapters has its own introduction, methodology, and conclusions sections. Chapter 5 is previously published as a part of a Construction Industry Institute Research Report by Jaselskis et. al (2016). Chapter 6 summarizes the findings, contributions, limitations and future work directions of this research. References of each chapter are listed as a whole, at the end of this dissertation. Table 1.1 provides an overview of the purposes and major contents of each chapter.
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<th>Purpose</th>
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<td>Problem statement and research background; research objectives and hypotheses.</td>
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<tr>
<td>2</td>
<td>Metric Framework</td>
<td>Identifying the gap in the existing body of research with regards to lack of systematic project controls applications, and addressing it with the development of a new metric categorization framework and typology.</td>
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<td>3</td>
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<td>Determining and validating a certain set of metrics as core, which provide actionable insights for improving progress and performance assessment of projects.</td>
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<td>4</td>
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<td>5</td>
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<td>Development of the Project Controls Improvement (PCI) Tool, which was built upon the aforementioned metric and reliability components for the purpose of providing the industry with a tool that can help improve progress and performance assessment.</td>
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<td>6</td>
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<td>Summary, contributions, limitations, future work.</td>
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2.1 Abstract

Assessment of project progress and performance is critically important to the successful delivery of capital facility projects. However, different companies use different metrics on different projects. Without a standardized structure for project control metrics, it is difficult to transform data into meaningful actionable insights for analyzing project progress and performance. This study aims to identify the gap in the existing body of research with regards to lack of systematic project controls applications, and addresses it with a new metric categorization framework. A novel typology was developed to identify project control metrics as either predictive or diagnostic. Project control metric calculations are visualized in metric maps and a network comprised of these maps clearly demonstrates the interconnectedness of metrics. Presented in this research, the new framework, together with relevant typology, metric maps and the network, establish a step towards standardization of project controls across the industry.
2.2 Introduction

Construction is a large industry valued $1.2 trillion in the US (US Census Bureau, 2016; IBISWorld, 2016) and $8.5 trillion globally (Construction Intelligence Center, 2016). Nevertheless, construction projects suffer from significant performance inefficiencies. According to the Construction Industry Institute (CII), only one in every 20 projects meets both its authorized cost and schedule within an acceptable margin (CII, 2012). Industrial-sector Engineering, Procurement and Construction (EPC) contractors among CII members struggle to generate any profits in three out of five of their projects (CII, 2014). Yet, an overwhelming majority of construction decision-makers believe that their projects are “healthy” (A.T. Kearney, 2012). Often, project managers are misled in their perceptions of project performance until the project nears its end (Lipke, 2003; Vandevoorde and Vanhoucke, 2006; Lipke, 2009; Vanhoucke, 2009; NDIA, 2014). This obvious disconnect between the perception and the reality of project performance is mainly due to the lack systematic measurement and assessment of construction project performance.

Many companies measure progress and performance during project execution by utilizing a variety of metrics and indicators without using a systematic approach, which is essential to understand the nature, type, and importance of various metrics and specify the relationships among metrics and their underlying data. The review of literature reveals that currently there are more than 110 distinct metrics used in construction project controls. However, the lack of a systematic approach prevents identifying the metrics that are the most insightful in representing the true performance of construction projects. Therefore, it is difficult to have a true comparison of one project's performance to another, much less to forecast future performance if the metrics vary by project.
The industry needs objective ways to assess a project’s progression and performance. Current project control approaches lack the categorization structure that would clearly define which metrics are more useful in terms of transforming project data into meaningful and actionable insights. There is an obvious need for development of a such structure to help improve project progress and performance assessment. Establishing a reliable framework might alleviate the necessity to “reinvent the wheel” for many projects.

This research presents a framework that systematically categorizes metrics based on how they can be used to answer a certain set of key project control questions. This intuitive categorization provides industry stakeholders with a tool to improve project controls and overall progress and performance of projects.

2.3 Current Project Control Systems

2.3.1 Background

A methodical review and synthesis enables the identification of gaps in the literature that can inform current and future research. Despite the vast body of literature in the area of project progress and performance assessment, few studies provide systematic review and gap analysis related to the key performance indicators of project controls. Individual project control systems and methods are studied extensively in the literature. Various studies have investigated project progress and performance assessment. Grau and Back (2014) thoroughly identified factors that influence the predictability of the project outcome through their “Four-casting Assessment Tool”, which included Project Characteristics, Forecasting Practices, Management Processes and Continuous Assessment, all under the foundation of Human Behavior and Organizational Cultural Influences. Understanding these parameters of project success is a helpful first step toward identifying the
metrics by which to measure project performance. They found that earned value is a common technique (or “indicator”) used to forecast both project cost and schedule (Grau and Back, 2014). In addition to predictability analysis, effective project progress and performance assessment requires robust measures that enable proactive monitoring and control.

Since the rise of project controls systems in the 1950s, the construction industry has gone through a great deal of transformation, and project control systems have adapted to these changes. From initial standardization efforts and birth of EVM in 1960s, to development of more versatile tools to meet the needs of international and megaprojects, systems of project controls have continued to evolve (Morris, 1982; O’Brien, 2006). Thanks to advancements in computing during the 1980s, project control systems have become an integral part of the project life cycle (Ibbs et al., 1987; O’Brien et al., 2012). All these efforts represent attempts to better manage and control construction projects. The construction industry has adopted many methods and terminology that were originally developed for military and defense purposes. For instance, well-known planning and scheduling techniques, such as Critical Path Method, or CPM, (by DuPont) and Program Evaluation and Review Technique, or PERT, (by US Navy) were initially developed to be utilized in certain military and defense projects in the 1950s (O’Brien, 2006; Kenley and Seppänen, 2010). Therefore, it is not surprising that military terms, such as “operational,” “tactical,” and “strategic” are frequently used to define different decision levels of construction project controls. However, there is no consensus among construction industry stakeholders as to what these terms represent in a traditional project controls setting. The Association for the Advancement of Cost Engineering (AACE) International approaches the “strategic” and “tactical” levels as different layers of the investment decision-making process, whereas the term “operational” defines ongoing endeavors
or activities (AACE International, 2012). The Project Management Institute (PMI) recognizes operational, tactical and strategic project levels as organizational layers of a portfolio management structure, which would require operational functionality, tactical efficiency and strategic planning (PMI, 2013). PMI also offers guidelines to identify the work performance structure through information and data flow between project control functions as they relate to project progress and performance (PMI, 2013). However, PMI’s and AACE’s considerations to defining project controls lack a single project emphasis, since both mainly focus on portfolio level management and consider each project only as a component of a bigger program. Concentration on project controls structure at the single project level would help identify areas of improvement.

2.3.2 Key Components

Key functional components of a project control structure (i.e., progress measurement, performance assessment, performance forecasting) take place in a cyclical manner. This cycle of assessment is repeated for every new reporting period until the project is completed. Based on an extensive literature review and input from industry experts the authors interviewed and developed a visual interpretation of the current project controls life-cycle commonly used in the industry (Fig. 2.1). The operational level basically serves the purpose of understanding the current state of the project. It mainly contains measurements of progress in terms of cost and schedule. At the tactical level, data from progress measurement metrics and indicators obtained in the operational level are compared against the authorized baseline values to identify cost, schedule and efficiency variances and to understand the true current state. Finally, at the strategic level, the future state is predicted based on the current performance trajectory. Influencing factors such as safety and quality are shown in the middle as they interact with different components of this structure by either affecting
or being affected by them. Considering the project controls cycle, it is essential to investigate components of this system further.

![Project Controls Cycle diagram](image)

**Figure 2.1** A typical project controls cycle for a single reporting period.

### 2.3.2.1 Progress Measurement

The successful execution of a project hinges on numerous factors, but one fundamental question that should be answered as the first step in the control process is, “What has been accomplished so far?” Progress measurement addresses this question at the operational level and serves as the basis for assessing, forecasting, and improving project performance.

The term “progress” is defined as forward or onward movement toward a destination (Merriam-Webster, 2015). Therefore, progress measurement relies on the data collected to determine the advancement of different work tasks (O'Brien et al., 2012). Here, the authors define progress measurement as the measurement of outcomes and throughput of a project at a certain point in
time. Progress measurement provides the fundamental information associated with where the project is in terms of completion.

Metrics and methods for measuring the progress of a project in terms of cost and schedule have been studied extensively by many researchers (Barrie and Paulson, 1992; Carr, 1993; Abudayyeh and Rasdorf, 1993; Thomas, 2000; Chin et al., 2004; Yang et al., 2007). There are several metrics used to measure construction project progress depending on the activities and work items. Since one complete project usually includes different types of tasks, multiple progress measurement methods are often used. One limitation in the existing body of knowledge is the lack of an integrated framework to facilitate applying various progress measurement methods systematically in the project. The implementation of different progress measurement methods is usually based on the project manager’s experience instead of objective criteria. This subjectivity may cause problems in providing true measurement of project progress in an efficient and effective way.

2.3.2.2 Performance Assessment

Progress measurement is essential for successful project execution, although it is not adequate by itself for effective project controls. Fundamentally, the term “performance” is defined as the act of doing a job, an activity, etc. (Merriam-Webster, 2015). Thus, performance assessment is vital in comparing measured progress against the baseline and identify variances from planned performance of the project (AACE International, 2012). Here, the authors identify performance assessment as the evaluation of the existing outcomes and results of the project cost, schedule and efficiency at a given point in the project cycle.

Essentially, performance assessment answers the question, “What should have been accomplished so far?” The answer determines whether a project has gone as intended by calculating variances
between actual and planned values of cost and schedule data (O’Brien et al., 2012). For this purpose, performance assessment methods and metrics seek answers for questions like: “Have activities been completed as planned? Have outputs been produced as anticipated? Is the work of the project progressing as projected?” Therefore, at a fundamental level, performance assessment is a passive process in which nothing changes about the project's progress or outcome. However, it tells the project manager about the current performance in terms of money, time, or other areas of performance (PM4NGOs, 2013). Performance assessment requires an established baseline of cost and schedule as a benchmark for comparing actual progress to planned work so that the progress and performance can be measured, assessed and, eventually, controlled (Oberlander, 1993; O’Brien et al., 2012).

There are several metrics and indicators used to assess performance of construction projects based on different approaches, with Earned Value Management (EVM) being the most commonly used in the construction industry. In the early 1960s, the Department of Defense lead the efforts for a standardized performance assessment and project control system, which eventually popularized the use of EVM in construction projects (Morris, 1982). Over time, due to not only certain shortcomings of EVM, but also the increasing complexity of construction projects, other innovative methods were offered as viable alternatives, such as Earned Schedule Method (ESM), Earned Duration Management (EDM) and Critical Chain Project Management (CCPM).

At the operational level, EVM captures three major values: Actual Cost (AC), Planned Value (PV) and Earned Value (EV) (Fleming and Koppelman, 2000). These values represent the measured progress in terms of cost. It is almost counter intuitive to measure time with dollar value. Therefore, one significant drawback of EVM is its inability to capture the schedule performance, especially
over the last third of the project (Lipke, 2009; Vanhoucke, 2009). In order to improve the schedule assessment ability of EVM, Earned Schedule Management (ESM) was proposed (Lipke, 2003). ESM relies on the same operational-level performance indicators as EVM (i.e., PV, AC and EV); however, it uses a new set of time-based performance assessment metrics to identify Earned Schedule (ES) as the point in time at which an amount of earned value should have been accomplished. Although ESM solves some limitations of time management in EVM, it still uses cost as a proxy to measure schedule performance of a project. Therefore, when a disparity exists between time and cost profiles, ESM fails to capture the distinctive schedule behavior of the project (Khamooshi and Golafshani, 2013). To address the limitations of EVM and ESM, Earned Duration Management (EDM) was developed, as an assessment method that decouples schedule and cost performance measures. EDM identifies a number of indices to measure progress and performance of schedule and cost, but separately (Khamooshi and Golafshani, 2013).

One common drawback of EVM, ESM and EDM is that none of methods make a distinction between delays on critical and none-critical paths. Also, the correlations between time and cost of different activities are not taken into consideration in any of these methods. The assessment of the project in all these methods is limited to time and cost; other performance measures, such as the quality of the final products, are not part of the analysis (Hall, 2012; Hazır, 2014). Critical Chain Project Management (CCPM) as an emerging approach for performance assessment, focuses on resource utilization and minimization of idle capacity (Goldratt, 1997; Leach, 2000). However, issues related to the stability of the critical chain and the network structure, as well as resource efficiencies and multitasking, remain problematic aspects of CCPM. The general weakness of
current performance assessment methodologies is the lack of consistency and implementation guidelines for metrics throughout the construction industry.

2.3.2.3 Performance Forecasting

Traditionally, the term “forecasting” is defined as to predict (something) after looking at the information that is available (Merriam-Webster, 2015). In a construction context, performance forecasting uses current state performance information to predict the future outcomes and results. This method basically answers the question, “What will be the performance outcome of the project?” Performance forecasting is a process of continuously predicting the final outcome of cost, time and other related resources that will be required to complete a project (O’Brien et al., 2012). Important to note is that performance forecasting relies on the information derived from progress measurement and performance assessment. Performance forecasting can be defined in three basic ways: (1) The remaining work will be completed at planned rates; (2) current performance rates will be sustained for the remainder of the project; and (3) an extrapolation of the trends to date will help project the rest of the work (CII, 1987). Most performance forecasting metrics utilize current knowledge to project future performance outcomes.

Earned Value Management (EVM) offers several useful metrics to forecast what the expected cost values are for the remainder of the project (Vanhouck, 2009). These metrics predict the final cost of the project based on the actual performance at the time of the assessment and the planned cost of the remaining work. However, these projections are highly dependent on the consistency of performance assessment metrics used and management’s opinion on some forecasted elements (Fleming and Koppelman, 2000). On the other hand, the adaptive behavior of the project managers is not factored into the progression of performance forecasts throughout the life of a project. (Hall,
Similar to the problems with assessment of schedule performance, schedule performance forecasting in EVM methodology suffers from using cost as a proxy and fails to deliver robust results towards the end of a project (Vanhoucke, 2009). ESM offers yet another alternative for schedule forecasting metrics (Lipke, 2009). The same pattern as with performance assessment metrics follows here: even though ESM metrics generate better results for schedule, they are yet to offer a robust forecasting alternative due to using cost as a proxy to estimate the schedule of a project. Overall, implicit issues with the performance forecasting is mostly due to the lack of consistent metrics throughout the construction industry.

2.4 New Project Control Concepts

2.4.1 Framework and Typology

Typically, project controls include the processes and tools necessary to execute, monitor and forecast all phases of capital projects (O’Brien et al., 2012). During project execution, be it during the engineering, procurement, construction, or the start-up and commissioning phases, the status of a project is constantly measured and carefully assessed (Choi et al., 2006). Without a consistent framework that identifies Key Performance Indicators (KPIs), it remains uncertain how effectively in-flight project controls data can be transformed into meaningful, actionable insights. It is vital to understand how data related to project progress and performance is utilized throughout the process. Adopting from the information science, knowledge management and systems thinking literature, one can explain how data is transformed into information, then into knowledge and finally into wisdom or insights through an effective process. This process – generally known as Data-Information-Knowledge-Wisdom, or DKIW, hierarchy (Ackoff, 1989; Bellinger et al., 2004;
Rowley, 2007; Sharma, 2008; Frické, 2009) – is often represented by a pyramid and depicts how each component builds onto each other.

Within the context of construction project controls, this structure shows how different project controls functions are tied to each other to provide meaningful, actionable insight for improving construction project performance (Fig. 2.2). The pyramidal model reflects the nature of how data are transformed to information, then to knowledge, which if interpreted correctly, provides valuable insight for current and future projects. As this framework explains how data lead into insight, it can also be aligned with different levels of decision making that take place in project management (Fig. 2.1). Operational level decisions can be based on data and information at hand; however, a project management/control team would require knowledge for tactical decisions. At a higher level, meaningful insights are needed for accurate strategic decisions. This modification to the pyramid provides value that did not exist before. This concept was also vetted with industry experts and has been validated as a robust framework to define project control functions.

According to Meredith (1993), Carlile and Christensen (2005), and O’Raghallaigh et al. (2010), creation of a typology is one of the key methods of conceptualizing and understanding complex data. Doty and Glick (1994) made a distinction between typology and classification and emphasized that typologies enable the achievement of elegant descriptions to explain complex processes that determine specific outcomes. In the body of knowledge and practice related to project controls, a critical missing element in the evaluation of metrics is a typology. The findings of this research addressed this knowledge gap and led to development of a typology of metrics (Fig. 2.2) based on their function, information hierarchy, and importance. In terms of function, metrics can be divided into two types: predictive metrics, and diagnostics metrics. Predictive
metrics help the user to forecast project cost and duration outcome based on an understanding of the current project progress and performance. Diagnostic metrics help the user to identify progress and performance issues to inform corrective actions. The use of both predictive and diagnostic metrics is critical in providing insight into a project progress and performance.

Figure 2.2 Framework and typology for project control metrics

The second aspect in the typology of metrics is an evaluation of metric hierarchy. In fact, information hierarchy enables an understanding of the process through which data is transformed into insight about a project’s likelihood of meeting its schedule and cost objectives. Hence, another dimension of the metric typology identified in this study is to position project control metrics within the information hierarchy (i.e., data, information, knowledge, insight). Accordingly, progress metrics (e.g., number of purchase orders (POs) completed, number of milestones achieved, and number of design reviews completed) are classified as data. These data can be further processed to obtain progress measures (e.g., percent deliverable completed and percent
POs issued). These progress measures still do not provide insight regarding a project’s likelihood of meeting its schedule and cost objectives. In fact, progress measures provide neither knowledge about the current performance of a project nor insight about the project’s odds of meeting its cost and schedule objectives. These data and measures are mainly intended to help understand where a project is, at a given time, to support operational decisions. Hence, progress measures are classified as information. When further processed, progress measures can be used in determination of performance metrics (e.g., SPI and CPI). Performance metrics provide an understanding about whether a project has achieved its cost and schedule objectives. While this understanding is important, it does not provide insight about whether a project will meet its ultimate cost and schedule objectives. Performance metrics are intended to enable a better understanding of where a project should be and to support tactical decisions. Hence, performance assessment metrics are classified as knowledge. Finally, performance forecasting metrics provide an understanding about whether a project can meet its ultimate cost and schedule objectives. Performance forecasting metrics are intended to provide an understanding about where a project will be at completion and support strategic decisions. Hence, performance forecasting metrics are classified as insight. Insight, then, is the highest level of understanding that can be derived from metrics and allows reliable assessment of project progress and performance.

As progress measurement and performance assessment metrics utilize much needed data for forecasting the future performance of the project, these three metric categories generally provide leading information about the project. Diagnostic metrics, however, have a supplementary but essential role within the project controls framework. These metrics provide information related to root causes of issues with progress and performance slippages or variances. Even though there are
progress measurement and performance assessment metrics used within the concept of diagnostics, none of them provides future performance projections. Diagnostic metrics function as lagging indicators of progress and performance problems.

2.4.2 Metric Maps

The hierarchical flow of project control metrics explained through the framework and the typology above, implicitly includes all the relationships among different metrics. However, the data and information used on calculating each metric can further be visualized by, what the authors called, metric maps. Even though the connections and calculations among metrics are common knowledge, metric maps help visualize the composition of each metric and follow the same hierarchical structure used in the framework. Understanding these relationships would be invaluable for all project stakeholders from all levels. Each map demonstrates how a metric is calculated using other metrics (or data points) in greater detail and was coded to illustrate and differentiate metrics by project control function (Fig. 2.3 and Fig. 2.4). This structure can be applied to any project controls metric. For example, Estimate at Completion (EAC) is a performance forecasting that can be categorized as a predictive metric. To calculate EAC, one should use Estimate to Completion (ETC – another performance forecasting metric) and Actual Cost (AC – a progress measurement data point). Even though AC can directly be incorporated into the calculation of EAC, ETC needs be calculated based on other metrics. The knowledge about the calculation of EAC or ETC is not new, per se. But the way these relationship are “mapped out” using the hierarchical framework, significantly clarifies how metrics are connected and work together. The remainder of the metric maps can be found in Appendix A.
**Figure 2.3** Metric map for Estimate at Completion.
Figure 2.4 Metric map for Efficiency of Productivity Index.
2.4.3 Network Analysis of Metrics

Project control metrics have high levels of interdependencies. As shown previously in the metric maps, the calculation of one metric usually depends on the input of various other metrics. Virtually, superposing all these metric maps would create a network of project control metrics with all the interdependencies. In this section, a network analysis approach is used to visualize and analyze the interdependencies between different project control metrics. The network analysis provides an innovative approach to identify the importance of core metrics based on quantitative network measures.

Figure 2.5 shows a directed network of major cost control metrics. To be able to compare similar measures and investigate the importance of some metrics, only the metrics relate to the different variations of Estimate at Completion (EAC) are considered in this analysis. In the metrics network, each node represents the information of a specific metric, and each link represents an information requirement relationship. For example, to calculate Cost Performance Index (CPI), data from Earned Value (EV) and Actual Cost (AC) are needed. Therefore, two links pointing from EV to CPI and from AC to CPI are built in the network. In total, there are 17 nodes and 29 links in this cost control metrics network.

In this analysis, the network measure of out-degree centrality is used to evaluate the importance of metric nodes in the cost control metrics network. Out-degree centrality is defined as the number of links emanating from a node normalized by the maximum number of such links. When a node has a large out-degree centrality, it implies that the node has significant influence in the network. In the context of the cost control metrics network, if a link exists between two metric nodes, the availability and accuracy of the source node is critical for generating the other metrics it influences.
Therefore, a node with a larger out-degree centrality value is more important as it provides the information for the calculation of many other metrics. Figure 2.6 shows the most important metrics identified in the cost control metrics network by out-degree centrality. Among the 17 cost metrics considered in the network, Actual Cost (AC), Earned Value (EV), Budget at Completion (BAC), Cost Performance Index (CPI), Schedule Performance Index (SPI), and Physical Percent Complete (PPC) have higher out-degree centrality values than others. For example, node AC has one of the highest out-degree centrality (0.375) in the network, since it has 6 outbound links. The out-degree centrality of AC is calculated as $6/(17-1) = 0.375$.

![A network of cost control metrics](image)

**Figure 2.5 A network of cost control metrics**
The six metrics with high out-degree centrality are all considered among the predictive metrics identified earlier. Therefore, it provides validity and offers additional insights by quantifying the importance of metrics using network measures. For example, from the analysis results in Figure 2.6, AC and EV are the most important metrics with an out-degree centrality of 0.375. BAC is ranked the third most important metrics among the 17 metrics considered with an out-degree centrality of 0.313. CPI, SPI, PPC have the same level of importance with an out-degree centrality of 0.125.

Findings of the network analysis highlight the metrics that can influence the quality and accuracy of other metrics in the network. Although the six metrics (i.e., AC, EV, BAC, CPI, SPI and PPC) mentioned above are relatively low-level, progress measurement and performance assessment metrics, they have a significant ability to influence other higher level performance assessment and performance forecasting metrics, which are calculated based on these six metrics. If the data and information gathered through these low-level metrics is wrong or erroneous, downstream metrics
relying in these would suffer from these errors and produce misleading results. Although high-level performance forecasting metrics in predictive and diagnostic metrics categories can be seen as more valuable in project controls decision-making, the network analysis highlights the value and importance of low-level metrics as much.

2.5 Conclusion
Understanding which metrics and indicators to use is important since it takes a great deal of effort to gather project data and convert it into information. Project managers and senior management want to know that the data gathered and processed will provide useful information about the status of a project and more importantly actionable insights to improve performance. To address this need, this study presented a systematic framework and relevant typology for project controls metrics. Predictive and diagnostic metric categories that can improve the understanding of a project’s actual progress, performance and forecast are identified. Additionally, the relationships between different project control metrics are visualized using metric maps. These maps might be highly beneficial especially for those new to project controls to learn more about how each metric is constructed and the connections among metrics, as part of initial training on project measurement and assessment. The metric maps might be invaluable sources for training project personnel on the determination, use, and interpretation of the metrics. Project decision makers can effectively utilize the metric maps to ensure the proper and consistent calculation of and information flow between predictive and diagnostic metrics. A combination of metric maps was also represented as a metric network. This network visually demonstrates the interdependencies of various project control metrics and highlights metrics with high influence in assessing progress and performance.
3 Metrics That Matter: Core Predictive and Diagnostic Metrics for Improved Project Controls and Analytics

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3.1 Abstract

Increasing project complexity and inefficiencies in project control system design and implementation hinder a construction projects’ ability to meet initial cost and schedule performance goals. Major challenges are related to the lack of consistent metrics and indicators, as project control approaches used in different projects vary significantly among owners and contractors. To address these gaps, the objective of this research is to identify the core metrics that provide true insights regarding project progress and performance. The authors identified 20 core predictive and diagnostic project control metrics that can help provide critical insights into a project’s progress measurement, performance assessment and forecasting. The research methodology involved a comprehensive literature review of current project control metrics used in the industry, a survey, Delphi session, and validation. Project data from forty-four surveys were analyzed to identify a comprehensive database of various project controls metrics utilized in the U.S. construction industry. The survey results were also examined through exploratory statistical analysis to determine the use and importance threshold values for the metrics. The Delphi method was adopted to further identify and validate the core predictive and diagnostic metrics for project
progress and performance assessment. Additional validation of the 20 core metrics is performed through a set of statistical validation processes (i.e., Spearman’s rank correlation and Multiple Correspondence Analysis). The impact project size, type, and contracting strategy were also considered. This study advances the assessment of project control metrics and identifies the more insightful measures on progress and performance.

3.2 Introduction

The construction industry has been growing consistently for the past few years and is expected to do so in the near future (IBISWorld, 2016; Construction Intelligence Center, 2016). This growth leads to bigger and more complex construction projects, but also with more challenges. According to an analysis by McKinsey, 98% of “megaprojects” (projects with over $1 billion budget) have to cope with 80% cost overruns and 20 months in schedule delays on average (Changali et al., 2015). With most of the project managers believing that their projects are “healthy” (A.T. Kearney, 2012), there is a clear miscommunication about the “true” progress and performance of projects. Various studies identified that this problem becomes more significant closer to the last quarter of project completion (Lipke, 2003; Vandevoorde and Vanhoucke, 2006; Lipke, 2009; Vanhoucke, 2009; NDIA, 2014). While there are various metrics and approaches used in the industry, the metrics that provide a “true” measure of project progress and performance are not fully known. Therefore, it is difficult to have a true comparison of one project's performance to another, much less to forecast future performance if the metrics vary by project.

As the size and complexity increase, construction projects require more resources, more work and eventually produce more data (Marr, 2016). To provide better project outcomes, it is vital to effectively evaluate this vast amount of data, using certain metrics and evaluation tools throughout
the lifetime of a project, especially during engineering, procurement, construction and commissioning phases – also collectively known as “in-flight” processes. Effective evaluation of cost and schedule outcomes in construction projects would significantly increase the analytical capabilities of project controls and managerial decision making. Therefore, this research identified several core and significant metrics that can help provide insights into a project’s actual progress, performance, and forecast at completion. Building upon the framework in the previous chapter, core and significant metrics are categorized as predictive and diagnostic to demonstrate the real value of project controls framework presented.

The existing methods in the construction industry fail to provide a “true” measure of project progress and performance. Some say that the metrics used to assess progress and performance are sound and that the larger issue pertains to conformity across the industry (Blanco et al., 2016). In other words, if all “players” in the industry used the same or similar methods to track progress and productivity, then there should be little ambiguity in reporting (Changali et al., 2015). However, during project setup, a great deal of time is spent between owners and contractors agreeing on which metrics should be monitored and how. This process could be streamlined with a concise set or list of metrics that are proven to correlate with successful project outcomes (e.g., on/under budget; on/ahead schedule, etc.).

The essential question this research answers is “how can we better assess project performance, and provide insight for future project improvement?” Therefore, the overarching objective was to enhance the current and future project progress and performance through the improvement of the assessment processes. In particular, this study aims to address three specific objectives:
• Identify the core metrics and their value for assessment of project progress and performance.
• Develop a proven, validated and accepted metric classification system that describes how projects should be properly controlled that accurately conveys the progress and performance during project execution at any phase.
• Specify the information related to the core metrics that need to be evaluated in order to properly assess project progress and performance.

The scope of this research was to identify core metrics by focusing on progress measurement, performance assessment, and performance forecasting of capital facility projects, from authorization to substantial completion (or “departure” through “landing” – hence the “in-flight” processes). In this context, in-flight project control metrics refer to the ones used for monitoring and assessing the progress and performance of an ongoing project (as opposed to metrics used at the end of a project for performance assessment and future benchmarking purposes). If project decision-makers for both owner and contractor organizations align on a standardized set of metrics for in-flight project controls, changes in project progress and performance can be proactively addressed during execution, leading to improved project outcomes.

3.3 Methods
The research approach used to accomplish the objectives included four main components: (1) literature review; (2) survey questionnaire; (3) Delphi method sessions; and (4) statistical validation of findings. First, it was essential to develop a better understanding of the status of project controls and metrics that are currently used in the industry; thus, an extensive literature review was performed. Then, a survey was conducted in order to collect information regarding the
usage and importance of various metrics. The survey provided overall guidance on the potential core predictive and diagnostic metrics. Exploratory analysis of survey data revealed high-level information about how several metrics are utilized and rated. Further refinement was established through a series of Delphi sessions with 16 subject matter experts (SMEs)—with more than 360 years of experience in total, who verified the results through multiple rounds of evaluation. Additional validation was provided through two different statistical approaches that complement the findings.

3.3.1 Literature Review

A review of the existing methods reveals that there is not a systematic, consistent and efficient approach to identifying and interpreting core progress and performance assessment metrics in the construction industry. This results in the true performance of construction projects being potentially misrepresented and misunderstood since the actual project progress and performance is not known with certainty.

In a field with a large number of studies and established methods and approaches, a systematic review and synthesis enables the identification of gaps (gap analysis) in the literature of studies that can inform current and future research. For the construction industry, then, a first step toward improving progress and performance assessment is to review and analyze the existing practices and identify core metrics, as well as to determine gaps and limitations in terms of use, interpretation and reliability of these metrics. Despite a vast body of literature in the area of project progress and performance assessment, few studies provide systematic review and gap analysis related to the core metrics and their use. Table 3.1 gives a summary of the major considerations and findings from some of the key resources reviewed.
Table 3.1 Selected key literature review sources and major considerations related to project control systems

<table>
<thead>
<tr>
<th>Reference</th>
<th>Objective</th>
<th>Project Control Functions</th>
<th>Metric Functions</th>
<th>Project Control Methods</th>
<th>Project Control Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>CII, 1986; CII, 1987 (a, b); CII, 1990 (a, b)</td>
<td>Providing tools to control and reduce cost and schedule in various phases of projects</td>
<td>x x x x</td>
<td>x</td>
<td>x x</td>
<td>x x</td>
</tr>
<tr>
<td>Russell et al., 1996</td>
<td>Improving predictability of project success</td>
<td>x x x</td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Fleming and Koppelman, 2000</td>
<td>Describing EVM and its most fundamental components for application to all projects</td>
<td>x x x x</td>
<td>x x</td>
<td>x x</td>
<td></td>
</tr>
<tr>
<td>Thomas, 2000</td>
<td>Characterizing different progress measurement and productivity methods</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Lipke, 2003; 2009</td>
<td>Critically analyzing EVM and proposing Earned Schedule as a new method</td>
<td>x x x</td>
<td>x x x</td>
<td>x x</td>
<td></td>
</tr>
<tr>
<td>Choi et al., 2006</td>
<td>Identifying leading indicators to better manage risk factors during project execution</td>
<td>x x x</td>
<td>x</td>
<td>x x</td>
<td></td>
</tr>
<tr>
<td>O'Brien et al., 2012</td>
<td>Adaptation of traditional project controls systems to modern projects</td>
<td>x x x</td>
<td>x</td>
<td>x x x</td>
<td></td>
</tr>
<tr>
<td>Grau &amp; Back, 2014</td>
<td>Measuring the predictability of cost and schedule outcomes at project completion</td>
<td>x x x</td>
<td>x</td>
<td>x x x</td>
<td></td>
</tr>
<tr>
<td>AACE, 2012</td>
<td>Managing cost of project through a systematic approach</td>
<td>x x x</td>
<td>x x x x x x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMI, 2013</td>
<td>Identifying a set of internal and external factors that may influence a project's success.</td>
<td>x x x</td>
<td>x x x x x x x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NDIA, 2014</td>
<td>Identifying project control metrics for predictive assessment and management of projects</td>
<td>x x x</td>
<td>x x x x x x x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMI, 2015</td>
<td>Project management practices related to EVM</td>
<td>x x x</td>
<td>x x x x x</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

34
3.3.2 Survey

In order to address research goals and gain a better understanding of the usage and importance of various metrics in construction projects, a web-based questionnaire survey was developed and distributed to project managers, and project controls professionals who were knowledgeable about progress and performance assessment metrics and methods (Appendix B). The respondents were asked to select the progress and performance metrics they used in a specific project from a list of metrics, and to evaluate their value in managing and controlling the project. The initial list of metrics used was created from two major sources: (1) the existing literature, and (2) progress and performance reports provided by member construction companies of Construction Industry Institute. The survey was distributed to collect data on metrics used on completed construction projects.

The survey questionnaire was structured into two parts: (1) background information; and (2) metrics used in the project (Fig. 3.1). The background information included respondent and project characteristics. This information was used to obtain a better understanding of the perspectives of the respondents and the projects they submitted. In the second part of the questionnaire, respondents were asked to select the progress measurement, performance assessment and performance forecasting metrics they used on a specific project and to evaluate their value in managing and controlling the project.

The survey was deployed to a targeted list of 75 projects, resulting in 44 valid survey responses. This represents a response rate of 59%, which is higher than the average response level (Running, Ligon, & Miskioglu, 1999). In the last step, all submitted surveys were reviewed to verify the completeness and validity. Respondents were contacted to clarify certain answers if needed. After
this final step, 44 completed and valid survey submissions were recognized, and data from the 44 submissions were used in data analysis.

3.3.3 Exploratory Analysis of Survey Responses

Exploratory analysis of the survey data included two steps: (1) data pull and clean-up; and (2) descriptive statistics. For ease of analysis, the response data from the web-based survey platform (e.g., project characteristics, cost and schedule information, metric usage and importance data, etc.) were exported to a customized MS Excel spreadsheet. After the data transfer was completed, the data set was cleaned-up and some responses lacking certain essential data points that were necessary for further analysis (i.e., detailed project cost and schedule information) were eliminated. Data from the remaining 44 projects were then analyzed.
Survey data analysis focused on two areas to analyze and then classify metrics: (1) number of projects using a metric, and (2) importance score of a metric as rated by respondents. First, the usage and importance values for all metrics were calculated separately from the survey responses, along with mean importance scores for each metric. In order to categorize metrics in terms of usage and importance, data on all metrics were aggregated for each project control function (i.e., progress measurement, schedule performance assessment, cost performance assessment, efficiency performance assessment and performance forecasting). Then, threshold values for metrics in each project control function were identified, using overall median usage numbers and overall median importance scores (Table 3.2). Based on the calculated threshold values metrics, metrics were labeled as “high” or “low”, in terms of usage and importance. For instance, metrics used in projects more than or equal to the usage threshold were labeled “high usage,” whereas those less than the threshold were coded as “low usage.” This categorization was later utilized in Delphi sessions to give subject matter experts an indication of the survey findings. Later, these categories were combined with responses gathered from subject matter experts in the Delphi sessions to create the final classification of metrics.

Table 3.2 Usage and importance score values for separate project control functions based on survey data.

<table>
<thead>
<tr>
<th>Project Control Function</th>
<th>Usage</th>
<th>Importance Score</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Threshold</td>
<td>Min.</td>
</tr>
<tr>
<td>Progress Measurement</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Schedule Performance Assessment</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Cost Performance Assessment</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Efficiency Performance Assessment</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>Performance Forecasting</td>
<td>12</td>
<td>1</td>
</tr>
</tbody>
</table>
3.3.4 Delphi Method

The Delphi method was used to validate core metrics identified from the survey. Delphi method is a structured technique that relies on interactive communication among a panel of experts to arrive at the most accurate answers to a set of questions. The process includes two or more rounds of voting and discussion. In each round, the experts answer the questions and provide reasons for their answers (Dalkey and Helmer, 1963). After each round, a facilitator provides a summary of the experts’ answers from the previous round, as well as the reasons they provided for their judgments. Thus, experts are encouraged to revise their earlier answers considering the replies from other members of their panel. It has shown that during this process the range of the answers will decrease and the group will converge towards a "correct" answer (Linstone and Turoff, 1975).

Finally, the process is stopped after a predefined stop criterion (e.g., number of rounds, achievement of consensus, stability of results) and the mean or median scores of the final rounds determine the results. The Delphi method has unique capabilities for research in the fields of construction management and project management in which other research methods require access to (usually inaccessible) sensitive or confidential data (Hallowell and Gambatese, 2009). In such an environment, the Delphi method allows researchers to obtain highly reliable data from certified experts through the use of a strategically designed method. Therefore, the Delphi method has previously been used in several different research studies in the field of construction/project management (e.g., Choi, 2004; Oh and Han, 2012). In the current study, the Delphi method enabled the authors to verify and validate the results obtained from online survey.

A panel of experts were invited into one face-to-face and one teleconference Delphi session. To ensure the quality of the selected panel, certain criteria were applied. First, all invited panel
members were experts who currently work as project managers, project directors, or project controls experts. Second, experts were invited to the panel only if they had a minimum of ten years of experience in these or similar areas. Through this process, 16 SMEs were selected to participate in the Delphi sessions (Table 3.3). The selected experts represented a cumulative experience of more than 360 years. The Delphi panel included 14 individuals from contractor organizations and two members from owner organizations. However, some of the SMEs who currently work with a contractor company had previous experience working in owner organizations.

To achieve the objectives of the Delphi session, it was decided to first limit the scope to a specific scenario of size and type of project, contract type, perspective of respondent (owner or contractor), and whether project was cost or schedule driven. The factors were selected based on the majority answers obtained in the online survey. The analysis of survey results revealed that the sample projects were typically large heavy industrial projects, with a moderate complexity, and with design-build delivery method and cost reimbursable contract. Hence, during the Delphi session, SMEs were asked to evaluate core metrics for a typical project with similar characteristics.

The main Delphi session included two parts: evaluation of (1) core metrics and (2) the impact of project characteristics. The first item of agenda for the Delphi session was to identify which project controls metrics were considered “core”. At this point core metrics were described to SMEs as metrics that provide the greater insight into a project progress and performance. To this end, an organized list of metrics, called metrics maps, were used to take votes from the SMEs. The relationships between metrics were illustrated in the metrics maps. For example, To Complete Performance Index (TCPI) is a performance forecasting metric whose calculation depends on calculating Estimate at Completion (another performance forecasting metric), Earned Value (a
(Fig. 3.2). Along with the metric map, metric definitions and the results of the online survey pertaining to importance and usage of each metric were also shared with SMEs. The process of identifying core metrics started from top level metrics and helped accelerate the discussion. For example, when TCPI – a top level metric – is identified as a core metric, the metrics which are required for calculating TCPI (i.e., EAC, EV, BAC) are automatically recognized as core metrics. Each metric was voted on for a maximum of three rounds. In each round the SMEs voted whether they think the metric is “core”, “not core”, “innovative”, or “not sure”. (An innovative metric was defined as a metric which has some unique strengths but requires more investigation before it could be widely accepted as a core metric.) Whenever there was a split in the votes of SMEs, the facilitator asked those with opposing opinions to explain the reason for their judgment. After giving SMEs enough time to discuss their points of view, the second or third rounds of voting was conducted, but in most cases, SME votes converged after the second round.

During the Delphi Session, core metrics were identified for a “typical” project with the following characteristics: large (>100 million), industrial (petrochemical), EPC, reimbursable cost contract, cost and schedule driven, moderate complexity and contractor perspective. These characteristics were chosen because most projects in the survey had these characteristics. It is important to consider how the core metrics might be different for other project characteristics, such as from an owner’s perspective, for a fixed price contract, smaller project, high complexity and schedule-driven. So later in the Delphi session, after all the core metrics were identified and classified, they were asked to consider the impact of different project characteristics on core metrics to understand what would change for different projects, as well.
Table 3.3 Professional background of subject matter experts as provided by the participants.

<table>
<thead>
<tr>
<th>SME ID</th>
<th>SME Position</th>
<th>Number of Years in Construction Industry</th>
<th>Experience related to project controls and/or project management</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Manager, Project Controls</td>
<td>35</td>
<td>30 years in project control positions</td>
</tr>
<tr>
<td>2</td>
<td>Director, Project Controls</td>
<td>10</td>
<td>15 years in overseeing all project controls activities for nuclear &amp; conventional construction projects in energy business unit</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20 years in planning and scheduling; project management; cost engineering; risk management</td>
</tr>
<tr>
<td>3</td>
<td>Manager of Project Controls</td>
<td>20</td>
<td>10 years in project management; 15 years in project controls</td>
</tr>
<tr>
<td>4</td>
<td>Project Manager</td>
<td>25</td>
<td>15 years in sales and marketing for general industrial/heavy manufacturing</td>
</tr>
<tr>
<td></td>
<td>Director, Business Development</td>
<td>18</td>
<td>45 years in scheduling, project cost management, construction coordination communication</td>
</tr>
<tr>
<td>5</td>
<td>Project Controls Manager</td>
<td>45</td>
<td>8 years in project controls; ranging from junior to manager roles; responsible for all aspects of reporting/forecasting</td>
</tr>
<tr>
<td>6</td>
<td>Project Controls Manager</td>
<td>10</td>
<td>6 years in Power field construction and DoD; 4 years managing and overseeing project management</td>
</tr>
<tr>
<td>7</td>
<td>Project Controls Manager</td>
<td>10</td>
<td>30 years in site/project assignments, functional management</td>
</tr>
<tr>
<td></td>
<td>Sr. Director of Project Services</td>
<td>30</td>
<td>25 years as quantity surveyor; cost, technical services manager; project controls manager; project controls director</td>
</tr>
<tr>
<td>8</td>
<td>Project Controls Manager</td>
<td>25</td>
<td>28 years in overall life cycle of projects; project controls with an emphasis on cost and schedule</td>
</tr>
<tr>
<td>9</td>
<td>Project Controls Manager</td>
<td>28</td>
<td>20+ years in offshore construction industry; as a design engineer and project controls engineer</td>
</tr>
<tr>
<td>10</td>
<td>Corporate Project Controls Supervisor</td>
<td>20+</td>
<td>18 years in scheduling; Project/cost engineer in field; Project control manager</td>
</tr>
<tr>
<td>11</td>
<td>Head, Project System Management</td>
<td>20</td>
<td>20 years in system designs, development and rollout</td>
</tr>
<tr>
<td>12</td>
<td>Lead Cost Manager</td>
<td>20+</td>
<td>20 years as scheduler, cost control, project controls manager, controls lead</td>
</tr>
<tr>
<td>13</td>
<td>Project Controls Lead</td>
<td>20</td>
<td>20+ years as project manager for large capital projects.</td>
</tr>
<tr>
<td>14</td>
<td>Project Senior Manager</td>
<td>29</td>
<td></td>
</tr>
</tbody>
</table>
Figure 3.2 Metric map for To Complete Performance Index (TCPI)

3.3.5 Statistical Methods for Validation

After core metrics were identified and classified through survey analysis and Delphi sessions, it was necessary to validate them through a set of quantitative analyses. For validation purposes, the authors utilized two hypotheses: (1) using core metrics is strongly connected with better project cost and schedule outcomes; and (2) certain core metrics are imperative in providing insights about a project’s schedule and cost performance. The first hypothesis was tested through a Spearman’s rank correlation; and for testing the second hypothesis, Multiple Correspondence Analysis was utilized to demonstrate the role that core metrics play in achieving better project outcomes.
To investigate the relationship between using core metrics and achieving better project outcomes, the authors revisited the survey data, more specifically metric usage along with cost and schedule performance of projects. Further statistical analysis of survey responses revealed, that compared to projects using fewer core metrics, projects that used more core metrics for project controls experienced higher rates of success at meeting their original budgets. A correlation between the use of more core metrics and better project cost outcomes was observed at the 95% confidence level using the Spearman’s rank correlation method. Multiple Correspondence Analysis builds onto this knowledge by visualizing which specific metrics are more closely tied to better cost and schedule outcomes.

3.3.5.1 Spearman’s Rank Correlation

To test the hypothesis that utilizing a higher number of core metrics improves schedule/cost performance, the authors applied the Spearman's rank correlation coefficient (commonly referred to as Spearman $\rho$), a nonparametric measure of statistical dependence. Spearman's coefficient does not require the assumption that the relationship between the variables is linear. Instead, it assesses how well an arbitrary monotonic function can describe a relationship between two variables, meaning an increase in the value of one variable only indicates that the value of the other variable also increases or decreases, but does not give an indication of quantity. In this study, since the relationship between the use of project control metrics and the cost/schedule performance of projects is not necessarily linear, testing the Spearman’s correlation coefficient offers a more robust alternative and was preferred over Pearson’s linear test.

Similar to Pearson’s coefficient, a perfect Spearman correlation of $+1$ or $-1$ occurs when each of the variables is a perfect monotone function of the other, whereas a Spearman correlation of zero
indicates that there is no correlation between the two sets of data. However, a differentiator of Spearman’s test is that the statistical significance limits of the analysis results also depend on the sample size, which means smaller Spearman ρ values can indicate significance based on the size of the data set. To test whether an observed value of Spearman’s coefficient is significantly different from zero, corresponding p values, which indicate the probability of the results occurring by chance, were calculated for each Spearman’s coefficient.

It is important to note that there were not any projects using all 20 core metrics. Additionally, there were no survey data for 3 predictive (i.e., Budget at Completion, Planned Value, and Physical Percent Complete) and 3 diagnostic (i.e., Baseline Execution Index for Critical Path, Number of Critical or Near Critical Paths, and Ratio of Actual Planned Progress) metrics, which had to be excluded from the following statistical analyses.

To calculate the Spearman's correlation coefficient and corresponding p value, the survey projects were first ranked based on the number of core metrics used in each project; first for all core metrics, then separately for predictive and diagnostic core metrics. The projects were then ranked based on the percentage discrepancy between their planned versus actual cost and schedule values. Then, the Spearman’s coefficients for the ranked number of metrics and ranked discrepancy values were calculated for the 44 online survey projects for which the planned versus actual values of cost and schedule data were available. Finally, the p values corresponding to each test was calculated using the JMP statistical software (JMP, 2016). The initial (null) hypothesis for these test is that there is not a statistical relationship between using more core metrics (i.e., all, predictive, diagnostic) and better project cost and schedule outcomes for projects. Being able to reject this null hypothesis with a statistical significance demonstrates a strong relationship in the opposite direction.
3.3.5.2 Multiple Correspondence Analysis

Identifying patterns in datasets with several predictors, such as core metric usage information in the survey data collected for this study, might prove harder than anticipated. When exploring relationships between multiple categorical dependent variables simultaneously, Multiple Correspondence Analysis (MCA) offers a robust statistical analysis method to analyze and identify patterns in data sets, especially in dealing with complexities of tables with a lot of variables (Abdi & Valentin, 2007; Le Roux & Rouanet, 2010). It is a multivariate method used for reducing the dimensions of the data MCA is an extension to correspondence analysis to allow analyzing more than two nominal variables at once (Sourial, et al., 2010). MCA is also known under various names such as optimal scaling, optimal or appropriate scoring, dual scaling, homogeneity analysis, scalogram analysis, and quantification method (Abdi & Valentin, 2007).

Due to the categorical (more precisely, binary – used versus not used) nature of usage data for core predictive and diagnostic metrics, MCA was an appropriate method to analyze the survey data from various projects, which are the observations in this case. There were two objectives in this analysis. First, the authors wanted to demonstrate which core metrics were used together more often, and second how these groups of core metrics were related to cost and schedule outcomes of projects. Interpretation of MCA is often based upon how close are certain points in a low-dimensional map (preferably two or three dimensions) (Abdi & Valentin, 2007). Additionally, by utilizing response variables in a supplementary role, the associations with and among observations can be investigated visually (Clausen, 1998; Le Roux & Rouanet, 2010). Supplementary variables are not included into the MCA calculations, but rather projected onto the low-dimensional map for visual representation of their association with categorical variables used in analysis. In studying
the effects of core metric usage on cost and schedule performance of projects, deploying the project performance data in a supplementary role considerably enriches the interpretation of the visualized results.

3.4 Results and Discussion

3.4.1 Classification of Metrics

Through the results of the survey analysis as well as validation through the Delphi method, various metrics were classified and core metrics were identified. As detailed in the methodology section, survey data analysis resulted in categorization of metrics into high vs. low usage and importance groups, using threshold values for each project control function (e.g., progress measurement, schedule performance assessment, cost performance assessment, efficiency performance assessment, and performance forecasting) (Table 3.2). Based on these values, the usage and importance category of each metric was identified and combined with Delphi session results to provide usage and importance information for each function. The classification of metrics is presented separately for predictive and diagnostic metrics in Tables 3.4 and 3.5, which include the survey and Delphi findings for each metric along with final classification. (Further metric details, such as metric definitions, equations and indicators, can be found in Appendix C.)

The Delphi method sessions further refined a list of metrics that are considered core (“must have”), validation (metrics that confirm the validity of the core metrics), innovative (metrics that are not currently in wide use, but are considered potentially beneficial), and other significant (other metrics that fall outside the previous categories, but are perceived to have value). In terms of importance, the metrics were divided into two main groups: core and significant metrics. Core metrics are the ones that provide the greatest insight into project progress measurement,
performance assessment and performance forecasting, for indicating the likely project schedule and cost outcomes. Core metrics can also be referred to as “must have” metrics, without which a project management and control team may not be able to obtain a true insight into the progress and performance of a project. Significant metrics include three categories: validation, innovative and other significant metrics. Validation metrics can be used in parallel to the core metrics and provide additional confirmation and proof for the insight obtained from the core metrics. Validation metrics can also be referred to as “good to have” metrics that increase the confidence of the project management and control team on the insight obtained from the core metrics. The value of validation metrics is in their usage in conjunction with core metrics. If validation metrics are used without core metrics, they may not provide a true insight into project progress and performance.

Based on the findings from the survey and the Delphi method, there are a number of metrics that may be considered core but have not been used extensively in the construction industry to adequately prove their value. The survey information, case studies, and Delphi validation showed that, although these metrics are being used by a few companies, those companies that use these metrics consider them to be very important. Hence, in classification of metrics, these metrics are referred to as “innovative metrics.” Examples of these metrics include the earned schedule metrics such as Schedule Performance Index Time (SPI(t)), used by a number of companies studied in this research. Also, the survey results show a low usage but high importance for SPI(t). Hence, SPI(t) and other innovative metrics cannot be classified as core, validation, and other significant until they are adopted by a larger number of companies and their value and importance is proven.

Finally, metrics in the “other significant” category might not add significant value into project progress and performance, but maybe used occasionally by project control teams on as needed.
basis. The insights provided by other significant metrics does not warrant the effort for monitoring them throughout a project.

While the Earned Value Management (EVM) approach uses cost as the basis for calculating the percent complete and earned value, the findings of this study showed that many companies use quantity-based measurement of progress and man-hours for calculation of the core predictive metrics. Among the identified core predictive metrics, SPI requires special consideration for use and interpretation. A cumulative SPI may not provide a true insight into schedule performance of a project. SPI merges to 1 in the last one third of a project (Lipke, 2003; Vandevoorde and Vanhoucke, 2006; Lipke, 2009; Vanhoucke, 2009). However, if SPI is calculated in each period (e.g., monthly) and then plotted over time, it provides a strong basis for assessing project schedule outcome based on the current progress and performance.

Another predictive core metric that requires attention is Estimate at Completion (EAC). This study identified five different approaches for calculation of EAC. However, only the EAC calculated based on CPI is considered as a core metric. EAC can also be calculated using SPI, which can be used as a proxy for confirmation of the EAC value determined using CPI. Hence, EAC calculated using SPI was identified as a validation metric. In addition, EAC can be calculated using the Earned Schedule (ES) approach. The metrics related to the Earned Schedule approach are not extensively adopted in the construction industry. However, the companies that adopted and used these metrics consider them to be core. Since the findings of this study are not sufficient to verify if the Earned Schedule metrics are core (due to limited use in the industry), they have been classified as innovative metrics.
### Table 3.4 Classification of predictive metrics.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Project Controls Function</th>
<th>Survey Results</th>
<th>Delphi Session</th>
<th>Final Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Usage</td>
<td>Importance</td>
<td>SME Votes</td>
</tr>
<tr>
<td>Variance at Completion</td>
<td>VAC</td>
<td>Performance Forecasting</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Estimate at Completion</td>
<td>EAC(CPI)</td>
<td>Performance Forecasting</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Estimate to Completion</td>
<td>ETC(CPI)</td>
<td>Performance Forecasting</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>To Complete Performance Index (EAC(CPI))</td>
<td>TCPI(EAC(CPI))</td>
<td>Performance Forecasting</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Cost Performance Index</td>
<td>CPI</td>
<td>Performance Assessment</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Schedule Performance Index</td>
<td>SPI</td>
<td>Performance Assessment</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Actual Cost</td>
<td>AC</td>
<td>Progress</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Earned Value</td>
<td>EV</td>
<td>Progress</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Physical Percent Complete</td>
<td>PPC</td>
<td>Progress</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Budget at Completion</td>
<td>BAC</td>
<td>Progress</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Planned Value</td>
<td>PV</td>
<td>Progress</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Estimate at Completion (SPI)</td>
<td>EAC(SPI)</td>
<td>Performance Forecasting</td>
<td>- **</td>
<td>- **</td>
</tr>
<tr>
<td>Estimate to Completion (SPI)</td>
<td>ETC(SPI)</td>
<td>Performance Forecasting</td>
<td>- **</td>
<td>- **</td>
</tr>
<tr>
<td>Monthly Cost Growth</td>
<td>MCG</td>
<td>Performance Assessment</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Estimate at Completion - Time</td>
<td>EAC(t)</td>
<td>Performance Forecasting</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Estimate to Completion - Time</td>
<td>ETC(t)</td>
<td>Performance Forecasting</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Schedule Performance Index - Time</td>
<td>SPI(t)</td>
<td>Performance Assessment</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Earned Schedule</td>
<td>ES</td>
<td>Performance Assessment</td>
<td>- ***</td>
<td>- ***</td>
</tr>
<tr>
<td>Actual Duration</td>
<td>AD</td>
<td>Progress</td>
<td>- ***</td>
<td>- ***</td>
</tr>
<tr>
<td>Planned Duration</td>
<td>PD</td>
<td>Progress</td>
<td>- ***</td>
<td>- ***</td>
</tr>
<tr>
<td>Estimate at Completion (CPI*SPI)</td>
<td>EAC(CPI*SPI)</td>
<td>Performance Forecasting</td>
<td>- **</td>
<td>- **</td>
</tr>
<tr>
<td>Estimate to Completion (CPI*SPI)</td>
<td>ETC(CPI*SPI)</td>
<td>Performance Forecasting</td>
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<td>- **</td>
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<tr>
<td>Estimate at Completion (Optimistic)</td>
<td>EAC(O)</td>
<td>Performance Forecasting</td>
<td>- **</td>
<td>- **</td>
</tr>
<tr>
<td>Estimate to Completion (Optimistic)</td>
<td>ETC(O)</td>
<td>Performance Forecasting</td>
<td>- **</td>
<td>- **</td>
</tr>
<tr>
<td>Estimate at Completion (Bottom-Up)</td>
<td>EAC(BU)</td>
<td>Performance Forecasting</td>
<td>- **</td>
<td>- **</td>
</tr>
<tr>
<td>Estimate to Completion (Bottom-Up)</td>
<td>ETC(BU)</td>
<td>Performance Forecasting</td>
<td>- **</td>
<td>- **</td>
</tr>
<tr>
<td>To Complete Performance Index (BAC)</td>
<td>TCPI(BAC)</td>
<td>Performance Forecasting</td>
<td>- **</td>
<td>- **</td>
</tr>
</tbody>
</table>

* Since these metrics are used in calculating other EVM metrics (e.g., EAC(CPI), CPI) that are marked as core, these are marked as core as well through association.

** Variations of EAC and ETC metrics categorized by SME with regards to their use.

*** Since these metrics are used in calculating other ESM metrics (e.g., EAC(t), SPI(t)) that are marked as Innovative, these are marked as Innovative as well through association.
### Table 3.5 Classification of diagnostic metrics.

<table>
<thead>
<tr>
<th>Metric</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<tr>
<td></td>
<td>Project Controls Function</td>
<td></td>
<td>Survey Results</td>
<td>Delphi Session SME Votes</td>
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<td></td>
<td>Main</td>
<td>Secondary</td>
<td>Usage</td>
<td>Importance</td>
<td></td>
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<tr>
<td>Efficiency or Productivity Index</td>
<td>E/PI</td>
<td>Performance Assessment</td>
<td>Cost Performance</td>
<td>High</td>
<td>High</td>
<td>Core</td>
<td>Core</td>
</tr>
<tr>
<td>Schedule Variance</td>
<td>SV</td>
<td>Performance Assessment</td>
<td>Schedule Performance</td>
<td>High</td>
<td>High</td>
<td>Core</td>
<td>Core</td>
</tr>
<tr>
<td>Cost Variance</td>
<td>CV</td>
<td>Performance Assessment</td>
<td>Cost Performance</td>
<td>High</td>
<td>Low</td>
<td>Core</td>
<td>Core</td>
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<tr>
<td>Unit Rate</td>
<td>UR</td>
<td>Performance Assessment</td>
<td>Cost Performance</td>
<td>High</td>
<td>Low</td>
<td>Core</td>
<td>Core</td>
</tr>
<tr>
<td>Procurement Cost Variance</td>
<td>PCV</td>
<td>Performance Assessment</td>
<td>Cost Performance</td>
<td>High</td>
<td>Low</td>
<td>Core</td>
<td>Core</td>
</tr>
<tr>
<td>Baseline Execution Index for Critical Path</td>
<td>BEI-CP</td>
<td>Performance Assessment</td>
<td>Schedule Performance</td>
<td>- *</td>
<td>- *</td>
<td>Core *</td>
<td>Core</td>
</tr>
<tr>
<td>Number of Critical (or Near Critical) Paths</td>
<td></td>
<td>Performance Assessment</td>
<td>Schedule Performance</td>
<td>- **</td>
<td>- **</td>
<td>Core **</td>
<td>Core</td>
</tr>
<tr>
<td>Percent Key Deliverables Completed on Time</td>
<td>PKDCT</td>
<td>Progress Measurement/ Data</td>
<td>Physical Progress</td>
<td>High</td>
<td>High</td>
<td>Core</td>
<td>Core</td>
</tr>
<tr>
<td>Ratio of Actual to Planned Progress</td>
<td>RAPP</td>
<td>Progress Measurement/ Data</td>
<td>Physical Progress</td>
<td>- **</td>
<td>- **</td>
<td>Core **</td>
<td>Core</td>
</tr>
<tr>
<td>Percent Activities Started on Time</td>
<td>PAST</td>
<td>Performance Assessment</td>
<td>Schedule Performance</td>
<td>High</td>
<td>High</td>
<td>Non-Core</td>
<td>Validation</td>
</tr>
<tr>
<td>Percent Activities Finished on Time</td>
<td>PAFT</td>
<td>Performance Assessment</td>
<td>Schedule Performance</td>
<td>High</td>
<td>High</td>
<td>Non-Core</td>
<td>Validation</td>
</tr>
<tr>
<td>Critical Path Length Index</td>
<td>CPLI</td>
<td>Performance Assessment</td>
<td>Schedule Performance</td>
<td>High</td>
<td>High</td>
<td>Non-Core</td>
<td>Validation</td>
</tr>
<tr>
<td>Percent Work Packages on Budget</td>
<td>PWPB</td>
<td>Performance Assessment</td>
<td>Cost Performance</td>
<td>High</td>
<td>High</td>
<td>Non-Core</td>
<td>Validation</td>
</tr>
<tr>
<td>Schedule Variance - Time</td>
<td>SV(t)</td>
<td>Performance Assessment</td>
<td>Schedule Performance</td>
<td>Low</td>
<td>High</td>
<td>Core</td>
<td>Innovative</td>
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<tr>
<td>Percent Milestones Achieved</td>
<td>PMA</td>
<td>Performance Assessment</td>
<td>Schedule Performance</td>
<td>High</td>
<td>High</td>
<td>Non-Core</td>
<td>Other Significant</td>
</tr>
<tr>
<td>Workerhours per Unit Item</td>
<td>WUI</td>
<td>Performance Assessment</td>
<td>Schedule Performance</td>
<td>High</td>
<td>High</td>
<td>Non-Core</td>
<td>Other Significant</td>
</tr>
<tr>
<td>Number of Backlog Activities</td>
<td>NBA</td>
<td>Performance Assessment</td>
<td>Schedule Performance</td>
<td>High</td>
<td>High</td>
<td>Non-Core</td>
<td>Other Significant</td>
</tr>
<tr>
<td>Purchasing Workerhours per PO</td>
<td>PWPO</td>
<td>Performance Assessment</td>
<td>Schedule Performance</td>
<td>High</td>
<td>Low</td>
<td>Non-Core</td>
<td>Other Significant</td>
</tr>
<tr>
<td>Feeding Buffer Burn Rate</td>
<td>FBBR</td>
<td>Performance Assessment</td>
<td>Schedule Performance</td>
<td>Low</td>
<td>High</td>
<td>Non-Core</td>
<td>Other Significant</td>
</tr>
<tr>
<td>Percent Equipment Delivered Late</td>
<td>PEDL</td>
<td>Performance Assessment</td>
<td>Schedule Performance</td>
<td>Low</td>
<td>Low</td>
<td>Non-Core</td>
<td>Other Significant</td>
</tr>
<tr>
<td>Project Buffer Index</td>
<td>PBI</td>
<td>Performance Assessment</td>
<td>Schedule Performance</td>
<td>- ***</td>
<td>- ***</td>
<td>Non-Core</td>
<td>Other Significant</td>
</tr>
</tbody>
</table>

* There were not enough data points for evaluation from survey, but SMEs identified it as core.
** This metric was not in the survey, but identified as Core by SMEs through consensus.
*** There were not enough data points for evaluation from survey, but SMEs suggested including.
On the diagnostics side, metrics identified as core provide strong foresight for proactive identification of cost and schedule performance issues and also insights into the issues that led to overruns and delays to inform corrective actions. It is important to note that as work productivity directly impacts project costs either favorably or unfavorably, Efficiency/Productivity Index provides greater insight for cost performance. However, this metric can also indicate a potential impact on the schedule if uncorrected. A productivity less than one may result in a delay in completion of the project or activity unless either resources are increased or productivity is improved. An increase in resources may maintain the schedule but will increase costs while an increase in productivity may allow maintaining schedule without a cost impact. For physical progress diagnostics, Ratio of Actual to Planned Progress can be calculated for different project deliverables, disciplines, and trades, whereas Percent of Key Deliverables Completed on Time depends on identification of key deliverables which is specific for each project and should be determined for different phases, disciplines, and trades.

In addition to the core diagnostics metrics, the findings highlighted four validation diagnostics metrics. These validation metrics provide confirmation of the core schedule performance diagnostics metrics in terms of issues that can lead to cost overruns and schedule delays. As mentioned earlier, the validation metrics may not be monitored continuously; however, their use can provide additional confirmation of the core diagnostics metrics.

### 3.4.2 Statistical Validation of Findings

Spearman $\rho$ values between the total number of core metrics used and the cost and schedule discrepancies were 0.3033 and 0.2390, respectively (Table 3.6). Also, based on the p values for the sample size ($n=44$) corresponding to each Spearman $\rho$, there is only less than 2.25 percent
probability that the rank correlation between using all core metrics and cost outcomes is by chance. Hence, it is concluded that at a 95 percent confidence level ($\alpha=0.05$), the use of more core metrics is correlated with better cost performance of the projects. This means that projects using more core metrics are more likely to achieve (or stay within) their authorized budgets. On the other hand, the probability that the schedule performance is not correlated with the use of core metrics is around 12 percent, which means with regards to the schedule performance, the initial hypothesis could not be rejected at 90 percent or higher significance. Therefore, the same confidence level cannot be established for core metric usage versus schedule performance. This is a significant finding as most of the core metrics identified are related to Earned Value Management (EVM) and their robustness in measuring cost performance are well studied by several researchers (Fleming and Koppelman, 2000; Lipke, 2003; Lipke, 2009; National Defense Industrial Association NDIA, 2014; Vandevoorde and Vanhoucke, 2006; Vanhoucke, 2009). Same studies also showed that EVM metrics struggle with measuring schedule performance in various occasions, especially after the projects achieve two thirds towards completion.

Same pattern can also be observed for predictive core metrics but with less statistical significance – $p$ value is 0.1335 for cost performance versus 0.5580 for schedule performance. Since the probability that the cost performance is not correlated with the use of predictive core metrics is around 14 percent (and even higher for schedule performance), the initial hypothesis could not be rejected at 90 percent or higher significance for predictive metrics. For using diagnostic metrics, however, there is a statistically significant relationship with schedule performance – even more significant than any others tested. The probability of chance that the rank correlation between using more diagnostic core metrics versus schedule and cost outcomes is only less than 2 percent and 7
percent, respectively. At a 95 percent confidence level (\(\alpha=0.05\)), the use of more diagnostic core metrics is correlated with better schedule performance of the projects, compared to 90 percent (\(\alpha=0.10\)) for cost outcomes. This is yet another significant finding as most core diagnostic metrics have a strong footing in schedule-related data (e.g., Efficiency Index, Percent Key Deliverables Completed on Time, Schedule Variance) and offer a useful medium for assessing schedule performance.

Table 3.6 Spearman’s rank correlation coefficient and corresponding p values between core metric usage and cost and schedule performance of projects (n=44).

<table>
<thead>
<tr>
<th>Core Metrics Used</th>
<th>Spearman (\rho) values *</th>
<th>p values **</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Core Metrics Used</td>
<td></td>
<td></td>
</tr>
<tr>
<td>vs. Cost Performance</td>
<td>0.3033</td>
<td>0.0453</td>
</tr>
<tr>
<td>vs. Schedule Performance</td>
<td>0.2390</td>
<td>0.1182</td>
</tr>
<tr>
<td>Predictive Core Metrics Used</td>
<td></td>
<td></td>
</tr>
<tr>
<td>vs. Cost Performance</td>
<td>0.2298</td>
<td>0.1335</td>
</tr>
<tr>
<td>vs. Schedule Performance</td>
<td>0.0908</td>
<td>0.5580</td>
</tr>
<tr>
<td>Diagnostic Core Metrics Used</td>
<td></td>
<td></td>
</tr>
<tr>
<td>vs. Cost Performance</td>
<td>0.2770</td>
<td>0.0687</td>
</tr>
<tr>
<td>vs. Schedule Performance</td>
<td>0.3491</td>
<td>0.0202</td>
</tr>
</tbody>
</table>

* Larger values represent better rank correlation  
** Smaller values represent more statistically significant relationship

Figures 3.3, 3.4, and 3.5 show schematic relationships between core metrics usage and project cost and schedule outcomes mentioned above and shown in Table 3.6. These figures visually demonstrate the statistical analysis results using ellipses covering all data points. Figure 3.3.a gives a better indication of the monotonic relationship between using more of all core metrics and better cost outcomes, while the ellipse in Figure 3.3.b is more flat on the x-axis and lacks any significant direction, or correlation. Similarly Figures 3.5.a and 3.5.b visualize the significant rank correlation between using more diagnostic metrics and cost and schedule outcomes.
After demonstrating the statistical relationship between using more core metrics and better project outcomes, the next logical avenue for exploration was to identify which core metrics are more closely tied to better cost and schedule outcomes using MCA. The key to MCA is to explain the variability in the data by using few dimensions. In constructing and developing these dimensions the relative variation accounted for each dimension – which is commonly referred to as “inertia” in MCA or “eigenvalue” in other comparable analysis methods (i.e. Principal component Analysis, Factor Analysis) – plays an important role. Due to the underlying statistical processes and assumptions in calculating these inertia values, Benzecri (1979; 1992) and Greenacre (1984; 1993) argued that the usual calculation of these inertia values is not necessarily correct and offered adjusted formulas that are more commonly used and widely accepted today. Table 3.7 shows the traditional MCA inertias along with Benzecri and Greenacre adjusted values. As shown, although the adjusted inertia values are the same in both Benzecri and Greenacre adjustments, percent contributions and cumulative percentages are different. While the former is argued to be more optimistic, the latter is deemed more conservative. (Greenacre, 1994; Abdi & Valentin, 2007; Le Roux & Rouanet, 2010; Sourial, et al., 2010).
Figure 3.3 Relationship between using more of all core metrics versus (a) cost and (b) schedule performance of projects (n=44)
Figure 3.4 Relationship between using more predictive core metrics versus (a) cost and (b) schedule performance of projects (n=44)
Figure 3.5 Relationship between using more diagnostic core metrics versus (a) cost and (b) schedule performance of projects (n=44)
Table 3.7 Traditional and adjusted MCA values.

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Traditional MCA</th>
<th>Benzecri Adjustment</th>
<th>Greenacre Adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inertia</td>
<td>Percent Contribution</td>
<td>Cumulative Percent</td>
</tr>
<tr>
<td>1</td>
<td>0.20887</td>
<td>20.89</td>
<td>20.89</td>
</tr>
<tr>
<td>2</td>
<td>0.15189</td>
<td>15.19</td>
<td>36.08</td>
</tr>
<tr>
<td>3</td>
<td>0.10698</td>
<td>10.70</td>
<td>46.77</td>
</tr>
<tr>
<td>4</td>
<td>0.08902</td>
<td>8.90</td>
<td>55.68</td>
</tr>
<tr>
<td>5</td>
<td>0.08156</td>
<td>8.16</td>
<td>63.83</td>
</tr>
<tr>
<td>6</td>
<td>0.07645</td>
<td>7.65</td>
<td>71.48</td>
</tr>
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</table>
There are different approaches in choosing the number of dimensions to be interpreted. Researchers in Benzecri school (i.e., Le Roux and Rouanet, 2010) consider the decrease in adjusted inertia percent contribution rates, whereas Greenace (2007) suggests the dimensions with adjusted percent inertia contributions larger than $1/Q$ to be considered, where $Q$ is the number of variables ($Q=14$ in our case, and $1/14=0.0714=7.14\%$). From either perspective, the first two dimensions seem to satisfy the requirements and should be enough for this case: Benzecri adjusted percent contributions decrease significantly after the first two dimensions, which have 51.43% and 17.63% Greenacre adjusted inertia contribution, respectively.

After selecting which dimensions to focus on, it is essential to decide on the factors for interpretation of selected dimensions. A rule of thumb is to select the category levels with more than average contribution to a selected dimension. In this case, with 14 variables with 2 levels each (i.e. Used or Not Used) the average contribution would be $100/(14 \times 2)=3.57$ for each of the metric usage levels. Table 3.8 shows partial contributions and coordinates on selected dimensions for each level of all categories. (In bold, metrics with higher than average percent contributions ($100/28=3.57$) were selected for interpretation of each dimension.) Visualization of coordinates is one of the most valuable results of MCA as it allows further interpretation of factors and corresponding variances (Fig. 3.6). One point to note here is that directions in principal dimensions are arbitrary and the coordinate signs for categories can be changed without effecting the inertia values (Le Roux & Rouanet, 2010). As a natural result of the underlying MCA calculations, two levels of the same categorical variable are placed symmetrically on the opposite sides of the origin (0,0). In visualizing cost and schedule as supplementary variables, “Good” represents project that achieve or perform better than their initial budgets and plans, whereas “Bad” represents the project
that missed the target. As supplementary variables, cost and schedule outcomes of the projects in the survey data are not incorporated into the MCA calculations but rather projected onto the low-dimensional MCA map (Fig. 3.6) after the fact, to explore relationships and improve interpretation. Looking at dimension 1, usage information for five metrics (i.e., EV, AC, VAC, CPI, and SPI) are located on each side of the axis. It is obvious that EV and AC are commonly used together and have the biggest contribution to the corresponding variance in this dimension followed by usage of VAC. Similarly, SPI and CPI are clustered on the opposite side of this dimension with good variance contributions. Considering cost and schedule supplementary variables in conjunction with explanatory categories for dimension 1, projects using EV, AC, and VAC ended up with better schedule performance, whereas projects using SPI and CPI are closer to achieving better cost outcomes. On the contrary, projects not using core predictive metrics; VAC, EAC(CPI) and ETC(CPI), nor diagnostic CV metric are more associated with worse cost performance, while not using predictive CPI and diagnostic EI are more seen in projects with worse cost outcomes.

In interpreting dimension 2, using SV, SPI, CPI, AC, UR and EV are associated with most of the variance, in addition to not using SV, CPI, SPI and PCV. Just like for dimension 1 usage of AC and EV, and SPI and CPI are clustered together with projects using SV somewhere in between. Considering the supplementary variables, projects with better cost and schedule outcomes are on the same side of the axis, on which, metrics used with significant contributions are all located as well, except for UR. UR being a more basic metric than others, it seems like projects using it are not using other more complex metrics such as SV, CPI, SPI, and PCV, all the while observing worse cost and schedule performances. This is a good example of how important it is to use core metrics together, as using one but not the others would not have much of a positive impact.
Table 3.8 Partial contribution percentages and principal dimension coordinates for levels of different categories to the overall inertia in first two dimensions.

<table>
<thead>
<tr>
<th>Category</th>
<th>Level</th>
<th>Percent Contributions</th>
<th>Factor Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Dimension 1</td>
<td>Dimension 2</td>
</tr>
<tr>
<td>VAC</td>
<td>Used (1)</td>
<td>7.92</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Not Used (0)</td>
<td>4.99</td>
<td>0.00</td>
</tr>
<tr>
<td>EAC(CPI)</td>
<td>Used (1)</td>
<td>2.15</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>Not Used (0)</td>
<td>3.76</td>
<td>1.47</td>
</tr>
<tr>
<td>ETC(CPI)</td>
<td>Used (1)</td>
<td>2.56</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Not Used (0)</td>
<td>6.11</td>
<td>0.01</td>
</tr>
<tr>
<td>TCPI(EAC(CPI))</td>
<td>Used (1)</td>
<td>0.89</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>Not Used (0)</td>
<td>0.07</td>
<td>0.01</td>
</tr>
<tr>
<td>CPI</td>
<td>Used (1)</td>
<td>7.53</td>
<td>12.63</td>
</tr>
<tr>
<td></td>
<td>Not Used (0)</td>
<td>5.22</td>
<td>8.74</td>
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<td>SPI</td>
<td>Used (1)</td>
<td>6.44</td>
<td>11.80</td>
</tr>
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<td></td>
<td>Not Used (0)</td>
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<tr>
<td></td>
<td>Not Used (0)</td>
<td>2.81</td>
<td>1.96</td>
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<td>Used (1)</td>
<td>13.24</td>
<td>5.46</td>
</tr>
<tr>
<td></td>
<td>Not Used (0)</td>
<td>2.50</td>
<td>1.03</td>
</tr>
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<td>EI</td>
<td>Used (1)</td>
<td>3.00</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>Not Used (0)</td>
<td>4.33</td>
<td>0.21</td>
</tr>
<tr>
<td>SV</td>
<td>Used (1)</td>
<td>0.03</td>
<td>13.19</td>
</tr>
<tr>
<td></td>
<td>Not Used (0)</td>
<td>0.02</td>
<td>10.03</td>
</tr>
<tr>
<td>CV</td>
<td>Used (1)</td>
<td>0.87</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Not Used (0)</td>
<td>4.59</td>
<td>0.00</td>
</tr>
<tr>
<td>UR</td>
<td>Used (1)</td>
<td>0.31</td>
<td>5.87</td>
</tr>
<tr>
<td></td>
<td>Not Used (0)</td>
<td>0.07</td>
<td>1.31</td>
</tr>
<tr>
<td>PCV</td>
<td>Used (1)</td>
<td>0.00</td>
<td>3.42</td>
</tr>
<tr>
<td></td>
<td>Not Used (0)</td>
<td>0.00</td>
<td>5.42</td>
</tr>
<tr>
<td>PKDCT</td>
<td>Used (1)</td>
<td>3.23</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>Not Used (0)</td>
<td>1.36</td>
<td>0.40</td>
</tr>
</tbody>
</table>
Core metrics not mentioned here might be explained by considering other dimensions not included in interpretation of MCA results. Still, using (or not using) certain core metrics explains a lot of good (or bad) performance in construction projects. This result adds another significant layer of validation to the findings by showing the importance of using core metrics for better project outcomes.

### 3.4.3 The Impact of Project Characteristics

Core metrics were initially selected based on the following project characteristics: large, industrial, reimbursable cost, balanced cost and schedule goals, moderate complexity, and contractor
perspective. However, through the Delphi sessions, SMEs were in agreement that the core metrics would be the same for other project characteristics, as well—the only differences relate to the frequency of data collection and level of effort involved in collecting, analyzing and reporting these data. The following subsections summarize some factors related to project characteristics that may influence project control metrics and processes.

**Perspective (Owner vs. Contractors):**

- Team size and resource availability: The project control teams in owner organizations are usually small and do not have significant resources to process the significant amount of data and metrics that contractors collect and monitor on large projects. Hence, owner organizations may track a smaller number of metrics compared to contractors.

- Use of influencing factor metrics: Some owner organizations tend to monitor the metrics related to influencing factors (e.g., quality, safety, and risk), in order to evaluate potential progress and performance issues and make proactive corrective actions. Although contractors also monitor influencing factor metrics, some owner organizations assess these metrics more closely in order to identify correlation to project progress and performance.

- Use of scope change and milestone metrics: Owner organizations consider the metrics related to scope change and achievement of milestones to be very important. For examples, metrics such as Actual vs. Planned Man-Hour, Phase Growth, and Percent of Milestone Completed On-Time are metrics that owner organizations may consider as part of their core metrics while contractors may not consider these metrics to be core.
**Project Size:**

- Use of the same predictive metrics: The project size may not affect the number of core and validation predictive metrics that need to be used to monitor project progress and performance in a project.

- Less frequent data collection: While the metrics stay the same, the frequency of data collection is less in smaller projects versus larger projects due to the smaller size of project control teams. Large projects require more frequent data collection and reporting in order to have better insight about project progress and performance.

- Use of bottom-up approaches: In smaller projects, organizations tend to use a bottom-up approach to determine the predictive metrics, such as Estimate at Completion and Estimate at Completion (Time). However, due to a larger number of activities, use of a bottom-up approach is not feasible in larger projects.

- Use of custom metrics: Organizations may develop and use custom metrics for monitoring certain activities in smaller projects since they typically have reduced margins of error.

**Contract Type:**

- Accessibility of data: Contracting strategy and commercial considerations can lead to difficulty in obtaining and understanding progress and performance information provided by the contractor. Better understanding is needed regarding the truly significant data, and key performance indicators that may provide a good understanding of the project status at any point in time. In addition, owner organization may not have access to certain data collected by contractors depending on the contract type.
Audit rights and reviews: Depending on the contract type, the owner may face limitations for auditing project progress and conducting reviews. Owners should consider including audit rights and “cold eye” reviews in the contract and mention this during the pre-kick-off meeting. Owners should be able to obtain copies of progress; labor force reports; material and equipment reports; off-site management reports; and value of materials installed. In addition, it is important for the owners to implement walk downs to ensure that the physical progress is reported correctly.

**Project Complexity:**

- Integration of changes: While the metrics to be used remain the same for projects with different levels of complexity, for complex projects, it is important to consistently integrate changes into project cost and schedule reports in order for the metrics to be reliable. Complex projects usually include significant changes due to their nature. Thus, both project costs and man-hours may change frequently in complex projects. Hence, these changes should be properly documented and integrated into project control metrics to provide a reliable basis for assessing project progress and performance.

- Importance of scope definition: In complex projects, it is very critical to have a well-defined project scope in order for the project control metrics to be reliable. When a project moves from Front End Engineering Design (FEED) to detailed design it should be sanctioned by owner. There should be material quantities at the end of the FEED package (e.g., # of pieces of equipment, tons of steel, etc.). If quantities go up, then costs are most likely going to increase. It was suggested to use a Project Definition
Rating Index (or another approach) to determine the project status at the end of the FEED stage (just before detailed design and construction).

- Data collection complications: Data collection for project progress and performance assessment has certain complications in complex projects. Obtaining data could take a longer time, introducing concerns over the data becoming stale or even compromised. Data may come in at different times making it more difficult to compare with other data. A potential solution is to make the data reporting contractual. It is a good idea to give the contractor (or subcontractors) a template for project control requirements.

**Schedule vs Cost Priority:**

- Definition of priorities in baseline development: While the metrics used for project control remain the same for schedule- and cost-driven projects, the definition of priorities affect the baseline development. If a project baseline is not developed from a schedule-driven perspective, higher costs may be realized due to not having the required resources and processes in the budget to maintain the project on schedule. The baseline should include budget for certain crashing activities (e.g., expedited material delivery, more overtime charges, etc.). Hence, lack of a clear definition of priorities may lead to greater variability in the metrics.

### 3.5 Conclusion

This research identified several core predictive and diagnostic metrics that can help provide insights into a project’s actual progress, performance, and forecast at completion. The research methodology involved gathering a list of all possible metrics from an extensive literature review.
as well as from industry research team members. A survey approach was implemented to identify the use and importance of the various predictive and diagnostic metrics. In total, 44 surveys were completed representing mostly large, industrial projects. Then, Delphi sessions was conducted with 16 subject matter experts to verify the findings from the survey data analysis. The Delphi session further refined the list of metrics into ones that are considered core (must have), validation (good to have to validate the core metrics), innovative (ones that are not currently in wide use but nevertheless found beneficial by some project control experts), and other significant (other metrics that were perceived to have value based on survey data).

These findings were further validated through statistical analyses. Spearman’s rank correlation revealed with a 95% confidence level that projects using more core metrics are more likely to achieve better cost results, whether it was not possible to establish such confidence for schedule outcomes. A further investigation into the metric typology showed that using more of the predictive metrics provide parallel results to using all metrics. However, using more diagnostic metrics increases the likelihood of better schedule results, again with a 95% confidence level.

Additionally, MCA findings showed in fact there are certain metrics that are more associated with better cost and schedule outcomes in the projects. For instance, projects that used EV, AC, and VAC ended up with better schedule performance, whereas projects using SPI and CPI are more closely related to achieving better cost outcomes. On the contrary, projects not using core predictive metrics, such as VAC, EAC(CPI) and ETC(CPI), nor diagnostic CV metric are more associated with worse schedule performance, while not using predictive CPI and diagnostic EI are more seen in project with worse cost outcomes.
Core metrics were selected based on the following project characteristics: large, industrial, reimbursable cost, balanced cost and schedule goals, moderate complexity, and contractor perspective. When considering core metrics from other project characteristics, it was discovered that the core metrics will be the same—the only difference relates to the frequency of data collection and level of effort involved in collecting and analyzing these data. Through a set of statistical analyses on survey data, importance of core metrics was validated by showing a strong correlation between their usage and cost and schedule outcomes of projects.

This research identified 20 core and 28 significant metrics for assessment of construction project progress and performance. This research may provide the industry with a better understanding of and more consistent methods for project assessment and improved project delivery.

There are few scope limitations to this study. Comparing project performance against industry standards or benchmarks is beyond the scope of this research. Likewise, evaluation of the quality of baseline plans is beyond the scope of this research; however, this research identified the metrics and indicators that could provide insight about the quality of the baseline plan. Evaluation and standardization of methods such as Earned Value Analysis was not investigated either. The researchers used a more qualitative approach to understanding the nature of core metrics for different kinds of projects and delivery approaches. The research scope also excluded progress and performance assessment implications at the portfolio or program-level. Progress and performance metrics related to the front-end planning, operations and maintenance phases were not considered. Furthermore, evaluation of technologies for real-time progress measurement and data collection also are beyond the scope of this research.
This research identified several key metrics for assessing and diagnosing construction project progress and assessment. The authors believe, using these findings, the construction industry can better assess projects and improve their performance significantly. It is hoped that this research is the beginning of more studies on key project control metrics and ways to improve project performance.
4 Critical Factors for Improving Reliability of Project Control Metrics Throughout the Project Lifecycle

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4.1 Abstract

Assessment of project progress and performance are critically important to the successful delivery of capital facility projects. Major challenges for effectively measuring project progress and performance are related to the lack of consistent, reliable, and objective metrics and indicators. Often, project managers are misled in their perceptions of project performance until the project nears its end. This lack of accurate project progress and performance information is a major issue that causes performance shortcomings and resource shortfalls. Establishing a reliable standard might alleviate the need to “reinvent the wheel” for many projects. The industry needs standard, objective ways to assess a project’s progression and performance. Currently, there is no proven, accepted standard for how projects should be properly controlled that accurately conveys timely progress and performance information. Through conducting a survey and 10 in-depth case studies, this research presents 15 critical reliability improvement factors and 85 total indicators with specific application timing and milestones. This robust framework for improving the reliability of project controls throughout the lifecycle of a project was also validated by a panel of experts.
Findings of this research provide the industry stakeholders with a tool that can significantly improve the reliability of project progress and performance assessment practices.

4.2 Introduction

Improving project performance in terms of project cost and schedule is a major challenge in construction industry. For example, from about a thousand projects reviewed by Construction Industry Institute (CII) only 53 projects met their original cost and time objectives, while nearly 70% of these projects ended up with more than 10% deviation from their authorized budget and schedule (CII, 2012). With a view to reduce such project inefficiencies, researchers in the fields of project management and project controls have developed various metrics, indicators, and tools to enhance the progress measurement and performance assessment in construction projects (Orgut et al., 2015). Some of these methods that are widely used include Earned Value Management (Flemming & Koppelman, 2000), Earned Schedule Management (Lipke, 2003; Lipke, 2009), Earned Duration (Khamooshi and Golafshani, 2013), and Critical Chain Management (Goldratt, 1997; Leach, 2000). Each of these methods was developed with consideration to overcome the limitations of others. As projects became larger and more complex (Bosch-Rekveldt et al., 2011), more advanced approaches such as system-of-systems modeling of performance (Zhu et al., 2014) and meta-network analysis (Zhu and Mostafavi, 2016) have been proposed for assessing efficiency of construction projects. However, despite decades of invaluable research on progress measurement and performance assessment of construction projects, project results continue to disappoint stakeholders (Cooke-Davies, 2002). Some researchers have argued that failure in meeting time and cost objectives is inherent in the increasingly complex nature of construction projects (Williams, 2002; Williams, 2005). Others persistently looked for key factors influencing
project success (Munns & Bjeirmi, 1996; Cooke-Davies 2002; Belout and Gauvreau 2004; Mir & Pinnington, 2014; Todorović et al., 2015). However, a key element to improve project controls is to acknowledge the distinction between project success and the success of the project management effort, bearing in mind that “good project management can contribute towards project success but is unlikely to be able to prevent failure” (de Wit, 1988). Therefore, a more practical path to improve project outcomes is neither to develop more advanced project controls techniques nor to look for universal project success metrics, but to enhance reliability of the existing approaches for progress measurement and performance assessment in construction projects. Issues such as subjectivity, lack of standardized procedures and rules of credit across the board undermine the value that project controls can deliver for decision making. The key missing element to enhance reliability of project control systems is a standardized guideline that delineates the requirements of robust progress measurement, performance assessment, forecasting and corrective actions in construction projects. To address this important gap in the existing body of knowledge, the objective of the present research is to identify critical factors and related indicators for improving reliability of project control processes with specific phase based timing throughout the lifecycle of a project. Through establishing reliability improvement guidelines for key project controls functions, this research aims to remove as much subjectivity as possible so that standardization and consistent assessment can be achieved across the industry. The robust framework present in this study includes 15 critical reliability improvement factors and 85 related indicators that would provide greater confidence in using and interpreting project control metrics.
4.3 Background

One major obstacle to understanding the actual conditions of a construction project is the subjective and inconsistent use and interpretation of in-flight project controls. This results in performance of projects being potentially misrepresented and causes issues since the true project progress and performance are not known. Too many subjective inputs allow for manipulation or misrepresentation of project progress and performance.

One of the key problems is the lack of guidance on improving metric reliability. For example, each company might use a slightly different approach for determining the percent complete of design documents. "Issued for Construction", or IFC drawings are assigned point and credit values differently from one company to another. Therefore, progress and performance assessment reliability of IFC drawings are bound by these mostly subjective credit values. There are also no consistent acceptance criteria for what IFC drawings should really entail. Such inconsistencies increase the potential for misrepresentation of information. Hence, it is essential to develop clear guidelines and procedures for improving the reliability of the metrics and indicators.

This research hypothesizes that there are guidelines and implementation approaches that can improve the reliability of existing progress and performance assessment methods. While various widely accepted project control methods exist, the “quality of the assessment” cannot be determined since there is no industry standard to evaluate the reliability of these methods.

Different project control approaches suffer from reliability problems in different ways. However, to exhibit inherent reliability issues in project controls systems, using progress measurement methods and metrics could be a good example. Although the names and definitions may vary, major progress measurement methods include: 1) units completed, 2) incremental milestones, 3)
weighted or equivalent units completed, 4) resource expenditure, and 5) judgment (supervisor opinion) (CII, 1987; O’Brien et al., 2012; AACE International, 2012). Each progress measurement method has its strengths, but also intrinsic weaknesses, which are the main sources for potential reliability issues (Table 4.1). For example, the Units Completed method provides the most detailed and accurate progress information. However, it is applicable only to homogenous units of work. Also, this method may require a significant amount of time for data collection. On the other hand, the Judgment method takes the least amount of time and effort. However, this subjective approach is vastly dependent on the experience of the supervisor, and can be highly inaccurate and misleading. In general, there is a trade-off relationship between accuracy/consistency and efficiency in progress measurement (Chin et al., 2004).

Additionally, the implementation of different progress measurement methods is usually based on the project manager’s experience and preference instead of a set objective criteria. This subjectivity may cause problems in providing true measurement of project progress in an efficient and effective way. For example, using the Incremental Milestone method for measuring the progress of a minor component of the project (e.g., landscaping), rather than the Judgment method, could improve the accuracy; however, it requires more time and effort to develop the criteria and collect the data.

4.4 Methods

This research aimed to identify critical factors and related indicators to improve reliability of project control processes with specific phase based timing throughout the lifecycle of a project. In order to attain this objective, the authors designed and conducted a three-level research methodology: (1) survey, (2) in-depth case studies, and (3) expert panel input. The authors
conducted a survey to examine existing reliability concepts and identify projects that are suitable for further investigation as case studies. The 10 in-depth case studies of selected projects focused on collecting detailed information related to critical factors affecting the reliability of the project control metrics in construction projects. The results obtained from the case studies were verified and validated with an expert panel who also provided phase timing for critical reliability factors and indicators. The following sections explain the components of the research methodology.
Table 4.1 Details of common progress measurement methods (CII, 1987; O’Brien et al., 2012; AACE International, 2012). In bold, inherent weakness for each method are highlighted as potential reliability issues (Thomas 2000).

<table>
<thead>
<tr>
<th>Method</th>
<th>Details</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
</table>
| Units Completed | Quantity surveys or physical measurement of work items using homogenous units of work (ex.: linear-feet of wire pulled, cubic-yard of concrete placed) | • Most detailed and accurate  
• Does not rely on subjective opinions or evaluations  
• Claimed output can be readily verified | • Time for data collection might be lengthy, especially if not applied correctly |
| Incremental Milestone | A percent completion credited for completion of key incremental tasks for deliverables with multiple activities performed in sequence when output for each subtask cannot be easily measured (ex.: equipment installation, alignment and testing - e.g., 50, 70, and 100 percent of completion, respectively) | • Easy to use  
• Simple to understand | • Long periods may elapse before an intermediate milestone is reached |
| Weighted (or Equivalent Units Completed | A hybrid of units completed and incremental milestones for activities with long durations and composed of two or more overlapping subtasks, each with different units of work measurement (ex.: subtasks in structural steel erection with different units of measure are converted to equivalent tons and then the weighted percent complete is calculated | • Detailed  
• Provides ability to compare and summarize several different subtasks and activity groups | • May be inaccurate, especially if there are few items and the activity durations are lengthy  
• Weighing or equivalency conversions and calculations might be complex, as well as requiring attention |
Table 4.1 (cont.) Details of common progress measurement methods (CII, 1987; O’Brien et al., 2012; AACE International, 2012).

In bold, inherent weakness for each method are highlighted as potential reliability issues (Thomas 2000; Chin et al., 2004).

<table>
<thead>
<tr>
<th>Method</th>
<th>Details</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource expenditure</td>
<td>The percent of the total planned or forecast duration hours, or cost spent for the control account without any discrete deliverables or milestones in the work package (ex.: inspection and quality assurance)</td>
<td>• Greater detail and objectivity than simply estimating how much work was done</td>
<td>• Requires much more effort than simply estimating the percent complete</td>
</tr>
<tr>
<td>Judgment</td>
<td>The person responsible for the work package estimates the percent complete based on his or her informed judgment mostly for relatively minor tasks where development of a more discrete method cannot be used (ex.: painting, installing architectural trim, landscaping)</td>
<td>• Simple, inexpensive, quick</td>
<td>• Can be very inaccurate and misleading</td>
</tr>
</tbody>
</table>

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4.4.1 Survey

In order to identify existing reliability problems and prevention mechanisms, a web-based survey questionnaire was developed and distributed to project managers, and project controls professionals who are knowledgeable about this topic (Appendix B). Respondents submitted their answers based on a completed construction project that they were a part of. The survey questionnaire was structured into two parts: (1) background information; and (2) reliability information (Fig. 4.1). The background information included respondent and project characteristics. This information was used to obtain a better understanding of the perspectives of the respondents and the projects they submitted. In the second part of the questionnaire, respondents were asked to provide information with regards to reliability problems they faced, as well as the mechanisms they utilized to identify and cope with reliability issues.

Two criteria were used in identification of projects for in-depth case studies: (1) projects that met the authorized cost and schedule and utilized a wide array of project controls metrics and methods, including some innovative metrics for assessing project progress and performance; and (2) projects that did not meet the authorized cost and schedule nor used many project controls tools. These criteria allowed the authors to examine two ends of the spectrum with regards to project controls applications, project outcomes and underlying reliability issues.
**Figure 4.1** Structure and components of the reliability survey questionnaire

### 4.4.2 Case Studies

The objective of the case studies was to collect in-depth information about critical factors that influence the reliability of project progress and performance assessment. In total, ten projects were identified and used for in-depth case studies (Table 4.2). Among the ten case studies, six projects were studied from the contractor perspective and four were studied from the owner side. Nine of the case studies were conducted through organization visits and face-to-face meetings with the project management and project control personnel of the projects, whereas one case study was conducted through a phone interview with the project director. In addition to the information collected from the interviews, the research team reviewed sample monthly progress reports and other relevant project documents for collection of information related to progress and performance assessment metrics and methods. A close examination of the use cases, underlying assumptions,
data collection and reporting mechanisms for various project controls metrics and methods allowed the authors to gather empirical information about the reliability concepts.

The case study interviews included questions regarding the metrics and methods used in the project for progress and performance assessment, the effectiveness of metrics and methods, and issues related to the reliability of project progress and performance assessment. (The case study interview guide can be found in the Appendix D.)

Table 4.2 Details of case study projects studied.

<table>
<thead>
<tr>
<th>Case Study ID</th>
<th>Perspective</th>
<th>Number of Interviewees</th>
<th>Role of Interviewees</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Contractor</td>
<td>2</td>
<td>Project Director and Project Business Manager</td>
</tr>
<tr>
<td>B</td>
<td>Contractor</td>
<td>1</td>
<td>Global Project Controls Manager</td>
</tr>
<tr>
<td>C</td>
<td>Contractor</td>
<td>2</td>
<td>Project Manager and Project Controls Manager</td>
</tr>
<tr>
<td>D</td>
<td>Contractor</td>
<td>4</td>
<td>Project Manager, Project Controls Manager, Schedule Planner, Cost Manager</td>
</tr>
<tr>
<td>E</td>
<td>Owner</td>
<td>1</td>
<td>Global Manager for Planning and Scheduling</td>
</tr>
<tr>
<td>F</td>
<td>Owner</td>
<td>3</td>
<td>Project Managers and Project Controls Manager</td>
</tr>
<tr>
<td>G</td>
<td>Contractor</td>
<td>2</td>
<td>Project Controls Manager and Global Project Controls Manager</td>
</tr>
<tr>
<td>H</td>
<td>Owner</td>
<td>2</td>
<td>Project Executive and Project Manager</td>
</tr>
<tr>
<td>I</td>
<td>Owner</td>
<td>1</td>
<td>Manager of Project Controls Systems</td>
</tr>
<tr>
<td>J</td>
<td>Contractor</td>
<td>1</td>
<td>Project Director</td>
</tr>
</tbody>
</table>

The process for analyzing the information related to reliability factors included four steps: (1) transcribing interviews, (2) compiling information, (3) coding and clustering information, and (4) conducting a mind map analysis in order to categorize and cluster information into different themes. The interviews were analyzed through transcription and coding to cluster the collected
information. Coding refers to deciphering the transcribed interviews and labeling the pieces of information pertaining to the reliability issues and factors. The codes were refined through within-case and cross-case pattern analysis (Yin, 2003) to summarize groups of codes into themes, which were then used in conducting a mind map analysis. Mind map analysis was used for analysis of case study information since it provides an effective approach for the analysis of qualitative data (Tattersal et al., 2007; Wheeldon et al., 2009). Mind map analysis enabled effective classification of information, identification of the themes and association between different themes through visual representation of information and associations (Fig. 4.2).

### 4.4.3 Expert Panel

An expert panel analyzed the mind maps in multiple rounds. In each round the clusters of reliability factors and their associations were evaluated by the expert panel and this feedback was used in the next round of mind map analysis. The analysis stopped when a consensus was reached by the expert panel members that the identified factors and clusters related to reliability improvement covered the most important and relevant factors. The expert panel consisted of professionals experienced in different aspects of project lifecycle such as project management, project controls, engineering/design, procurement, and construction (Table 4.3). In addition to shaping the list of critical reliability improvement factors into its final version, they also provided phase specific timing details for each factor and related indicators.
Table 4.3 Members of the expert panel that reviewed and validated critical reliability improvement factors and indicators.

<table>
<thead>
<tr>
<th>Expert ID</th>
<th>Company Type</th>
<th>Expert Title</th>
<th>Years of Related Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Contractor</td>
<td>Global Manager of Project Controls &amp; Estimating</td>
<td>20+</td>
</tr>
<tr>
<td>2</td>
<td>Contractor</td>
<td>Project Controls Manager</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>Owner (Government Organization)</td>
<td>Program Manager</td>
<td>34</td>
</tr>
<tr>
<td>4</td>
<td>Contractor</td>
<td>VP of Nuclear Operations</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>Contractor</td>
<td>Senior Director, Global Supply Chain Quality &amp; Procurement</td>
<td>28</td>
</tr>
<tr>
<td>6</td>
<td>Contractor</td>
<td>Principal &amp; Managing Director</td>
<td>37</td>
</tr>
<tr>
<td>8</td>
<td>Contractor</td>
<td>Manager of Project Controls Division</td>
<td>22</td>
</tr>
<tr>
<td>9</td>
<td>Owner</td>
<td>Head of Project Risk Management &amp; Acting Head of Program/Project Management</td>
<td>21</td>
</tr>
<tr>
<td>10</td>
<td>Contractor</td>
<td>Commercial Manager</td>
<td>19</td>
</tr>
<tr>
<td>11</td>
<td>Owner</td>
<td>Refining Engineer</td>
<td>11</td>
</tr>
<tr>
<td>12</td>
<td>Owner</td>
<td>Project Engineering Manager</td>
<td>10</td>
</tr>
<tr>
<td>13</td>
<td>Contractor</td>
<td>Department Manager of Process Engineering</td>
<td>15</td>
</tr>
</tbody>
</table>
Figure 4.2 Mindmap representation of the case study interviews
4.5 Results and Discussion

4.5.1 Critical Reliability Factors and Indicators

This research identified critical reliability factors (CRFs) and indicators that influence and improve the project controls systems. CRFs are defined as factors that individually and collectively influence the reliability of the project progress and performance assessment metrics. The fifteen CRFs identified in this study are summarized in Table 4.4. For each CRF, various indicators were identified that ensure the reliability improvements are achieved through the application of CRFs. In total, 85 achievement indicators with phase specific timing are identified and connected to fifteen CRFs (Fig. 4.3).

**Table 4.4 Critical reliability factors (CRFs) of project control metrics.**

<table>
<thead>
<tr>
<th>Critical Reliability Factors</th>
<th>9. Metric Trend Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Project Scope Definition</td>
<td>10. Schedule Forecasting</td>
</tr>
<tr>
<td>2. Project Execution Planning</td>
<td>11. Cost Forecasting</td>
</tr>
<tr>
<td>7. Risk Management</td>
<td></td>
</tr>
<tr>
<td>8. Progress Audits</td>
<td></td>
</tr>
</tbody>
</table>

- Project scope definition significantly influences the reliability of related project control metrics. The achievement of the three indicators under this CRF helps ensure that the level of project scope definition required for reliable project controls is achieved.

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• Project execution planning is essential in defining project objectives and requirements, and thus, establishing the basis for reliable project control metrics. Fulfilling five achievement indicators related to this CRF would help ensure that project execution planning requirements are met in order to establish reliable project control metrics.

• Project control planning is a key component for establishing reliable project control metrics. Accomplishing its five achievement indicators would provide the required project control planning necessary for establishing reliable project control metrics.

• Progress measurement relies heavily on establishing consistent rules of credit and four achievement indicators were identified for that purpose. If these achievement indicators are realized in a project, the rules of credit will have the required consistency in order to establish reliable progress and performance measurement metrics.

• Schedule and cost development and tracking can significantly affect the reliability of metrics. Through fulfilling its nine achievement indicators, a project will have a robust schedule and cost development and tracking approach in order to ensure the reliability of project control metrics.

• Use of a robust change management process is an essential component in improving the reliability of metrics used for project progress and performance assessment as identified by previous studies (CII, 1994; AACE International, 2012; PMI, 2013). To this end, five achievement indicators were identified for this CRF, achievement of which would ensure that changes are incorporated in the data and measures used in determining progress and performance assessment metrics.
• Establishing a robust risk management process is another key component required to obtain reliable project control metrics. There are eight achievement indicators identified in this research for a robust risk management process. Through timely fulfillment of these indicators, a project would obtain the required risk management process in order to achieve reliable project control metrics.

• Progress audits are another necessary element for ensuring the reliability of project progress and performance metrics. The three achievement indicators would ensure that a proper progress audit is followed in order for the project control metrics to be reliable.

• While performance metrics provide insights into project cost and schedule performance, metric trend analysis is a critical factor for enhancing the reliability of project control. This study identified three achievement indicators for ensuring the use of a robust performance trending approach. A key aspect of trend analysis is to periodically evaluate performance trends and identify issues affecting performance and conduct forecasting based on recent performance trends. By attaining these achievement indicators, the required performance trending process would be in place in order to enhance the reliability of project control metrics.

• Conducting a robust schedule forecasting process is essential for improving the reliability of project control metrics. Twelve achievement indicators identified for this CRF would ensure a robust schedule forecasting process necessary for enhancing project control reliability.

• Similar to schedule forecasting, establishing a robust cost forecasting process is also an essential component in improving the reliability of project control metrics. Through
fulfilling the five achievement indicators, a project would have a robust cost forecasting process in place.

- Establishing an effective communication process among stakeholders is a critical component influencing the reliability of metrics used for project progress and performance assessment. This study identified 10 achievement indicators for ensuring a proper communication process. Fulfillment of these achievement indicators will ensure a proper communication process that is necessary for improving the reliability of progress and performance metrics.

- Teamwork is another CRF necessary to enhance stakeholder alignment towards improving the reliability of project control metrics. Enhancing team alignment has been long established as a best practice (Griffith & Gibson Jr., 1997; AACE International, 2012; PMI, 2013). To highlight the importance of team alignment in improving project progress and performance metrics, this study identified five achievement indicator and the realization of these achievement indicators will ensure the required level of alignment and teamwork for improving the reliability of project control metrics.

- The accountability of various stakeholders is an essential component of reliability in project control metrics. All the stakeholders in a project should be held accountable to monitor and report their respective project progress and performance and ensure that project schedule and cost objectives are attained. To this end, five achievement indicators were identified and accomplishing these achievement indicators would ensure the required level of accountability to improve the reliability of project control metrics.
• Implementing periodic project control audits is necessary for enhancing the reliability of project control metrics and two achievement indicators were identified to ensure a proper project control audit process. The periodic internal peer and external third-party reviews provide the project team with unbiased feedback regarding the effectiveness of project control processes and metrics. Periodic project control meetings ensure the proper level of communication among the stakeholders to have accurate information for determination of various project progress and performance metrics.

Fifteen CRFs and 85 indicators affect the reliability of project control metrics individually and collectively. Failing to attain one or more these CRF may have a ripple effect on other CRFs and eventually on project outcomes. For example, failing to establish a robust change management process will influence the schedule and cost forecasting processes, and thus, have a greater influence on the reliability of project progress and performance metrics. Hence, the objective of a project should be to fulfill all identified CRFs to improve the reliability of project control metrics.

4.5.2 Timing of Critical Reliability Factors

Each of the CRFs identified above must be achieved at specific times during different phases of a project to be effective. This research utilized a phase gate process (process in which a project must pass through formal gates at well-defined milestones before proceeding to the next phase) and identified four phases at which CRFs should be achieved: (1) pre-detailed design, (2) detailed design, (3) construction, and (4) start-up and commissioning. To this end, for each of the CRF categories and corresponding achievement indicators, the timing for achievements was identified. The timing of an achievement might be only in one project phase or multiple phases. Each indicator has a specific timing assigned to it, and it can be observed at or between any of the five timing
milestones; (1) prior to, (2) at the beginning of, (3) during, (4) at the end of, or (5) after that phase. It is also possible that an indicator be observed over the course of the phase, starting at any one of the five timing milestones, and ending at another.

The checklist shown in Fig. 4.3 includes the CRFs and indicators along with their specific application timing. The first column of the checklist in Fig. 4.3 shows the CRF categories and the second column lists the associated indicators for each CRF. Columns three through six present reliability indicator timing information for different project phases, using specific shapes to mark the timing for different indicators as explained in the legend. Each indicator is associated with one or multiple project phases (pre-detailed design, detailed design, construction, or start-up and commissioning) during which the related CRFs and indicators must be completed.

Additionally, the CRFs identified in this study are generic and can be applied to different projects. There may be additional CRFs depending on project characteristics, requirements, and perspective (i.e., owner vs. contractor). Project teams should identify the additional CRFs based on the specific circumstances of each project.

4.6 Conclusion

Project controls play an essential role in realization of desired project outcomes. However, major challenges are related to the lack of reliable, consistent, and objective metrics and indicators. Through ten in-depth cases studies, this research provides information on ways to improve the reliability of these metrics. Fifteen CRFs and 85 indicators with phase specific timing are included for improving metric reliability in several areas such as project scope definition, execution planning, and risk management.
The checklist provided in this research would help industry stakeholders to identify and improve inherent reliability issues in their existing project controls processes. Although the research presented in this study includes qualitative analyses, it is still highly valuable considering the wide range of projects and characteristics examined through case studies.

Future research might explore how CRFs and indicators included in the checklist are related to specific project control metrics and methods. Investigating this relationship would allow for more precise reliability improvement actions and overall project performance enhancement.
<table>
<thead>
<tr>
<th>Critical Reliability Factor (CRF)</th>
<th>Indicator of CRF Achievement</th>
<th>Pre-Detailed Design</th>
<th>Detailed Design</th>
<th>Construction</th>
<th>Start-up and Commissioning</th>
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</thead>
<tbody>
<tr>
<td>1. Project Scope Definition</td>
<td>1.1. Clear scope of work and baseline documents are defined</td>
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<td></td>
<td>1.2. Project Definition Rating Index (PDRI) assessment is planned and/or implemented</td>
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<td></td>
<td>1.3. A detailed and integrated work breakdown structure (WBS) that accurately captures project scope is created and implemented</td>
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<tr>
<td>2. Project Execution Planning</td>
<td>2.1. Project organizational chart is developed and maintained</td>
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<td></td>
<td>2.2. Detailed execution and labor contracting strategies are created, maintained, and communicated to all stakeholders</td>
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<td>2.3. Project execution plan adequately addresses project scope</td>
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<td>2.4. Priority between cost and schedule are defined</td>
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<td></td>
<td>2.5. The project organizational chart includes all the positions listed and associated roles and responsibilities are defined clearly</td>
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<tr>
<td>3. Project Control Planning</td>
<td>3.1. Metrics and their thresholds are determined based on project characteristics (e.g., size, type, and complexity)</td>
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<td>3.2. Metrics are aligned with contractual requirements</td>
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<td>3.3. The quality and detail requirements of the schedule is defined</td>
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<td>3.4. Project control plan defines reporting requirements</td>
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<td></td>
<td>3.5. The commercial and technical milestones are aligned with project delivery requirements</td>
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<tr>
<td>4. Progress Measurement</td>
<td>4.1. Rules of credit for project deliverables are defined to provide accurate progress measurement</td>
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<td></td>
<td>4.2. Consistent rules of credit are tied to tangible deliverables to provide accurate progress measurement</td>
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<td></td>
<td>4.3. Level of effort and percent complete are aligned for project deliverables</td>
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<td>4.4. Discipline-specific, and trade-specific rules of credit are used consistently</td>
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<td>4.5. Discipline specific quantity-based commodity curves are used</td>
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<td></td>
<td>4.6. Commodity curves based on project schedule are used</td>
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<tr>
<td>5. Schedule and Cost Development and Tracking</td>
<td>5.1. A detailed resource-loaded schedule (including quantities, man-hours, and productivity rates) for all WBS work packages is developed</td>
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<td></td>
<td>5.2. Key project deliverables are identified and updated for different phases</td>
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<td></td>
<td>5.3. Milestones are defined at the appropriate level for the project schedule</td>
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<td>5.4. Project milestones are tied to critical path activities</td>
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<td></td>
<td>5.5. Third party or peer reviews are conducted to ensure schedule quality</td>
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<td></td>
<td>5.6. Baseline schedule is developed without contingency</td>
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<td>5.7. The original budget is set to align with project control estimate</td>
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<td></td>
<td>5.8. Project progress is periodically evaluated with respect to both forecasted completion date and physical progress of work packages</td>
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<td></td>
<td>5.9. Cost curves are aligned with the schedule of expenditures (i.e., cost and schedule are integrated)</td>
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</tbody>
</table>

Figure 4.3 CRF and related indicators with specific timing for improving reliability of project controls systems and metrics.

91
<table>
<thead>
<tr>
<th>Critical Reliability Factor (CRF)</th>
<th>Indicator of CRF Achievement</th>
<th>Pre-Detailed Design</th>
<th>Detailed Design</th>
<th>Construction</th>
<th>Start-up and Commissioning</th>
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</thead>
<tbody>
<tr>
<td>6. Change Management</td>
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<tr>
<td>6.1.</td>
<td>An effective process is established and conducted using best practices to proactively manage changes on the project</td>
<td>PR</td>
<td>B</td>
<td>D</td>
<td>E</td>
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<tr>
<td>6.2.</td>
<td>A change log is created and maintained</td>
<td>PR</td>
<td>B</td>
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</tr>
<tr>
<td>6.3.</td>
<td>All changes are documented</td>
<td>PR</td>
<td>B</td>
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<tr>
<td>6.4.</td>
<td>Approved changes are integrated with project baseline</td>
<td>PR</td>
<td>B</td>
<td>D</td>
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</tr>
<tr>
<td>6.5.</td>
<td>Approved changes are reflected in budget and design documents</td>
<td>PR</td>
<td>B</td>
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<td>7. Risk Management</td>
<td></td>
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<tr>
<td>7.1.</td>
<td>A risk register is created for the project</td>
<td>PR</td>
<td>B</td>
<td>D</td>
<td>E</td>
</tr>
<tr>
<td>7.2.</td>
<td>Risks are captured on one risk register</td>
<td>PR</td>
<td>B</td>
<td>D</td>
<td>E</td>
</tr>
<tr>
<td>7.3.</td>
<td>Project risk management plans include communication requirements and roles and responsibilities for all stakeholders</td>
<td>PR</td>
<td>B</td>
<td>D</td>
<td>E</td>
</tr>
<tr>
<td>7.4.</td>
<td>High Likelihood/High Impact risks are integrated into the schedule</td>
<td>PR</td>
<td>B</td>
<td>D</td>
<td>E</td>
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<tr>
<td>7.5.</td>
<td>The risks associated with critical and near-critical paths are periodically evaluated and updated in the risk register</td>
<td>PR</td>
<td>B</td>
<td>D</td>
<td>E</td>
</tr>
<tr>
<td>7.6.</td>
<td>Risk register is periodically reviewed and updated</td>
<td>PR</td>
<td>B</td>
<td>D</td>
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</tr>
<tr>
<td>7.7.</td>
<td>Effectiveness of risk register is periodically evaluated</td>
<td>PR</td>
<td>B</td>
<td>D</td>
<td>E</td>
</tr>
<tr>
<td>7.8.</td>
<td>Scenario analysis is conducted through schedule risk analysis to evaluate possible changes in critical and near-critical milestones</td>
<td>PR</td>
<td>B</td>
<td>D</td>
<td>E</td>
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<tr>
<td>8. Progress Audits</td>
<td></td>
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<tr>
<td>8.1.</td>
<td>Frequent reviews of physical progress and status of milestones are performed</td>
<td>PR</td>
<td>B</td>
<td>D</td>
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</tr>
<tr>
<td>8.2.</td>
<td>Physical progress information is obtained per specified frequency in project control plan</td>
<td>PR</td>
<td>B</td>
<td>D</td>
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<tr>
<td>8.3.</td>
<td>Planned productivity rates are verified with staff plans/wage rates to evaluate if the planned progress is achievable</td>
<td>PR</td>
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<tr>
<td>9. Metric Trend Analysis</td>
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<tr>
<td>9.1.</td>
<td>Core metrics trend analysis is conducted</td>
<td>PR</td>
<td>B</td>
<td>D</td>
<td>E</td>
</tr>
<tr>
<td>9.2.</td>
<td>Cost trend analysis is implemented for different trades and disciplines using actual productivity rates</td>
<td>PR</td>
<td>B</td>
<td>D</td>
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<tr>
<td>10. Schedule Forecasting</td>
<td></td>
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<tr>
<td>10.1.</td>
<td>Trend analysis of planned vs. earned vs. actual man-hours are conducted for different trades and disciplines</td>
<td>PR</td>
<td>B</td>
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<td>E</td>
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<tr>
<td>10.2.</td>
<td>The critical and near-critical path activities are monitored to evaluate the forecasted completion date of the overall project</td>
<td>PR</td>
<td>B</td>
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<tr>
<td>10.3.</td>
<td>Look-ahead analysis of milestones is conducted</td>
<td>PR</td>
<td>B</td>
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<tr>
<td>10.4.</td>
<td>Agreed-upon conditions for re-baselining the schedule are defined</td>
<td>PR</td>
<td>B</td>
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<tr>
<td>10.5.</td>
<td>Actual productivity rates are used to forecast project completion date</td>
<td>PR</td>
<td>B</td>
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<tr>
<td>10.6.</td>
<td>The outcomes of schedule risk analysis are used as a proxy to verify forecasted project completion date</td>
<td>PR</td>
<td>B</td>
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<tr>
<td>10.7.</td>
<td>Near-critical path activities are monitored to avoid changes to the critical path</td>
<td>PR</td>
<td>B</td>
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<tr>
<td>10.8.</td>
<td>Critical path activities are reviewed with each discipline and trade</td>
<td>PR</td>
<td>B</td>
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<tr>
<td>10.9.</td>
<td>Project progress milestones are frequently monitored using graphical tools (e.g., Skyline analysis)</td>
<td>PR</td>
<td>B</td>
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<tr>
<td>10.10.</td>
<td>Approved changes are incorporated in schedule forecasting</td>
<td>PR</td>
<td>B</td>
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<tr>
<td>10.11.</td>
<td>The current schedule is periodically compared against the base-line for assessment of schedule deviation</td>
<td>PR</td>
<td>B</td>
<td>D</td>
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</table>

PR: Prior to; B: At the Beginning; D: During; E: At the End; PO: Post

represents the reliability indicator observed at a specific time
represents monitoring a reliability indicator over a certain period of time within the phase
represents the reliability indicator achievement milestones

* Indicators occurring prior to Pre-Detailed Design phase are mostly programming requirements that must be done prior to project approval/authorization.

Fig. 4.3. (cont.) CRF and related indicators with specific timing for improving reliability of project controls systems and metrics.

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**Critical Reliability Factor (CRF)**

<table>
<thead>
<tr>
<th>Indicator of CRF Achievement</th>
<th>Pre-Detailed Design</th>
<th>Detailed Design</th>
<th>Construction</th>
<th>Start-up and Commissioning</th>
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</thead>
<tbody>
<tr>
<td>Pre-Detailed Design:</td>
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<tr>
<td>11.1. Quantity changes are incorporated into cost and schedule forecast</td>
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<tr>
<td>11.2. Costs of remaining tasks are forecasted based on actual man-hour rates</td>
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<td>11.3. Contingency cost of remaining activities is determined based on risk trends, remaining risk exposure, and forecasted schedule duration</td>
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<td>11.4. Approved changes are incorporated in cost forecasting</td>
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<tr>
<td>11.5. Costs of remaining materials are forecasted based on current market prices and possible cost escalation</td>
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<tr>
<td>Detailed Design:</td>
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<tr>
<td>12.1. Project communication matrix is defined for project control reporting and is kept current</td>
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<td>12.2. Regular status meetings are held with project stakeholders</td>
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<tr>
<td>12.3. Communication of progress and performance metrics with stakeholders is open and effective</td>
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<tr>
<td>12.4. Effective dashboards and infographic visualization tools are used for project control reporting</td>
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<tr>
<td>12.5. All stakeholders are aligned regarding contractual requirements related to project control needs at the early stages of the project</td>
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<td>Construction:</td>
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<tr>
<td>12.6. Contractual reporting requirements (i.e., form, format, frequency, and timing) are communicated to all stakeholders in project team</td>
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<td>12.7. Stakeholders are engaged and educated about core project metrics</td>
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<td>12.8. All stakeholders understand the rules of credit at the beginning of a project</td>
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<tr>
<td>12.9. Audit processes and procedures are communicated to all stakeholders</td>
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<td>Start-up and Commissioning:</td>
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<tr>
<td>12.10. Evaluation meetings are conducted to document lessons learned related to project control metrics</td>
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**Teamwork**

<table>
<thead>
<tr>
<th>Indicator of CRF Achievement</th>
<th>Pre-Detailed Design</th>
<th>Detailed Design</th>
<th>Construction</th>
<th>Start-up and Commissioning</th>
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<tr>
<td>Pre-Detailed Design:</td>
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<tr>
<td>13.1. Effective team alignment is conducted using best practices</td>
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<td>13.2. The project team culture fosters trust, honesty, and shared values</td>
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<tr>
<td>Detailed Design:</td>
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<td>13.3. Formal onboarding process for new project management personnel is conducted using a well-defined responsibility matrix by discipline</td>
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<tr>
<td>Construction:</td>
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<tr>
<td>13.4. Team building sessions are conducted to define, obtain consensus, and follow up regarding project success indicators</td>
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<tr>
<td>Start-up and Commissioning:</td>
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**Accountability**

<table>
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<th>Indicator of CRF Achievement</th>
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<th>Detailed Design</th>
<th>Construction</th>
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<tr>
<td>Pre-Detailed Design:</td>
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<tr>
<td>14.1. All stakeholders agree and adhere to reporting cut-off deadlines</td>
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<td>14.2. All stakeholders know the impacts of their current and proposed changes on the project schedule/cost/quality</td>
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<td>14.3. All stakeholders buy-in and own their requirements for project progress and performance assessment</td>
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<td>14.4. Project team is empowered to make timely decisions</td>
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<tr>
<td>14.5. All stakeholders know the impacts of deliverables on project schedule</td>
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<tr>
<td>Detailed Design:</td>
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<td></td>
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<tr>
<td>Construction:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start-up and Commissioning:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Project Control Audits**

<table>
<thead>
<tr>
<th>Indicator of CRF Achievement</th>
<th>Pre-Detailed Design</th>
<th>Detailed Design</th>
<th>Construction</th>
<th>Start-up and Commissioning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Detailed Design:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.1. Internal peer-reviews and external third-party audits are conducted</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.2. Periodic project control meetings and audits are conducted with all stakeholders</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PR: Prior to; B: At the Beginning; D: During; E: At the End; PO: Post

- Indicates the reliability indicator observed at a specific time
- Represents monitoring a reliability indicator over a certain period of time within the phase
- Represents the reliability indicator achievement milestones

* Indicators occurring prior to Pre-Detailed Design phase are mostly programming requirements that must be done prior to project approval/authorization.

---

**Fig. 4.3. (cont.) CRF and related indicators with specific timing for improving reliability of project controls systems and metrics.**
5 Project Controls Improvement Tool

5.1 Introduction

The broad goal of this research was to develop high impact, high value resources that can assist in identifying critical data from project progress and performance assessments. These resources will provide effective means for improving outcomes at both the project and organizational levels.

The research outcomes were translated into a tool that enables various project stakeholders to better monitor, control, and communicate project progress and performance assessment. The tool created in this study will be beneficial for various project stakeholders including engineering managers, project managers, project control teams, cost engineers, and schedulers in owner and contractor organizations. The tool provides means to identify and better implement core metrics through enhanced reliability and consistent use and interpretation. The researchers determined that development of standard definitions and evaluation techniques that are broadly accepted and adopted would be beneficial for both owners and contractors. Therefore, this study’s findings have been implemented as a software tool that enables various project stakeholders to better monitor, control, and communicate project progress and performance assessment. The Project Controls Improvement (PCI) Tool is a software package that integrates essential metric and reliability information regarding project control systems. The PCI Tool will be beneficial for various project stakeholders, including engineering managers, project managers, project control teams, cost engineers, and schedulers in owner and contractor organizations. The tool provides the means to identify and better implement core metrics through enhanced reliability and consistent use and interpretation.
The user guide provides an understanding of how to use the software and briefly explains the project control metrics and reliability improvement factors. Figure 5.1 shows how the components of the software are connected and how they target the improvement of current and future projects through better and more insightful assessment of project performance.

**Figure 5.1** Overview of implementation resource modules.

The primary function of this software is to identify and address possible gaps in progress and performance assessment. The software enables the user to identify any gaps in the use of core metrics, as well as any gaps in the implementation of critical reliability factors in order to improve project progress and performance assessment. Project stakeholders can utilize this software to evaluate current practices regarding project progress and performance assessment in their own projects. Users will receive customized suggestions regarding improvements that can be made by using additional core metrics and/or by implementing critical reliability factors. The analysis results can be easily saved, printed, and shared among project team members. Figure 5.2 depicts the input-output structure and flow of the PCI Tool.
5.2 Metrics Gap Analysis

The metrics gap analysis module enables users to evaluate the progress and performance metrics that are used in their projects. The software can identify gaps in the use of metrics and provide recommendations of additional useful metrics. The user input page of this module (Figure 5.3) asks users to determine the predictive and diagnostic metrics that are currently used in their projects.
Based on user input, the software provides a metric gap analysis report that includes the following information:

- The core, validation, innovative, and other significant metrics that are currently used in the projects;
- The additional core, validation, innovative, and other significant metrics that can be potentially used in the projects; and
- An overall score related to the use of core predictive and diagnostic metrics in the project.

Figure 5.4 shows an example of the output page of the metrics gap analysis module. Users can see the lists of “selected metrics” and “additional metrics” in each sub-category based on the type and importance of metrics. By clicking “Radar Graph” in the output page, users can obtain a radar
graph showing the selection of core metrics by category (Figure 5.5). Using the radar graph, users can visualize the usage of core metrics on each specific category. In the gap analysis report, by clicking on the name of each metric, users can review the detailed information of each metric, including definition, equation, indicator, use and interpretation, and metric map. This information provides users with insights regarding additional metrics to be used in order to improve project progress and performance assessments. In addition, the information can sharpen the focus of a company’s progress and performance assessment by monitoring core metrics.

Figure 5.4 Metric gap analysis output interface for predictive metrics.
5.3 Reliability Gap Analysis

The second component of the PCI Tool is the reliability gap analysis module. This module helps users to better assess their practices regarding reliability issues in project progress and performance assessment. The reliability gap analysis module enables the users to assess the gaps in implementation of critical reliability factors at the beginning of each project phase (i.e., pre-detailed design, detailed design, construction, and startup and commissioning). The input page (Figure 5.6) of this module enables users to select the project phase of interest, and accordingly, to evaluate the achievement of critical reliability factors related to that phase. Once users select a specific phase, all relevant critical reliability factors (CRFs) and corresponding achievement
indicators will appear on the screen. The users will be asked to evaluate the implementation of different CRF related to the specific phase of the project.

![Reliability Gap Analysis](image)

**Figure 5.6** Reliability gap analysis input page.

In the output information of the reliability gap analysis module, users receive a reliability score for each phase based on the overall percentage of CRF indicators achieved in that phase, and the percentage of achievement indicators achieved for each CRF (as shown in Figure 5.7. This information will highlight the extent of implementing CRFs that improve the reliability of project progress and performance assessment metrics during each phase. In addition, the output information highlights any CRFs that need improvement in order to enhance the reliability of project performance assessment. Users can access the CRF implementation timing guide in the
output page of this module, as well, in order to gain additional information regarding the timing of implementation for CRFs.

Figure 5.7 Reliability gap analysis output page.

5.4 Metrics Dictionary and Maps

The Metrics Dictionary and Maps provide users with a resource to access information related to metrics available in the PCI Tool. At the top of the page, the user can read instructions about the elements of the dictionary. Using the Metrics Dictionary search box, the user can search for metrics by name (Figure 5.8). Metrics information can also be filtered based on category and classification. For example, if a user wants to look up core predictive metrics, he/she can select the “Forecasting” and “Core” options of the dictionary (Figure 5.9) and click the search button, presenting all filtered results.
Figure 5.8 Metrics dictionary and maps: searching metrics

Figure 5.9 Filtering metrics by classification and category
When the user finds the intended metric, the metric can be selected in order to see detailed information associated with the metric on the right pane (Figure 5.10). This detailed information includes the definition, equation, use and interpretation, indicators, and additional references for learning about the metric. In addition, the user can access the metric map to see the data and information used in calculating the metric (Figure 5.11). Each metric map demonstrates how a metric is calculated using other metrics (or data points) in greater detail. Understanding these relationships would be invaluable for all project stakeholders from all levels.

**Figure 5.10** Detailed information for a selected metric
Figure 5.11 The metric map for a selected metric in the dictionary

5.5 Project Control Utilities

The Project Controls Utilities Module includes two elements: (1) a Core Metrics Directory and (2) a Reliability Improvement Checklist (Figure 5.12). Users can access the utilities for project control metrics and reliability improvement by clicking their respective buttons. The Core Metrics Directory is a spreadsheet composed of information related to metrics, definitions, equations, classifications, and use and interpretation, as well as metric maps. A complete list of metrics maps can also be downloaded in Core Metrics Directory. Similarly, the Reliability Improvement Checklist is a spreadsheet that includes information about critical reliability factors (CRFs), indicators, and their implementation timing in different project phases. Users can save both the
Core Metrics Directory and Reliability Improvement Checklist and use them for training and communication purposes.

Figure 5.12 Project controls utilities overview page

5.5.1 The Core Metrics Directory and Maps
The Core Metrics Directory provides a categorization system to distinguish metrics based on their role (predictive vs. diagnostic) and level of importance (core vs. significant). Also, the Core Metrics Directory provides guidelines for project control metrics and their intended usage, formulas, and indicators to improve measurement standardization (see Tables 3.3 and 3.4 in Chapter 3, and Tables C.1 and C.2 in Appendix C). Additionally, users can access the metric maps to see the data and information flow used for calculation of the metric. Maps are also provided to help visualize the composition of each metric which are based on calculations involving data and other feeder metrics. Metric maps are color coded to differentiate metrics by project control function.
5.5.2 Reliability Improvement Checklist

The Reliability Improvement Checklist includes fifteen CRFs and 85 indicators related to different CRFs. The checklist’s first column (see Figure 4.2 in the previous chapter) shows the CRF categories and the second column lists the associated reliability indicators for each category. Columns three through six present reliability indicator timing information for different project phases, using specific shapes to mark the timing for different indicators as explained in the legend. Each indicator is associated with one or multiple project phases (pre-detailed design, detailed design, construction, or start-up and commissioning) during which the related CRFs and indicators must be completed.

5.6 Examples of PCI Tool use cases

The PCI Tool is intended for use in a team setting to evaluate projects’ progress and performance metrics, to better assess their reliability, and to establish a common understanding of metric definitions and usage in the industry. This software was developed for a wide range of owner and contractor organizations, project types, and project phases. Figure 5.13 provides example use cases for PCI implementation.

<table>
<thead>
<tr>
<th>Who?</th>
<th>How?</th>
<th>When?</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Project managers</td>
<td>• Resource for project execution planning</td>
<td>• Project planning</td>
</tr>
<tr>
<td>• Project control managers</td>
<td>• Standardization of project control metrics</td>
<td>• Project execution</td>
</tr>
<tr>
<td>• Project control specialists</td>
<td>• Improve communication</td>
<td>• Team training and alignment</td>
</tr>
<tr>
<td>• Cost engineers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Schedulers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Entry-level professionals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.13 Potential implementation alternatives

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Endless combinations of possible use cases can occur during projects, but some possible future applications are explored below:

- **An aid for project managers and control teams to use when developing project control execution plans for a specific project:**
  Project managers and control teams can refer to the Core Metrics Directory and Reliability Improvement Checklist provided in the PCI Tool to develop their project control execution plans during the pre-planning phase.

- **A tracking document for reliability improvement practices throughout a project’s lifecycle:**
  Using the Reliability Gap Analysis Module of the PCI Tool, project managers and control teams can perform a reliability gap analysis at different time points during a project to track the changes (in percentage) of CRFs completed, confirm that previously identified areas for improvement have been addressed, and ensure continuity of projects’ reliability practices.

- **A training reference for entry-level project controls professionals:**
  Due to its interactive software platform, PCI Tool encourages entry-level project professionals to engage with the material, and offers information on metrics and reliability assessment in a user-friendly format. For example, the software’s metric maps provide visual demonstrations of the interrelationships between different metrics. This might be highly beneficial especially for those new to project controls to learn more about how each metric is constructed and the connections among metrics, as part of initial training on project measurement and assessment.
• **An owner’s reference for formulating project controls in contractual requirements:**

An owner organization can use the recommended practices, such as core metrics and CRFs in the PCI Tool, to develop the contractual requirements for improved project controls.

• **A benchmarking basis for performance assessment metrics and reliability practices:**

The PCI Tool provides a tool for owners and contractors to identify core metrics gaps and conduct project controls benchmarking across various projects. In addition, the Reliability Gap Analysis Module in the PCI Tool enables companies to implement benchmarking related to percent reliability indicators achieved across different phases in various projects. Through continuous benchmarking using the PCI Tool, companies can identify their own thresholds related to core metrics and reliability indicator percentages that lead to successful project outcomes.

**Case #1:** A project controls manager or operations manager receives feedback that the company’s project controls do not meet industry standards. He/she wants to determine how project control metrics can be improved to increase accountability.

**PCI Tool Use:** In this case, the project controls manager can select the Metrics Gap Analysis module and use the radar diagram to identify gaps in company’s current use of metrics. The manager can identify additional metrics from the analysis results to be incorporated into the company’s practices and utilize the Core Metrics Directory, Metrics Dictionary and Metric Maps to train personnel on the calculation, use, and interpretation of the additional metrics.

**Case #2:** A project manager recognizes that his/her projects experience cost overruns and delays, and project control metrics do not seem to be reliable. He/she wants to know how to strengthen
the company’s progress and performance assessment processes to improve project controls reliability.

**PCI Tool Use:** In this case, the project manager can use the Reliability Gap Analysis module to determine gaps in the company’s approaches to improving project control reliability. The identified gaps and analysis results can be saved and shared with other departments in the company. In addition, the project manager can use the Reliability Improvement Checklist as a guide to train personnel and implement CRFs in his/her company.

**Case #3:** A project controls department in an owner organization needs to determine specifications for an upcoming project’s control requirements. The project controls manager wants to identify which core metrics to monitor in order to increase the likelihood of project success.

**PCI Tool Use:** In this case, the project controls manager can use the Metrics Dictionary to review all core metrics and compare them to the upcoming project’s goals and objectives, as well as company’s past projects. The list of core metrics, their definitions, and equations can be saved and incorporated into the project’s specifications. In addition, the manager can use the metrics maps to ensure the proper and consistent calculation of and information flow between core metrics.

**Case #4:** A new graduate has joined the project controls department of a contractor organization. He/she is asked to review monthly progress reports and interpret progress and performance assessment metrics. However, he/she is not familiar with various metrics and how they should be interpreted.

**PCI Use:** The Metrics Dictionary provides a guide for individuals with limited prior project controls knowledge or experience to learn about different types of metrics, their definitions, calculations, indicators, and use and interpretation.
6 Conclusion

6.1 Summary

This research developed a metric typology of predictive and diagnostic metrics that can improve the understanding a project’s actual progress, performance and forecast. Understanding which metrics and indicators to use is important since it takes a great deal of effort to gather project data and convert it into information. Project manager and senior management want to know that the data gathered and processed will provide useful information about the status of a project. The typology of predictive and diagnostic metrics was connected to a framework that demonstrates how each project control function plays a significant role in transforming project data into meaningful, actionable insights. The connections among metrics were visualized via a set of metric maps, which were then aggregated to create a metric network that clarifies the interrelationships among metrics.

A list of all possible metrics from an extensive literature review was gathered. A survey was implemented to identify the use and importance of the various predictive and diagnostic metrics. In total, 44 surveys were completed representing mostly large, industrial projects. A Delphi session was conducted with 16 subject matter experts with more than 360 years of combined experience to verify and validate the findings from the survey. The Delphi session further refined the list of metrics into ones that are considered 20 core (must have), 7 validation (good to have as a way to validate the core metrics), 7 innovative (ones that are not currently in wide use but nevertheless has found benefit by some project control experts), and 14 other significant metrics (noncore metrics that were perceived to have value based on survey data).
Core metrics were selected based on the following project characteristics: large, industrial, reimbursable cost, balanced cost and schedule goals, moderate complexity, and contractor perspective. When considering core metrics from other project characteristics, it was discovered that the core metrics will be the same—the only difference relates to the frequency of data collection and level of effort involved in collecting and analyzing these data.

The same survey also contained questions pertaining to improving the reliability of these metrics. Ten case studies were selected among the surveyed projects that included different characteristics—some were innovative in their use of metrics and achieved their cost and schedule goals while others experienced performance and reliability issues. In-depth analysis of these projects lead to development of a reliability improvement framework which included 15 critical reliability factors and 85 indicators with phase specific timing information.

Overall this research presented a holistic approach to enhance and standardize project control systems. Through a typology (i.e. predictive vs. diagnostic), framework (transforming data to insights) and categorization structure (core and significant) for metrics, consistency and standardization are provided to project control measurement and assessments. By determining critical reliability factors and achievement indicators with application milestones, overall reliability and objectivity of the project controls is enhanced. These contributions would increase the likelihood of achieving better cost and schedule outcomes for projects, and improve overall performance in construction industry.
6.2 Contribution of This Work

This research contributes to the existing literature in the following ways:

- A new typology that distinguishes between predictive (helps forecast project cost and duration outcomes) and diagnostic (helps identify progress and performance issues) metrics
- By adopting from the field of information science, a new framework that shows how key project control functions and decision levels are utilized to transform project data into meaningful and actionable project insights
- Visualization metric information via metric maps and metric network
- A new metric categorization that identifies core metrics, which provide the greatest insight about a project’s progress and performance
- Validation of core metrics that shows the real value in using more core metrics and the relationship of certain metrics with cost and schedule outcomes
- Development of a new framework of critical reliability factors and indicators for significantly improving reliability of project control metrics and indicators
- Phase specific milestones for consistent, standardized and timely application of the mentioned factors and indicators

6.3 Limitations

The limitations of this study stemmed from the lack of quantitative project data, namely, in the form of monthly progress reports. Due to concerns over confidentiality, construction stakeholders were not eager to provide detailed quantitative project performance data. Using the relatively qualitative forms of data (i.e., survey, case studies, Delphi method), this research has laid the
foundation for further exploration of understanding and interpreting the nature of core forecasting and diagnostic metrics for different kinds of projects and delivery approaches.

6.4 Recommendations for Future Research

With the help of more quantitative project data, future research can focus on increasing the predictive capabilities of identified core and significant metrics and determine if some metrics are statistical predictors of future project performance. Additional research could be pursued as it pertains to investigating trending approaches (e.g., use of moving averages) on progress and performance data to see if progress and performance metrics can lead to improved forecasts.

Since the main role of predictive and diagnostic core metrics are to identify cost and schedule deviation from original budgets and plan, a logical step forward from this research would be identifying response mechanisms to these deviations. Exploring metric threshold values that would trigger corrective actions would be a valuable and worthy addition. Collecting data on projects over time and tapping into cyclical nature of project control reporting (see Figure 2.1) would allow quantifying the effects of the corrective actions and help with tailoring future actions through prescriptive analytics.

Additional research could expand the diagnostic category of the metric framework to include influencing factors such as safety, quality, risk, complexity and change management. Understanding the relationships and correlations between a project’s cost and schedule performance, and influencing factors, might help identify root causes of performance issues and establish better corrective action plans.

Associations between project control metrics and reliability factors within the project control systems play a critical role in the successful monitoring and completion of projects. Even though
the critical reliability factors and achievement indicators are established with a close consideration to the metrics identified in this research, there are no organic or direct connections between the reliability framework and metric framework. Exploring interactions reliability improvement and metrics would help substantiate the value of both components significantly. For this purpose, it would be appropriate to adopt a Design Structure Matrix (DSM) methodology, which is a straightforward and highly flexible network modeling method with extensive applications in engineering management and many other fields (Eppinger and Browning, 2012).

It was pointed out earlier that the selection criteria for core metrics were for larger, industrial projects from a contractor’s perspective. Although, the research has qualitatively shown that these core metrics apply to other project characteristics (e.g., owner perspective, smaller, low-complexity, schedule-driven projects) more can be done to validate these conclusions by studying more projects reflecting these other characteristics. This research was limited in its ability to perform an in-depth quantitative analysis of core metrics due to a limited sample data and thus heavily relied upon testimony from subject matter experts. Future research can involve collecting more project data that would allow quantitative analyses and validate understanding the core metrics for these other project characteristics.
References


Appendices
Appendix A: Metric maps for all predictive and diagnostic metrics identified
MAP 1: Variance at Completion | VAC

Performance Forecasting (Insight)

Variance at Completion
VAC = BAC – EAC(CPI)

Estimate at Completion (CPI)
EAC(CPI) = AC + ETC(CPI)

Estimate to Completion (CPI)
ETC(CPI) = (BAC – EV) / CPI

Cost Performance Index (CPI)
CPI = EV / AC

Earned Value (EV)
EV = BAC x PPC

Performance Assessment (Knowledge)

Procurement Phase:
- % Purchase Requisition Completed
- % Purchase Orders (POs) Issued

Construction Phase:
- % Equipment Installed
- % Commodities Installed

Commissioning & Startup:
- % System Turnovers Completed

Rules of Credit
- Weighted Milestones
- Incremental Milestones
- Level of Effort
- Judgment

Progress Measurement (Information)

Physical % Complete (PPC)

Engineering Phase:
- % Design Reviews Completed
- % DataSheets Completed
- % 3D Model Review Completed

Procurement Phase:
- % Purchase Requisition Completed
- % Purchase Orders (POs) Issued

Construction Phase:
- % Equipment Installed
- % Commodities Installed

Commissioning & Startup:
- % System Turnovers Completed

Rules of Credit
- Weighted Milestones
- Incremental Milestones
- Level of Effort
- Judgment

Project Records (Data)

Budget at Completion (BAC)
AC = Paid Costs + Accruals

Actual Cost (AC)

Quantity Based Measurements
- # of Design Deliverables Completed
- # of PO's Issued/Completed
- # of Commodities Installed
- # of System Turnovers Completed

Rules of Credit
- Weighted Milestones
- Incremental Milestones
- Level of Effort
- Judgment
Core Forecasting Metric Map

MAP 2: Estimate at Completion (CPI) | EAC(CPI)

Performance Forecasting (Insight)

Estimate at Completion (CPI)
EAC(CPI) = AC + ETC(CPI)

Cost Performance Index (CPI)
CPI = EV / AC

Cost Performance Index (CPI)
Estimate to Completion (CPI)
ETC(CPI) = (BAC – EV) / CPI

Performance Assessment (Knowledge)

 Earned Value (EV)
EV = BAC x PPC

Earned Value (EV)

Progress Measurement (Information)

Physical % Complete (PPC)
Engineering Phase:
% Design Reviews Completed
% DataSheets Completed
% 3D Model Review
Procurement Phase:
% Purchase Requisition Completed
% Purchase Orders (POs) Issued
Construction Phase:
% Equipment Installed
% Commodities Installed
Commissioning & Startup:
% System Turnovers Completed

Rules of Credit
Weighted Milestones
Incremental Milestones
Level of Effort
Judgment

Project Records (Data)

Budget at Completion (BAC)
AC = Paid Costs + Accruals

Actual Cost (AC)
Quantity Based Measurements
# of Design Deliverables Completed
# of PO’s Issued/Completed
# of Commodities Installed
# of System Turnovers Completed

Rules of Credit
Weighted Milestones
Incremental Milestones
Level of Effort
Judgment

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MAP 3: Estimate to Completion (CPI) | ETC(CPI)

- **Cost Performance Index (CPI)**
  \[ \text{CPI} = \frac{\text{EV}}{\text{AC}} \]

- **Earned Value (EV)**
  \[ \text{EV} = \text{BAC} \times \text{PPC} \]

- **Physical % Complete (PPC)**
  - Engineering Phase:
    - % Design Reviews Completed
    - % DataSheets Completed
    - % 3D Model Review
  - Procurement Phase:
    - % Purchase Requisition Completed
  - Construction Phase:
    - % Equipment Installed
    - % Commodities Installed
  - Commissioning & Startup:
    - % System Turnovers Completed

- **Estimate to Completion (CPI)**
  \[ \text{ETC(CPI)} = \frac{\text{BAC} - \text{EV}}{\text{CPI}} \]

**Project Records (Data)**
- **Budget at Completion (BAC)**
- **Actual Cost (AC)**
  \[ \text{AC} = \text{Paid Costs} + \text{Accruals} \]

**Quantity Based Measurements**
- # of Design Deliverables Completed
- # of PO’s Issued/Completed
- # of Commodities Installed
- # of System Turnovers Completed

**Rules of Credit**
- Weighted Milestones
- Incremental Milestones
- Level of Effort
- Judgment
MAP 4: To Complete Performance Index - EAC(CPI) | TCPI(EAC(CPI))

Core Forecasting Metric Map

Performance Forecasting (Insight)

To Complete Performance Index - EAC(CPI)

TCPI(EAC(CPI)) = (BAC – EV) / (EAC(CPI) – AC)

Estimate at Completion (CPI)

EAC(CPI) = AC + ETC(CPI)

Estimate to Completion (CPI)

ETC(CPI) = (BAC – EV) / CPI

Performance Assessment (Knowledge)

Cost Performance Index (CPI)

CPI = EV / AC

Earned Value (EV)

EV = BAC x PPC

Project Records (Data)

Budget at Completion (BAC)

Actual Cost (AC)

AC = Paid Costs + Accruals

Quantity Based Measurements

- # of Design Deliverables Completed
- # of PO’s Issued/Completed
- # of Commodities Installed
- # of System Turnovers Completed

Rules of Credit

- Weighted Milestones
- Incremental Milestones
- Level of Effort
- Judgment

Physical % Complete (PPC)

Engineering Phase:
- % Design Reviews Completed
- % Datasheets Completed
- % 3D Model Review

Procurement Phase:
- % Purchase Requisition Completed
- % Purchase Orders (POs) Issued

Construction Phase:
- % Equipment Installed
- % Commodities Installed

Commissioning & Startup:
- % System Turnovers Completed

Rules of Credit

Weighted Milestones
Incremental Milestones
Level of Effort
Judgment

130
MAP 5: Cost Performance Index | CPI

**Core Forecasting Metric Map**

### Performance Forecasting (Insight)

- Cost Performance Index (CPI)
  \[ \text{CPI} = \frac{\text{EV}}{\text{AC}} \]

### Performance Assessment (Knowledge)

- Earned Value (EV)
  \[ \text{EV} = \text{BAC} \times \text{PPC} \]

### Progress Measurement (Information)

- Physical % Complete (PPC)
  - Engineering Phase:
    - % Design Reviews Completed
    - % Datasheets Completed
    - % 3D Model Review Completed
  - Procurement Phase:
    - % Purchase Requisition Completed
    - % Purchase Orders (POs) Issued
  - Construction Phase:
    - % Equipment Installed
    - % Commodities Installed
  - Commissioning & Startup:
    - % System Turnovers Completed

### Project Records (Data)

- Actual Cost (AC)
  \[ \text{AC} = \text{Paid Costs} + \text{Accruals} \]

- Budget at Completion (BAC)

- Quantity Based Measurements
  - # of Design Deliverables Completed
  - # of POs Issued/Completed
  - # of Commodities Installed
  - # of System Turnovers Completed

- Rules of Credit
  - Weighted Milestones
  - Incremental Milestones
  - Level of Effort
  - Judgment
MAP 6: Schedule Performance Index | SPI

**Performance Forecasting (Insight)**

- Schedule Performance Index (SPI)
  - SPI = EV / PV

- Earned Value (EV)
  - EV = BAC x PPC

**Performance Assessment (Knowledge)**

- Physical % Complete (PPC)
  - Engineering Phase:
    - % Design Reviews Completed
    - % DataSheets Completed
    - % 3D Model Review
  - Procurement Phase:
    - % Purchase Requisition Completed
    - % Purchase Orders (POs) Issued
  - Construction Phase:
    - % Equipment Installed
    - % Commodities Installed
  - Commissioning & Startup:
    - % System Turnovers Completed

**Progress Measurement (Information)**

- Rules of Credit
  - Weighted Milestones
  - Incremental Milestones
  - Level of Effort
  - Judgment

**Project Records (Data)**

- Planned Value (PV)
- Budget at Completion (BAC)
- Quantity Based Measurements
  - # of Design Deliverables Completed
  - # of PO's Issued/Completed
  - # of Commodities Installed
  - # of System Turnovers Completed

- Rules of Credit
  - Weighted Milestones
  - Incremental Milestones
  - Level of Effort
  - Judgment
MAP 8: Physical Percent Complete | PPC

Performance Forecasting (Insight)

Performance Assessment (Knowledge)

Progress Measurement (Information)

Project Records (Data)

Physical % Complete (PPC)
- Engineering Phase:
  - % Design Reviews Completed
  - % DataSheets Completed
  - % 3D Model Review
- Procurement Phase:
  - % Purchase Requisition Completed
  - % Purchase Orders (POs) Issued
- Construction Phase:
  - % Equipment Installed
  - % Commodities Installed
- Commissioning & Startup:
  - % System Turnovers Completed

Quantity Based Measurements
- # of Design Deliverables Completed
- # of PO's Issued/Completed
- # of Commodities Installed
- # of System Turnovers Completed

Rules of Credit
- Weighted Milestones
- Incremental Milestones
- Level of Effort
- Judgment
MAP 9: Estimate at Completion (SPI) | EAC(SPI)

Performance Forecasting (Insight)

- Estimate at Completion (SPI)
  \[ EAC(SPI) = AC + ETC(SPI) \]

Performance Assessment (Knowledge)

- Earned Value (EV)
  \[ EV = BAC \times PPC \]

Schedule Performance Index (SPI)

- SPI = EV / PV

- Physical % Complete (PPC)
  - Engineering Phase:
    - % Design Reviews Completed
    - % Datasheets Completed
    - % 3D Model Review
  - Procurement Phase:
    - % Purchase Requisition Completed
    - % Purchase Orders (POs) Issued
  - Construction Phase:
    - % Equipment Installed
    - % Commodities Installed
  - Commissioning & Startup:
    - % System Turnovers Completed

Project Records (Data)

- Budget at Completion (BAC)
- Actual Cost (AC)
  \[ AC = Paid \text{ Costs} + \text{ Accruals} \]

Quantity Based Measurements
- # of Design Deliverables Completed
- # of POs Issued/Completed
- # of Commodities Installed
- # of System Turnovers Completed

Rules of Credit
- Weighted Milestones
- Incremental Milestones
- Level of Effort
- Judgment

Planned Value (PV)
Validation Forecasting Metric Map

**Performance Forecasting (Insight)**

- **Estimate to Completion (SPI)**
  
  \[
  ETC(SPI) = \frac{(BAC - EV)}{SPI}
  \]

**Performance Assessment (Knowledge)**

- **Earned Value (EV)**
  
  \[
  EV = BAC \times PPC
  \]

- **Schedule Performance Index (SPI)**
  
  \[
  SPI = \frac{EV}{PV}
  \]

**Progress Measurement (Information)**

- **Physical % Complete (PPC)**
  
  - Engineering Phase:
    - % Design Reviews Completed
    - % DataSheets Completed
    - % 3D Model Review
  
  - Procurement Phase:
    - % Purchase Requisition Completed
    - % Purchase Orders (POs) Issued
  
  - Construction Phase:
    - % Equipment Installed
    - % Commodities Installed
  
  - Commissioning & Startup:
    - % System Turnovers Completed

**Project Records (Data)**

- **Budget at Completion (BAC)**
- **Quantity Based Measurements**
  - # of Design Deliverables Completed
  - # of PO's issued/Completed
  - # of Commodities Installed
  - # of System Turnovers Completed
- **Rules of Credit**
  - Weighted Milestones
  - Incremental Milestones
  - Level of Effort
  - Judgment
- **Planned Value (PV)**
MAP 11: Monthly Cost Growth | MCG

Monthly Cost Growth (MCG)

\[
MCG = \frac{EAC(CPI(i)) - EAC(CPI(i-1))}{EAC(CPI(i))}
\]

i: Current month
i-1: Previous month

Cost Performance Index (CPI(i))

\[
CPI(i) = \frac{EV(i)}{AC(i)}
\]

Earned Value (EV) (i)

\[
EV(i) = BAC \times PPC
\]

Actual Cost (AC) (i)

\[
AC(i) = \text{Paid Costs} + \text{Accruals}
\]

Budget at Completion (BAC)

Quantity Based Measurements

- # of Design Deliverables Completed
- # of PO's Issued/ Completed
- # of Commodities Installed
- # of System Turnovers Completed

Rules of Credit

- Weighted Milestones
- Incremental Milestones
- Level of Effort
- Judgment

Rules of Credit

Physical % Complete (PPC(i))

Engineering Phase:
- % Design Reviews Completed
- % DataSheets Completed
- % 3D Model Review

Procurement Phase:
- % Purchase Requisition Completed
- % Purchase Orders (POs) Issued

Construction Phase:
- % Equipment Installed
- % Commodities Installed

Commissioning & Startup:
- % System Turnovers Completed
MAP 12: Estimate at Completion – Time | EAC(t)

**Innovative Forecasting Metric Map**

**Performance Forecasting (Insight)**

- **Estimate at Completion - Time**
  \[ EAC(t) = AD + ETC(t) \]

**Performance Assessment (Knowledge)**

- **Earned Value (EV)**
  \[ EV = BAC \times PPC \]
- **Earned Schedule (ES)**
  (The planned duration for the planned value of work actually completed)
- **Schedule Performance Index - Time [SPI(t)]**
  \[ SPI(t) = \frac{ES}{AD} \]

**Progress Measurement (Information)**

- **Physical % Complete (PPC)**
  - **Engineering Phase**:
    - % Design Reviews Completed
    - % Datasheets Completed
    - % 3D Model Review
  - **Procurement Phase**:
    - % Purchase Requisition Completed
  - **Construction Phase**:
    - % Equipment Installed
    - % Commodities Installed
    - % System Turnovers Completed

**Project Records (Data)**

- **Budget at Completion (BAC)**
- **Quantity Based Measurements**
  - # of Design Deliverables Completed
  - # of PO's Issued/Completed
  - # of Commodities Installed
  - # of System Turnovers Completed
- **Rules of Credit**
  - Weighted Milestones
  - Incremental Milestones
  - Level of Effort
  - Judgment
- **Planned Value (PV)**
- **Planned Duration (PD)**
- **Actual Duration (AD)**

**Rules of Credit**

- Weighted Milestones
- Incremental Milestones
- Level of Effort
- Judgment

**Estimate to Completion - Time**

\[ ETC(t) = \frac{PD - ES}{SPI(t)} \]
MAP 13: Estimate to Completion – Time | ETC(t)

Innovative Forecasting Metric Map

Estimate to Completion - Time
ETC(t) = (PD – ES) / SPI(t)

Earned Value (EV)
EV = BAC x PPC

Earned Schedule (ES)
(The planned duration for the planned value of work actually completed)

Schedule Performance Index - Time [SPI(t)]
SPI(t) = ES / AD

Physical % Complete (PPC)
Engineering Phase:
% Design Reviews Completed
% Datasheets Completed
% 3D Model Review

Procurement Phase:
% Purchase Requisition Completed
% Purchase Orders (POs) Issued

Construction Phase:
% Equipment Installed
% Commodities Installed

Commissioning & Startup:
% System Turnovers Completed

Quantity Based Measurements
# of Design Deliverables Completed
# of PO’s Issued/Completed
# of Commodities Installed
# of System Turnovers Completed

Rules of Credit
Weighted Milestones
Incremental Milestones
Level of Effort
Judgment

Budget at Completion (BAC)

Planned Value (PV)

Actual Duration (AD)

Planned Duration (PD)
MAP 14: Schedule Performance Index – Time | SPI(t)

**Performance Forecasting (Insight)**

**Performance Assessment (Knowledge)**

Schedule Performance Index - Time [SPI(t)]

SPI(t) = ES / AD

(Earned Schedule (ES)
(The amount of time that was originally planned to reach the current level work value)

Earned Value (EV)
EV = BAC x PPC

**Progress Measurement (Information)**

Physical % Complete (PPC)
- Engineering Phase:
  - % Design Reviews Completed
  - % DataSheets Completed
  - % 3D Model Review
- Procurement Phase:
  - % Purchase Requisition Completed
  - % Purchase Orders (POs) Issued
- Construction Phase:
  - % Equipment Installed
  - % Commodities Installed
- Commissioning & Startup:
  - % System Turnovers Completed

**Project Records (Data)**

Actual Duration (AD)

Planned Duration (PD)

Planned Value (PV)

Quantity Based Measurements
- # of Design Deliverables Completed
- # of PO's Issued/Completed
- # of Commodities Installed
- # of System Turnovers Completed

Rules of Credit
- Weighted Milestones
- Incremental Milestones
- Level of Effort
- Judgment

Budget at Completion (BAC)
**Innovative Forecasting Metric Map**

**MAP 15: Earned Schedule | ES**

**Performance Forecasting (Insight)**

**Performance Assessment (Knowledge)**

**Progress Measurement (Information)**

**Project Records (Data)**

---

**Earned Schedule (ES)**

(The amount of time that was originally planned to reach the current level work value)

**Earned Value (EV)**

\[ EV = BAC \times PPC \]

**Physical % Complete (PPC)**

- Engineering Phase:
  - % Design Reviews Completed
  - % DataSheets Completed
  - % 3D Model Review
- Procurement Phase:
  - % Purchase Requisition Completed
- Construction Phase:
  - % Purchase Orders (POs) Issued
- Commissioning & Startup:
  - % Equipment Installed
  - % Commodities Installed
  - % System Turnovers Completed

**Quantity Based Measurements**

- # of Design Deliverables Completed
- # of PO’s Issued/Completed
- # of Commodities Installed
- # of System Turnovers Completed

**Rules of Credit**

- Weighted Milestones
- Incremental Milestones
- Level of Effort
- Judgment

**Budget at Completion (BAC)**

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### MAP 16: Estimate at Completion (CPI*SPI) | EAC(CPI*SPI)

#### Performance Forecasting (Insight)

- Estimate at Completion (CPI*SPI)
  
  \[ \text{EAC(CPI*SPI)} = \text{AC} + \text{ETC(CPI*SPI)} \]

- Estimate to Completion (CPI*SPI)
  
  \[ \text{ETC(SPI)} = \frac{\text{BAC} - \text{EV}}{\text{CPI} \times \text{SPI}} \]

#### Performance Assessment (Knowledge)

- Cost Performance Index (CPI)
  
  \[ \text{CPI} = \frac{\text{EV}}{\text{AC}} \]

- Earned Value (EV)
  
  \[ \text{EV} = \text{BAC} \times \text{PPC} \]

- Schedule Performance Index (SPI)
  
  \[ \text{SPI} = \frac{\text{EV}}{\text{PV}} \]

#### Progress Measurement (Information)

- Physical % Complete (PPC)
  - Engineering Phase:
    - % Design Reviews Completed
    - % Datasheets Completed
    - % 3D Model Review
  - Procurement Phase:
    - % Purchase Requisition Completed
    - % Purchase Orders (POs) Issued
    - % Equipment Installed
    - % Commodities Installed
    - % System Turnovers Completed

#### Project Records (Data)

- Budget at Completion (BAC)
  
  \[ \text{AC} = \text{Paid Costs} + \text{Accruals} \]

- Actual Cost (AC)
  
  \[ \text{AC} = \text{Paid Costs} + \text{Accruals} \]

- Quantity Based Measurements
  - # of Design Deliverables Completed
  - # of PO’s Issued/Completed
  - # of Commodities Installed
  - # of System Turnovers Completed

- Rules of Credit
  - Weighted Milestones
  - Incremental Milestones
  - Level of Effort
  - Judgment

- Planned Value (PV)
MAP 17: Estimate to Completion (CPI*SPI) | ETC(CPI*SPI)

Performance Forecasting

- Cost Performance Index (CPI)
  \[ CPI = \frac{EV}{AC} \]

- Earned Value (EV)
  \[ EV = BAC \times PPC \]

- Schedule Performance Index (SPI)
  \[ SPI = \frac{EV}{PV} \]

Estimate to Completion (CPI*SPI)

\[ ETC(CPI*SPI) = \frac{(BAC - EV)}{(CPI \times SPI)} \]

Other Significant Forecasting Metric Map

- Budget at Completion (BAC)
- Actual Cost (AC)
  \[ AC = Paid \text{ Costs} + \text{ Accruals} \]
- Quantity Based Measurements
  # of Design Deliverables Completed
  # of PO's Issued/Completed
  # of Commodities Installed
  # of System Turnovers Completed
- Rules of Credit
  Weighted Milestones
  Incremental Milestones
  Level of Effort
  Judgment
- Planned Value (PV)

Project Records

- Physical % Complete (PPC)
  Engineering Phase:
  % Design Reviews Completed
  % Datasheets Completed
  % 3D Model Review
  Procurement Phase:
  % Purchase Requisition Completed
  % Purchase Orders (POs) Issued
  Construction Phase:
  % Equipment Installed
  % Commodities Installed
  Commissioning & Startup:
  % System Turnovers Completed
MAP 18: Estimate at Completion (Optimistic) | EAC(O)

Other Significant Forecasting Metric Map

Performance Forecasting (Insight)

- Estimate at Completion (Optimistic)
  \[ EAC(O) = AC + ETC \]
- Estimate to Completion (Optimistic)
  \[ ETC(O) = BAC - EV \]

Performance Assessment (Knowledge)

- Earned Value (EV)
  \[ EV = BAC \times PPC \]

Progress Measurement (Information)

- Physical % Complete (PPC)
  Engineering Phase:
  - % Design Reviews Completed
  - % DataSheets Completed
  - % 3D Model Review
  - % Design Deliverables Completed
  Procurement Phase:
  - % Purchase Requisition Completed
  - % Purchase Orders (POs) Issued
  - % Equipment Installed
  - % Commodities Installed
  - % System Turnovers Completed

- Construction Phase:
  - % Equipment Installed
  - % Commodities Installed
  - % System Turnovers Completed

- Commissioning & Startup:
  - % System Turnovers Completed

Project Records (Data)

- Budget at Completion (BAC)
- Actual Cost (AC)
  \[ AC = \text{Paid Costs} + \text{Accruals} \]
- Quantity Based Measurements
  - # of Design Deliverables Completed
  - # of PO’s Issued/Completed
  - # of Commodities Installed
  - # of System Turnovers Completed

Rules of Credit

- Weighted Milestones
- Incremental Milestones
- Level of Effort
- Judgment
MAP 19: Estimate to Completion (Optimistic) | ETC(O)

- **Performance Forecasting (Insight)**
  - Estimate to Completion (Optimistic)
    - \( ETC(O) = BAC - EV \)

- **Performance Assessment (Knowledge)**
  - Earned Value (EV)
    - \( EV = BAC \times PPC \)

- **Progress Measurement (Information)**
  - Physical % Complete (PPC)
    - Engineering Phase:
      - % Design Reviews Completed
      - % DataSheets Completed
      - % 3D Model Review
    - Procurement Phase:
      - % Purchase Requisition Completed
      - % Purchase Orders (POs) Issued
    - Construction Phase:
      - % Equipment Installed
      - % Commodities Installed
    - Commissioning & Startup:
      - % System Turnover Completed

- **Project Records (Data)**
  - Budget at Completion (BAC)
  - Quantity Based Measurements
    - # of Design Deliverables Completed
    - # of PO’s Issued/Completed
    - # of Commodities Installed
    - # of System Turnovers Completed
  - Rules of Credit
    - Weighted Milestones
    - Incremental Milestones
    - Level of Effort
    - Judgment
MAP 20: Estimate at Completion (Bottom-Up) | EAC(BU)

Other Significant Forecasting Metric Map

Performance Forecasting (Insight)

- Estimate at Completion (Bottom-Up)
  \[ EAC(BU) = AC + ETC(BU) \]

Performance Assessment (Knowledge)

- Estimate to Completion (Bottom-up)
  \[ ETC(BU) = \text{Re-estimate of the remaining work} \]

Progress Measurement (Information)

- Physical % Complete (PPC)
  - Engineering Phase:
    - % Design Reviews Completed
    - % Datasheets Completed
    - % 3D Model Review
  - Procurement Phase:
    - % Purchase Requisition Completed
    - % Purchase Orders (POs) Issued
  - Construction Phase:
    - % Equipment Installed
    - % Commodities Installed
  - Commissioning & Startup:
    - % System Turnover Completed

Project Records (Data)

- Actual Cost (AC)
  \[ AC = \text{Paid Costs} + \text{Accruals} \]

- Quantity Based Measurements
  - # of Design Deliverables Completed
  - # of PO’s Issued/Completed
  - # of Commodities Installed
  - # of System Turnovers Completed

- Rules of Credit
  - Weighted Milestones
  - Incremental Milestones
  - Level of Effort
  - Judgment
MAP 21: Estimate to Completion (Bottom-Up) | ETC(BU)

**Estimate to Completion (Bottom-up)**

ETC(BU) = Re-estimate of the remaining work

**Physical % Complete (PPC)**

**Engineering Phase:**
- % Design Reviews Completed
- % DataSheets Completed
- % 3D Model Review

**Procurement Phase:**
- % Purchase Requisition Completed
- % Purchase Orders (POs) Issued

**Construction Phase:**
- % Equipment Installed
- % Commodities Installed

**Commissioning & Startup:**
- % System Turnover Completed

**Quantity Based Measurements**
- # of Design Deliverables Completed
- # of PO's Issued/Completed
- # of Commodities Installed
- # of System Turnovers Completed

**Rules of Credit**
- Weighted Milestones
- Incremental Milestones
- Level of Effort
- Judgment
MAP 22: To Complete Performance Index – BAC | TCPI(BAC)

Performance Forecasting (Insight)

To Complete Performance Index - BAC

TCPI(BAC) = (BAC – EV) / (BAC – AC)

Performance Assessment (Knowledge)

Earned Value (EV)

EV = BAC * PPC

Other Significant Forecasting Metric Map

Progress Measurement (Information)

Physical % Complete (PPC)
- Engineering Phase:
  - % Design Reviews Completed
  - % DataSheets Completed
  - % 3D Model Review
- Procurement Phase:
  - % Purchase Requisition Completed
  - % Purchase Orders (POs) Issued
- Construction Phase:
  - % Equipment Installed
  - % Commodities Installed
- Commissioning & Startup:
  - % System Turnover Completed

Rules of Credit
- Weighted Milestones
- Incremental Milestones
- Level of Effort
- Judgment

Project Records (Data)

Actual Cost (AC)
AC = Paid Costs + Accruals

Budget at Completion (BAC)

Quantity Based Measurements
- # of Design Deliverables Completed
- # of PO’s Issued/Completed
- # of Commodities Installed
- # of System Turnovers Completed

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MAP 23: Baseline Execution Index for Critical Path | BEI-CP

Baseline Execution Index for Critical Path (BEI-CP)
BEI-CP = (AAC-CP) / (APC-CP)

Activities Planned to be Completed on Critical Path (APC-CP)
Activities Actually Completed on Critical Path (AAC-CP)
MAP 24: Number of Critical (or Near Critical) Paths

Number of Critical (or Near Critical) Paths

Number of Critical (or Near Critical) Paths in Previous Reporting Period

Number of Critical (or Near Critical) Paths in Current Reporting Period

Number of Critical (or Near Critical) Paths on the Baseline Schedule
MAP 25: Schedule Variance | SV

Performance Assessment (Knowledge)

- Schedule Variance (SV)
  \[ SV = EV - PV \]

- Earned Value (EV)
  \[ EV = BAC \times PPC \]

Progress Measurement (Information)

- Physical % Complete (PPC)
  - Engineering Phase:
    - % Design Reviews Completed
    - % Datasheets Completed
    - % 3D Model Review
  - Procurement Phase:
    - % Purchase Requisition Completed
    - % Purchase Orders (POs) Issued
  - Construction Phase:
    - % Equipment Installed
    - % Commodities Installed
  - Commissioning & Startup:
    - % System Turnovers Completed

Project Records (Data)

- Planned Value (PV)
- Budget at Completion (BAC)
- Quantity Based Measurements
  - # of Design Deliverables Completed
  - # of PO’s Issued/Completed
  - # of Commodities Installed
  - # of System Turnovers Completed

Rules of Credit
- Weighted Milestones
- Incremental Milestones
- Level of Effort
- Judgment
MAP 26: Unit Rate | UR

Core Diagnostic Metric Map

Performance Assessment (Knowledge)

Progress Measurement (Information)

Project Records (Data)

Unit Rate (UR)

UR = TC / TNPU

Total Cost (TC)

Total Number of Product Units (TNPU)
**Core Diagnostic Metric Map**

**MAP 27: Cost Variance | CV**

### Performance Assessment (Knowledge)
- **Cost Variance (CV)**
  
  \[ CV = EV - AC \]

- **Earned Value (EV)**
  
  \[ EV = BAC \times PPC \]

### Project Records (Data)
- **Actual Cost (AC)**
  
  \[ AC = \text{Paid Costs} + \text{Accruals} \]

- **Budget at Completion (BAC)**

- **Quantity Based Measurements**
  - # of Design Deliverables Completed
  - # of PO’s Issued/Completed
  - # of Commodities Installed
  - # of System Turnovers Completed

- **Rules of Credit**
  - Weighted Milestones
  - Incremental Milestones
  - Level of Effort
  - Judgment

### Progress Measurement (Information)
- **Physical % Complete (PPC)**
  - Engineering Phase:
    - % Design Reviews Completed
    - % Datasheets Completed
    - % 3D Model Review
  - Procurement Phase:
    - % Purchase Requisition Completed
    - % Purchase Orders (POs) Issued
  - Construction Phase:
    - % Equipment Installed
    - % Commodities Installed
  - Commissioning & Startup:
    - % System Turnovers Completed
Procurement Cost Variance (PCV)

PCV = BCP - ACP

- Budgeted Cost of Purchases (BCP)
- Actual Cost of Purchases (ACP)
MAP 29: Efficiency or Productivity Index | E/PI

Performance Assessment (Knowledge)

- Efficiency or Productivity Index (E/PI)
  \[ E/PI = \frac{EMH}{AMH} \]

Progress Measurement (Information)

- Earned Manhours (EMH)
  \[ EMH = BMAC \times PPC \]

- Physical % Complete (PPC)
  - Engineering Phase:
    - % Design Reviews Completed
    - % DataSheets Completed
    - % 3D Model Review
  - Procurement Phase:
    - % Purchase Requisition Completed
    - % Purchase Orders (POs) Issued
  - Construction Phase:
    - % Equipment Installed
    - % Commodities Installed
  - Commissioning & Startup:
    - % System Turnovers Completed

Project Records (Data)

- Actual Manhours (AMH)
- Budgeted Manhours at Completion (BMAC)
### Core Diagnostic Metric Map

**MAP 30: Ratio of Actual to Planned Progress | RAPP**

<table>
<thead>
<tr>
<th>Performance Assessment (Knowledge)</th>
<th>Progress Measurement (Information)</th>
<th>Project Records (Data)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ratio of Actual to Planned Progress (RAPP)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Design Reviews Completed vs. Planned</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Equipment Installed Completed vs. Planned</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% System Turnovers Completed vs. Planned</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$RAPP = PPC / PP$</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Physical % Complete (PPC)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Engineering Phase:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Design Reviews Completed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% DataSheets Completed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% 3D Model Review</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Procurement Phase:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Purchase Requisition Completed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Purchase Orders (POs) Issued</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Construction Phase:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Equipment Installed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Commodities Installed</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Commissioning &amp; Startup:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% System Turnovers Completed</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
MAP 31: Percent Key Deliverables Completed on Time | PKDCT

Percent Key Deliverables Completed on Time (PKDCT)

PKDCT = NKDCT / TNKD

- **Performance Assessment**
  - Knowledge
- **Progress Measurement**
  - Information
- **Project Records**
  - Data

Number of Key Deliverables Completed on Time (NKDCT)

Total Number of Key Deliverables (TNKD)
MAP 32: Percent Activities Started on Time | PAST

Percent Activities Started on Time (PAST)

\[ \text{PAST} = \frac{\text{AAS}}{\text{APS}} \]

- Activities Planned to be Started (APS)
- Activities Actually Started (AAS)
MAP 33: Percent Activities Finished on Time | PAFT

Percent Activities Finished on Time (PAFT)

\[
PAFT = \frac{AAF}{APF}
\]

Activities Planned to be Finished (APF)

Activities Actually Finished (AAF)
MAP 34: Critical Path Length Index | CPLI

Validation Diagnostic Metric Map

Critical Path Length Index (CPLI)

CPLI = (CPL + CPTF) / CPL

Critical Path
Total Float
(CPTF)

Critical Path
Length
(CPL)

Performance Assessment
(Knowledge)

Progress Measurement
(Information)

Project Records
(Data)

Critical Path Length (CPL)

Critical Path Total Float (CPTF)
MAP 35: Percent Work Packages on Budget | PWPB

\[
PWPB = \frac{NWPB}{NFWP}
\]

- **Number of Work Packages on Budget (NWPB)**
- **Number of Finished Work Packages (NFWP)**

**Validation Diagnostic Metric Map**
**MAP 36: Schedule Variance - Time | SV(t)**

- **Performance Assessment (Knowledge)**
  - Schedule Variance - Time [SV(t)]
    - \( SV(t) = ES - AD \)
  - Earned Schedule (ES)
    - (The amount of time that was originally planned to reach the current level work value)
  - Earned Value (EV)
    - \( EV = BAC \times PPC \)

- **Progress Measurement (Information)**
  - Physical % Complete (PPC)
    - Engineering Phase:
      - % Design Reviews Completed
      - % Datasheets Completed
      - % 3D Model Review
      - % Purchase Requisition Completed
      - % Purchase Orders (POs) Issued
    - Construction Phase:
      - % Equipment Installed
        - % Commodities Installed
        - % System Turnovers Completed

- **Project Records (Data)**
  - Actual Duration (AD)
  - Planned Duration (PD)
  - Planned Value (PV)
  - Quantity Based Measurements
    - # of Design Deliverables Completed
    - # of PO's Issued/Completed
    - # of Commodities Installed
    - # of System Turnovers Completed
  - Rules of Credit
    - Weighted Milestones
    - Incremental Milestones
    - Level of Effort
    - Judgment
  - Budget at Completion (BAC)
MAP 37: Percent of Milestones Achieved | PMA

Performance Assessment (Knowledge)

Progress Measurement (Information)

Project Records (Data)

Percent of Milestones Achieved (PMA)

\[ PMA = \frac{NMA}{NMP} \]

Number of Milestones Planned (NMP)

Number of Milestones Achieved (NMA)
Workerhours per Unit Item (WUI)

\[ WUI = \frac{WH}{CU} \]
Percent Equipment Delivered Late (PEDL)

PEDL = EDL / TNED

- Equipment Delivered Late (EDL)
- Total Number of Equipment Delivered (TNED)
MAP 41: Project Buffer Index | PBI

Project Buffer Index (PBI)

PBI = PPBC / PCCC

Percent Critical Chain Completed (PCCC)

Percent Project Buffer Consumed (PPBC)
Feeding Buffer Burn Rate (FBBR)

FBBR = OTAFB / RSAFB

- Original Total of All Feeding Buffer (OTAFB)
- Remaining Size of All Feeding Buffer (RSAFB)
Appendix B: Survey Details

Several features, such as instruction videos, table-of-contents navigation menu, and hover-over text boxes were used in the web-based survey to facilitate the respondents to better complete the survey. In this web-based survey, the team developed and embedded three videos. The first video was shown on the first web page of the online survey (Fig. B.1). It conveyed a welcome message to the respondents and listed the benefits of taking this survey. The second video provided an overview of the survey structure and contents (Fig. B.2), and the third video provided instructions on filling out the survey, with some illustrative examples (Fig. B.3).

![Figure B.1](image-url) Screenshot of video #1, welcome message and benefits of survey participation.
Since the web-based survey has several sections, a table of contents feature was created to facilitate respondents as they moved between different sections. The table of contents features helped the respondents to visualize the sections and to start from any specific section (Fig. B.4).
Second, a table of contents navigation menu was displayed on the top left side of every web page in the survey (Fig. B.5). This menu allowed respondents to switch between sections during the survey and showed the respondent’s percentage completion of that section.
At the end of the survey, the table of contents was displayed once again (Fig. B.6) to reveal which sections had and had not been completed, allowing the respondent to click on the incomplete sections, as well as back to the completed ones, before the survey was submitted.

**Figure B.5** Table of contents navigation menu.
In order to ensure the completeness of each submitted survey, a forced response feature was developed. With this feature, a message requiring the responses for unanswered questions appears before allowing the respondents to continue. Fig. B.7 shows an example of the force response feature. Because the respondent clicked the “Next” button on the bottom right corner without providing a response to question 9.2.4, a message box notes that there is one unanswered question on this page (Fig. B.7).

**Figure B.6** Table of contents at the end of the web-based survey.

**Figure B.7** Force response feature.
### Appendix C: Predictive and diagnostic metric details

**Table C.1 Details of predictive metrics**


<table>
<thead>
<tr>
<th>Metric</th>
<th>Project Controls Function</th>
<th>Definition</th>
<th>Equation</th>
<th>Indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variance at Completion</td>
<td>Forecasting</td>
<td>VAC indicates the cost deviation at the project completion.</td>
<td>VAC = BAC - EAC(CPI)</td>
<td>VAC&gt;0 The project is under budget; VAC=0 The project is on budget; VAC&lt;0 The project is over budget.</td>
</tr>
<tr>
<td>Estimate at Completion</td>
<td>Forecasting</td>
<td>EAC(CPI) is a metric to project total cost using the cost performance to date.</td>
<td>EAC(CPI) = AC + (BAC-EV) / CPI</td>
<td></td>
</tr>
<tr>
<td>Estimate to Completion</td>
<td>Forecasting</td>
<td>The expected cost to finish all the remaining project work.</td>
<td>ETC(CPI) = (BAC - EV) / CPI</td>
<td></td>
</tr>
<tr>
<td>To Complete Performance Index (EAC(CPI))</td>
<td>Forecasting</td>
<td>A measure of the cost performance that is achieved with the remaining resources in order to meet a specified management goal, expressed as the ratio of the cost to finish the outstanding work to the remaining budget.</td>
<td>TCPI_EAC(CPI) = (BAC-EV) / (EAC(CPI)-AC)</td>
<td>TCPI_EAC(CPI) ≤ 1: Cost objective (EAC) is achievable; TCPI_EAC(CPI) &gt; 1: Cost objective (EAC) becomes more difficult to achieve</td>
</tr>
<tr>
<td>Cost Performance Index</td>
<td>Assessment</td>
<td>A measure of the cost efficiency of budgeted resources expressed as a ratio of earned value to actual cost.</td>
<td>CPI = EV / AC</td>
<td>CPI &gt; 1: Project cost performance favorable; CPI = 1: Project cost performance on track; CPI &lt; 1: Project cost performance unfavorable.</td>
</tr>
<tr>
<td>Schedule Performance Index</td>
<td>Assessment</td>
<td>A measure of schedule efficiency expressed as the ratio of earned value to planned value.</td>
<td>SPI = EV / PV</td>
<td>SPI &gt; 1: Project schedule performance favorable; SPI = 1: Project schedule performance on track; SPI &lt; 1: Project schedule performance unfavorable.</td>
</tr>
<tr>
<td>Actual Cost</td>
<td>Measurement/Data</td>
<td>The actual cost of the work determined by the paid costs to date and accruals.</td>
<td>AC = Paid Costs (PC) + Accruals</td>
<td></td>
</tr>
<tr>
<td>Earned Value</td>
<td>Measurement/Data</td>
<td>The measure of work performed expressed in terms of the budget authorized for that work.</td>
<td>EV = BAC x Physical % Complete</td>
<td>EV &gt; PV: Project cost performance favorable; EV = PV: Project cost performance on track; EV &lt; PV: Project cost performance unfavorable.</td>
</tr>
<tr>
<td>Physical Percent Complete</td>
<td>Measurement/Data</td>
<td>Represents the amount of work performed as a percent of the total physical work required.</td>
<td>PPC ≥ Planned percent complete: Project component is on track; PPC &lt; Planned percent complete: Project component is lagging.</td>
<td></td>
</tr>
<tr>
<td>Budget at Completion</td>
<td>Measurement/Data</td>
<td>The sum of all budgets established for the work to be performed.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planned Value</td>
<td>Measurement/Data</td>
<td>The authorized budget assigned to scheduled work.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimate at Completion (SPI)</td>
<td>Forecasting</td>
<td>A variation of EAC which calculates the future cost performance based on the past schedule performance.</td>
<td>EAC(SPI) = AC + ETC(SPI)</td>
<td></td>
</tr>
<tr>
<td>Estimate to Completion (SPI)</td>
<td>Forecasting</td>
<td>A variation of ETC which calculates the future cost performance based on the past schedule performance.</td>
<td>ETC(SPI) = (BAC-EV) / SPI</td>
<td></td>
</tr>
<tr>
<td>Monthly Cost Growth</td>
<td>Assessment</td>
<td>The monthly change in the Estimate at Completion (EAC).</td>
<td>MCG = (EAC(i) - EAC(i-1)) / EAC(i-1)</td>
<td>MCG ≤ 0: Favorable MCG &gt; 0: Unfavorable</td>
</tr>
</tbody>
</table>
Table C.1. (cont.) Details of predictive metrics

<table>
<thead>
<tr>
<th>Metric</th>
<th>Project Controls Function</th>
<th>Definition</th>
<th>Equation</th>
<th>Indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimate at Completion - Time</td>
<td>Performance Forecasting</td>
<td>The expected total duration stated in reporting periods of the project or project component when completed based upon schedule performance to date.</td>
<td>EAC(t) = AD + ETC(t)</td>
<td></td>
</tr>
<tr>
<td>Estimate to Completion - Time</td>
<td>Performance Forecasting</td>
<td>The expected remaining duration stated in reporting periods to complete the project or project component based upon the schedule performance to date.</td>
<td>ETC(t) = (PD - ES) / SPI(t)</td>
<td></td>
</tr>
<tr>
<td>Schedule Performance Index - Time</td>
<td>Performance Assessment</td>
<td>A measure of schedule performance expressed as the ratio of the earned schedule divided by the actual duration.</td>
<td>SPI(t) = ES / AD</td>
<td>SPI(t) = 1: Project schedule performance on track; SPI(t) &gt; 1: Project schedule performance favorable; SPI(t) &lt; 1: Project schedule performance unfavorable.</td>
</tr>
<tr>
<td>Earned Schedule</td>
<td>Performance Assessment</td>
<td>The planned duration stated in reporting periods for the Planned Value or budgeted amount for work actually completed at a particular point in time.</td>
<td>ES = Planned Duration (PD) for work actually achieved</td>
<td></td>
</tr>
<tr>
<td>Actual Duration</td>
<td>Progress Measurement/Data</td>
<td>The actual duration stated in reporting periods for the work actually completed at a particular point in time.</td>
<td>AD = Actual time to achieve work</td>
<td></td>
</tr>
<tr>
<td>Planned Duration</td>
<td>Progress Measurement/Data</td>
<td>The planned duration stated in reporting periods for the planned value or budgeted amount for work at a particular point in time.</td>
<td>PD = Planned duration to achieve work</td>
<td></td>
</tr>
<tr>
<td>Estimate at Completion (Optimistic)</td>
<td>Performance Forecasting</td>
<td>A variation of EAC which assumes future cost performance will be the same as planned cost performance.</td>
<td>EAC(O) = AC + ETC(O)</td>
<td></td>
</tr>
<tr>
<td>Estimate to Completion (Optimistic)</td>
<td>Performance Forecasting</td>
<td>A variation of ETC which assumes future cost performance will be the same as planned cost performance.</td>
<td>ETC(O) = (BAC-EV)</td>
<td></td>
</tr>
<tr>
<td>Estimate at Completion (Bottom-Up)</td>
<td>Performance Forecasting</td>
<td>A projection of the project cost expressed as the sum of the actual cost and a bottom-up projection of the remaining work.</td>
<td>EAC(BU) = AC + ETC(BU)</td>
<td></td>
</tr>
<tr>
<td>Estimate to Completion (Bottom-Up)</td>
<td>Performance Forecasting</td>
<td>A projection of the project cost expressed as a bottom-up projection of the remaining work.</td>
<td>ETC(BU) = Re-estimate of remaining work</td>
<td></td>
</tr>
<tr>
<td>To Complete Performance Index (BAC)</td>
<td>Performance Forecasting</td>
<td>A measure of the cost performance that is required to achieve the budget at completion.</td>
<td>TCPI(BAC) = (BAC-EV) / (BAC-AC)</td>
<td>TCPI_BAC ≤ 1: Cost objective achievable; TCPI_BAC &gt; 1: It becomes more difficult to achieve the BAC.</td>
</tr>
</tbody>
</table>
Table C.2 Details of diagnostic metrics

<table>
<thead>
<tr>
<th>Metric</th>
<th>Project Controls Function</th>
<th>Definition</th>
<th>Equation</th>
<th>Indicator</th>
</tr>
</thead>
</table>
| Efficiency or Productivity Index | Performance | Cost Performance | The ratio between earned manhours (EMH) and actual manhours (AMH). | E/PI = EMH / AMH | E/PI ≥ 1: Favorable  
E/PI < 1: Unfavorable |
| Schedule Variance | Performance | Schedule Performance | A measure of schedule performance expressed as the difference between the Earned Value (EV) and the Planned Value (PV). | SV = EV - PV | SV = 0: Project schedule performance on track  
SV > 0: Project schedule performance favorable  
SV < 0: Project schedule performance unfavorable |
| Cost Variance | Performance | Cost Performance | The difference between the Earned Value (EV) and Actual Cost (AC). | CV = EV - AC | CV = 0: Project cost performance on track  
CV > 0: Project cost performance favorable  
CV < 0: Project cost performance unfavorable |
| Unit Rate | Performance | Cost Performance | Cost per Unit Item | UR = Total Cost / Total Number of Product Units |
| Procurement Cost Variance | Performance | Cost Performance | The difference between the Actual Cost of Purchases (ACP) and Budgeted Cost for all project Purchases (BCP). | PCV = BCP - ACP | PCV ≥ 0: Favorable  
PCV < 0: Unfavorable |
| Baseline Execution Index for Critical Path | Performance | Schedule Performance | The ratio between the Number of Activities Actually Completed on the Critical Path (AAC-CP) and the number of Activities Planned to be Completed on the Critical Path (APC-CP). | BEI-CP = (AAC-CP) / (APC-CP) | BEI-CP ≥ 1: Favorable  
BEI-CP < 1: Unfavorable |
| Number of Critical (or Near Critical) Paths | Performance | Schedule Performance | Number of Critical (or Near Critical) Paths on the Baseline Schedule for the previous and current period. | # of Critical (or Near Critical) Paths | Increasing number of critical (or near critical paths) indicates increasing risk of schedule delay. |
| Percent Key Deliverables Completed on Time | Performance | Physical Measurement/Data | The percentage of key deliverables completed on time. | PKDCT = # of key deliverables completed on time / Total number of key deliverables | Indicator threshold will be based on prior project performance from historical data |
| Ratio of Actual to Planned Progress | Performance | Physical Measurement/Data | The ratio between the actual (physical) and planned progress (e.g., % Deliverables Completed vs. Planned). | RAPP = Actual / Planned Progress | RAPP ≥ 1: Favorable  
RAPP < 1: Unfavorable |
| Percent Activities Started on Time | Performance | Schedule Performance | The ratio between the number of Activities Actually Started (AAS) and the number of Activities Planned to be Started (APS). | PAST = AAS / APS | PAST ≥ 1: Favorable  
PAST < 1: Unfavorable |
| Percent Activities Finished on Time | Performance | Schedule Performance | The ratio between the number of Activities Actually Finished on Time (AAF) and the number of Activities Planned to be Finished (APF). | PAFT = AAT / APF | PAFT ≥ 1: Favorable  
PAFT < 1: Unfavorable |
Table C.2 (cont.) Details of diagnostic metrics

<table>
<thead>
<tr>
<th>Metric</th>
<th>Project Controls Function</th>
<th>Definition</th>
<th>Equation</th>
<th>Indicator</th>
</tr>
</thead>
</table>
| Critical Path Length Index | CPLI | Performance Assessment | Schedule Performance | CPLI is a ratio that uses the remaining duration of a project and the critical path total float to help quantify the likelihood of meeting the project completion requirements. In the calculation, Critical Path Length (CPL) is the remaining duration of the project, and Critical Path Total Float (CPTF) is the calculated total float on the final activity along the project's critical path. | CPLI = (CPL + CPTF) / CPL | CPLI > 1: Favorable  
CPLI = 1: Target  
0.95 ≤ CPLI < 1: Schedule Objective Achievable  
CPLI < 0.95: Schedule Objective Unattainable |
| Percent Work Packages on Budget | PWPB | Performance Assessment | Cost Performance | The ratio between the Number of Work Packages on Budget (NWPB) and the total Number of Finished Work Packages (NFWP). | PWPB = NWPB / NFWP | PWPB = 1: Favorable  
PWPB < 1: Unfavorable |
| Schedule Variance - Time | SV(t) | Performance Assessment | Schedule Performance | A measure of schedule performance expressed as the difference between the earned schedule and the actual duration. | SV(t) = ES - AD | SV(t) = 0: Project schedule performance on track.  
SV(t) > 0: Project schedule performance favorable.  
SV(t) < 0: Project schedule performance unfavorable. |
| Percent Milestones Achieved | PMA | Performance Assessment | Schedule Performance | The ratio between the Number of Milestones Achieved (NMA) and the Number of Milestones Planned (NMP). | PMA = NMA / NMP | PMA ≥ 1: Favorable  
PMA < 1: Unfavorable |
| Workerhours per Unit Item | WUI | Performance Assessment | Schedule Performance | The ratio between the total number of Workerhours (WH) and the total number of commodity units (CU). | WUI = WH / CU | N/A |
| Number of Backlog Activities | NBA | Performance Assessment | Schedule Performance | The number of activities that are ready to start yet not have been initiated. | N/A | N/A |
| Purchasing Workerhours per PO | PWPO | Performance Assessment | Schedule Performance | The ratio between the total number of Purchasing Workerhours (PWH) and the total number of POs (PO). | PWPO = PWH / PO | N/A |
| Feeding Buffer Burn Rate | FBBR | Performance Assessment | Schedule Performance | A measure of the total feeding buffer consumed | FBBR = (original total feeding buffer-remaining feeding buffer)/original total feeding buffer | FBBR < 50%: Favorable  
FBBR ≥ 50%: Unfavorable |
| Percent Equipment Delivered Late | PEDL | Performance Assessment | Schedule Performance | The ratio between the number of Equipment Delivered Late (EDL) and the Total Number of Equipment Delivered (TED). The measure of Percent Project Buffer Consumed (PPBC) relative to the project timeline in terms of Percent Critical Chain Completed (PCCC). | PEDL = EDL / TED  
PBI = PPBC / PCCC | PEDL = 0: Favorable  
PEDL > 0: Unfavorable  
PBI < 1: Favorable  
PBI ≥ 1: Unfavorable |
| Project Buffer Index | PBI | Performance Assessment | Schedule Performance | N/A | N/A |
Appendix D: Case study interview guide

The purpose of this case study guide is to collect *more in depth information* on a project that your company has already provided some information on through an on-line survey. The additional project information gathered from this case study will provide a deeper understanding of the metrics and indicators used on your project to help better understand their effectiveness for predicting project progress, performance assessment, and forecasting project outcomes. Respondents should include knowledgeable personnel in the area of project management and controls which will preferably include the project manager, project controls manager, lead scheduler, and business manager. To make this meeting as efficient and productive as possible, please be prepared to discuss these questions at the interview.

**General Information**

- Project Name:
- Company Name:
- Perspective (circle one)
  - Owner
  - Contractor
- Respondent
  - Title:
  - Briefly describe your role on this project:
Use of Metrics on this Project

1. Describe the metrics that you used for determining project progress, performance assessment, and forecasting for different phases (e.g., engineering, procurement, construction, and commissioning).

2. Describe the quantitative “influencing” factor metrics that you used on this project (e.g., safety and quality metrics).

3. Do you feel the use of metrics and indicators to assess project progress, performance assessment, and forecast project outcome was sufficient? Please circle one response.
   - Strongly Agree
   - Agree
   - Neutral
   - Disagree
   - Strongly Disagree

   Please explain why you selected this response:

4. Was there anything that worked particularly well in terms of your current practices and procedures in the selection and use of metrics and indicators on this project? Consider the following:
   - Did some metrics and indicators provide more insight than others?
   - How did you use the metrics to drive behavior or activities (implies root cause analysis)?
   - Were there any innovative or breakthrough methods and metrics used on this project? How effective were these metrics?
- Was there anything unique that was done as it pertained to data collection, analysis, and reporting?

5. What were your lessons learned regarding project progress and performance?
   - Considering the engineering, procurement, construction, and start-up/commissioning phases of the project, were there any problems or other issues that arose with regard to the metrics that needed to be improved?
   - What metrics did you use to trigger corrective actions?
   - Did you implement lessons learned from this project on other projects?

6. How did you ensure the reliability of progress and performance metrics? Consider reliability issues related to each specific phase, detailed physical progress metrics, and issues related to the interpretation of metrics for proactive progress and performance assessment.

7. Did you experience any risk associated with the use of your project progress, performance assessment, and forecasting approaches (e.g. risks due to use of erroneous performance forecasts)?
   - What risks did you identify based on using project progress, performance assessment, and forecasting metrics?
   - What metrics were associated to the identified risk?
   - How did you integrate risk assessment with project control?
   - Did your risk assessment derive you to use different metrics or use the metrics differently?
   - Did the metrics used help you in timely identification of risk?
• Did you identify risks that affected your use of metrics? (Consider risk as influencing factor).

8. As changes occurred on your project from scope changes, new technologies, new regulatory requirements, etc., did you need to modify the metrics that you used to assess the project progress and performance (e.g., adding new metrics, providing more granularity to existing approaches).

9. Please provide information on your company’s change management procedures in terms of how you adjusted the cost and schedule. How did you account for change in the assessment of project progress and performance?

10. Was a retro analysis performed on this project? A retro analysis relates to looking back on a completed project to see if other metrics and indicators would have provided better insight on the true project progress and performance. Did you apply the same project data to new metrics such as earned schedule to see if these metrics would have been better predictors of project progress and performance? Is there a combination of metrics that can be used to provide the greatest insights?

**Qualitative Influencing Factor Metrics**

This section involves identifying the influencing factors that were used on your project.

1. Did you use client surveys and audits to manage the quality of the project? If yes, to what extent they helped you?

2. Did alignment of bid package with work scope and/or involvement of customer help you to better manage the changes in the project? Please explain.
3. How did the team building and integration affect the project progress and performance?

4. Did the qualification of suppliers affect project progress and performance?

5. What other influencing factors affected the project progress and performance?

Would you be willing to provide the research team with a copy of all monthly progress reports for this project?

Thank you for participating in this study.