Construction, Commissioning, and Startup Execution: Problematic Activities on Capital Projects

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Abstract: The commissioning and startup (CSU) stage of industrial capital projects is made up of a large number of discrete activities. These activities are executed across the construction, precommissioning, commissioning, and startup (CCSU) project phases by a host of organizations and disciplines. CCSU activities are often fraught and have adverse consequences which may broadly impact overall project success. This research sought to discover which activities are commonly problematic across industrial sectors, and how these activities are characterized. A better understanding of commonly problematic activities (so-called Hot Spots) will give insight into how best to address problems when or before they arise. Contributions made by this research include a list of 20 of the most common problematic CCSU activities, characterizations of 7 attributes for each of the 20 Hot Spots, an analysis of themes recurring among the characterizations, and a model for implementation of research findings on projects. These contributions will provide perspective on common CCSU shortcomings and guidance on how to remedy them. **DOI: 10.1061/(ASCE)CO.1943-7862.0001621.** © *2019 American Society of Civil Engineers.*

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Introduction

In the context of industrial capital projects, commissioning and startup, together referred to as CSU, represent the conversion of a newly constructed physical asset into an integrated, operational unit (Killcross 2012). Because of the multiple organizations, disciplines, technologies, and processes involved, CSU is an inherently complex undertaking (Cagno et al. 2002; CII 2017; Kirsilä et al. 2007). Industry trends towards greater process control, refined process optimization, wireless instrumentation, and big data collection and analysis, have all contributed to the increased complexity of systems that need to be installed and commissioned. Greater systems complexity has naturally led to increased complexity for construction, precommissioning, commissioning, and startup (CCSU). Some facilities have hundreds of systems and tens of thousands of input/output (I/O) points; the potential for failures leading to nonfulfillment is high. Illustratively, a previous study of Construction Industry Institute (CII) General Program data found that of 162 projects, nearly 50% overran the CSU budget to some extent, and one-third overran the CSU budget by over 25% (O'Connor et al. 2016a). The same study highlighted that, of 16 factors critical to CSU success, 6 (37.5%) were found to be implemented only occasionally (O'Connor et al. 2016a).

The purpose of this research was to identify the most common problematic CCSU transition activities, and to determine how to address them. The large number of possible CCSU activities, as well as the large number of parties involved, necessitates a focus on a few activities that are most commonly problematic across industrial sectors. Research objectives include the following:

- Identify the most problematic activities from among a pool of activities;
- Characterize this subset of activities to provide insight into why problems occur;
- Confirm accountability and responsibility assignments for each of the most problematic activities;
- Identify strategies that may help solve the problems; and
- Analyze commonalities across problematic activity characterizations.

The scope of this research was limited to industrial CCSU (post-design) activities, and did not consider commercial construction contexts. Further, process/process control technical issues were not covered in depth; these issues vary widely between industrial sectors, and as such would not be considered commonly problematic for all sectors. Both new construction (greenfield) and retrofit (brownfield) projects were considered.

Literature Review

Case for CCSU Improvement

CCSU has been described as the most critical of all project stages (Almasi 2014; Cagno et al. 2002). Lawry and Pons also described CCSU as having significant implications for project success (2013). CCSU is a high-risk component of the capital project process (O'Connor et al. 1999). Cagno et al. noted that uncertainty in events, time pressure, and managerial and technical complexity all contribute to this increased risk (2002). Lager observed the potent effect of even minor process/plant problems on both production volume and product quality (2012). Mills also identified the potential operations savings from improved CCSU on commercial projects (2011). Complex systems being commissioned and started-up

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inherently contain latent potential for failures (Cook 2002). The case for better knowledge about CCSU problem activities and their prevention and mitigation is strong.

Common CCSU Execution Problems and Solutions

Several literature sources list CCSU problems and limitations across multiple industrial applications. Multiple sources also give guidance on ideal best practices for one or a few aspects of CCSU. Here the authors present a sample of issues and solutions that are mentioned in the literature. While not comprehensive, the sample represents some of the key challenges industry professionals face today.

Mobilizing Resources

Previous CII research identified the importance of allocating appropriate resources for CCSU based on planning and strategy, not simply as a percentage of total installed costs (TICs) (2015). Tribe and Johnson identified multiple human resources necessary for CCSU success, including operations and maintenance personnel, equipment manufacturer technical representatives, process control specialists, and others (2008).

Operations and Maintenance

Operations problems may seriously undermine plant performance (Cagno et al. 2002). The involvement of operations and maintenance (O&M) personnel is widely acknowledged as a best practice for CCSU, although it is often still a challenge. The inclusion of O&M personnel during the CCSU process is important because it enables the transfer of knowledge of the physical asset from the temporary commissioning personnel, who will eventually leave for another project (Killcross 2012; Tribe and Johnson 2008). Operations personnel also bring an important perspective representing those who will be working with the plant, and should thus be included in CCSU planning activities and decision making (Todd and Todd 2017). Al-Bidaiwi et al. (2012) cited two Qatar Petroleum industrial oil and gas CCSU case study examples in which the role and involvement of O&M personnel was greatly expanded. In these cases, O&M personnel made contributions by identifying and resolving various design and engineering issues, assisting in smooth handover of assets, and making meaningful contributions to improved safety and reliability (Al-Bidaiwi et al. 2012). Rodgers (2005) also identified the involvement of O&M personnel in all project phases, from detailed design through project close-out, as a best practice in data center/telecom construction. The Building Commissioning Association (2016) recommends involving O&M personnel on the commissioning team even before the detailed design phase, during conceptual planning.

Handover/Turnover

The terms *handover* and *turnover* have been defined differently at certain times and at others have been used interchangeably (CII 2017). Whatever the exact definition used, however, they always involve the transfer of assets from one organization to another. This process has long been problematic. Killcross (2012) pointed out the problems that a lack of definition or agreement about the handover process can create. The shift in responsibilities and accountabilities that occurs during asset transfer, as noted by Todd and Todd (2017), can also be troublesome. The first turnover package can set the tone for the entire commissioning effort (Bowen 1998). Transition points remain a challenging part of CCSU (CII 2017).

Hazard Management

The energization of systems during CCSU introduces new and more hazardous working conditions for personnel on-site (Tribe and Johnson 2008). General CCSU best practices contribute to a reduction in hazardous risk. For example, failure to implement any of the 16 CSU critical success factors (CSFs) identified by O'Connor et al. (2016b) will threaten safety and/or increase hazards. Conducting a hazard and operability study (HAZOP) as part of the CCSU effort has become a common way to assess safety risks and identify operational problems (Cagno et al. 2002). Even some commercial projects, such as labs or hospitals, may require special attention during the commissioning effort to reduce the risk to future occupants. Mantai and Stanley recommended that special consideration be given to cleaning and protection of HVAC ductwork and filters during hospital CCSU (2005). On the commissioning effort for an experimental fusion reactor constructed for the Max Planck Institute, the need to avoid exposing personnel to any hazards was stressed (Vilbrandt et al. 2015). This project, as well as multiple others, identified lockout/tagout (controlling work access within designated areas) as a best practice for personnel safety (Bahadori 2014; Bowen 1998; CII 1990; Tribe and Johnson 2008; Vilbrandt et al. 2015). While these traditional measures have been found to be effective, they may not be adequate to eliminate "the numerous risk factors involved throughout the commissioning process" (Cagno et al. 2002, p. 310).

Team Building

While commissioning and startup are highly technical, many issues often stem from human interactions. Friction between project players was identified as a key contributor to ineffective commissioning (Sohmen 1992). The aforementioned case study from the Max Planck Institute accented the importance of responsibilities and competencies being clearly defined (Vilbrandt et al. 2015). Time pressure and uncertainty around commissioning activities make the execution of team building beforehand important, so that when problems inevitably occur the team can persist through adversity. CCSU teams usually work together only for one project, making team building that much more important, as many team members will not have worked together in the past. Tribe and Johnson found team building to be essential for successful startup (2008). Close working relations and teamwork between operations and construction personnel contributed to the success of the previously mentioned Qatar Petroleum projects (Al-Bidaiwi et al. 2012). The relationship between the construction manager and the commissioning manager is also particularly important (Killcross 2012; Tribe and Johnson 2008). Lack of training for supervisors and operators has also been identified as a typical problem (Horsley 1998). From a CII sample of 26 CCSU managers, 18 (69%) reported not having received any formal training (O'Connor et al. 1999). The multiplicity of organizations, disciplines, and trades, as well as the competing interests within and among those parties, suggests that research will need to continue to focus on other human issues.

Testing and Checks

CCSU is at its core concerned with testing of disparate equipment and systems to make them work in tandem as a process (CII 2017). Numerous tests and checks are commonly performed during CCSU; only a few of the most commonly mentioned in the literature are referenced here. Factory acceptance tests (FATs) for major equipment is mentioned as an important CCSU step (Killcross 2012; Rodgers 2005; Todd and Todd 2017). Killcross (2012) also offered example scenarios for things that can go wrong with FATs, mostly focused on what can go wrong if they are neglected. Horsley (1998) identified the tendency of CCSU managers to assume that proprietary equipment will work without checking or testing. Loop checks for instrumentation and electronics and leak testing for piping are also normal CCSU activities (Bahadori 2014; CII 2015; Killcross 2012). Leaving these activities undone is a contributor to schedule and cost disruption later in the CCSU sequence (Almasi 2014; CII 2015; Killcross 2012). "Reluctance to consult specialists on problems and their remedies" exacerbates complications (Horsley 1998, p. 71).

Construction Quality Assurance/Quality Control

Killcross and Horsley both mentioned construction quality assurance/quality control (QA/QC) in their outlines of CCSU best practices (Killcross 2012; Horsley 1998). Using punch lists for identifying and rectifying installation incongruities is another tool identified in the literature (Al-Bidaiwi et al. 2012; CII 2017; Tribe and Johnson 2008). It would be preferable, however, if issues were avoided entirely and never needed to be punch-listed, but some will be the result of design oversights and defects, making some punch-listing always necessary.

New Technology Implementation

According to Cagno et al. (2002), CSU outcomes are particularly uncertain when new technology is implemented. For a set of 318 industrial megaprojects (cost > $1 billion) executed worldwide between 1995 and 2010, the inclusion of substantially new technology was shown to increase both startup time and the risk of operational failure (Merrow 2011). Lager (2012, p. 17) called the startup of a facility with a new technology "an extreme event associated with … uncertainty." Bagsarian (2001) provided anecdotal evidence of new technology slowing down startup for steel mills in the United States. Mobilization of a full, strong CSU team is particularly recommended to counteract uncertainty in the case of new technology being implemented (Lager 2012). Training of O&M personnel and specialists on new technology processes is mentioned in the literature as another way to cope with the uncertainty (CII 1998; Horsley 1998).

Discussion

This section has shown that there are numerous examples of problems that can occur on industrial project CCSU. A few literature sources have also suggested a limited number of solutions. Problems and solutions suggested in the literature are somewhat scattered, and many of them are specific to a sector, a certain phase of CCSU, or a selected engineering discipline. The lack of general applicability among the problems and solutions suggested represents a substantial knowledge gap. Further, few literature sources consider commissioning as a whole across project phases and industrial sectors. The piecemeal consideration of issues and solutions in the literature can be rectified by research seeking to identify common CCSU problems and solutions across project phases and industrial sectors. The need to identify the most common problems and the solution strategies for dealing with them across industrial sectors seems clear.

Research Methodology

Panel of Industry Practitioners

The authors used a panel of industry practitioners to provide industry insight, assist with data collection, and help improve research products. Members of the panel came from a range of industrial sectors, with a mix of both owner and contractor organizations represented. Panel members had a cumulative total of 247 years of industry experience and had participated in CCSU on a total of 247 projects. Background information on the panel is provided in Table 1. The use of industry practitioners to assist in the research effort is standard practice on CII research projects; the research presented in this article resulted from the CII Research Team (RT) 333 project.

Table 1. Panel of industry practitioners background information

Category	Subcategory	Value
Organization type	Owner	7
	Construction contractor	5
	Software contractor	2
	Service contractor	2
Industry sectors represented	Petrochemical/oil and gas	4
	Pharmaceutical	1
	Metals manufacturing	1
	Government buildings	1
	Multisector contractors	9
Years of CSU experience	Total	247
	Average	15.4
Participation in project CSUs	Total	247
	Average	15.4

Methodology Overview

Research objectives and scope, described earlier, provided guidance on the literature review and informed the flow of research from one step to another. This research sought to discover which CCSU activities were most commonly problematic for project professionals across industrial sectors and disciplines. For this purpose, researchers had to draw from a pool of previously identified activities. Commonly problematic CCSU activities, known as Hot Spots, were identified from among the 124 activities listed in a flowchart of CCSU activities created by CII (2017). While the flowchart itself is outside the scope of this article, its importance is briefly explained here. The 124 activities are CSU execution activities, performed between the construction phase and project close-out, inclusive. These activities were identified via an extensive literature review, and verified by the panel of industry practitioners. Activities listed are not sector-specific, but rather apply generally to most industrial-type construction projects. The flowchart gives activity names, timing, and some differentiation between types of activities. Commonly problematic Hot Spot activities were identified from among the set of 124 activities included in the CCSU activity flowchart by members of the panel of industry practitioners and other experts in their organizations. After Hot Spot activities had been identified, and in order to accomplish research objectives, the Hot Spots were characterized according to seven attributes (detailed later in this section). Data for populating characterization attribute descriptions for the Hot Spots was obtained through semistructured interviews of CCSU experts outside of the panel of practitioners. Characterizations documented data about why each Hot Spot was problematic and problem-solving strategies for each one. Hot Spot data were analyzed via statistical and other methods to explore basic relationships between Hot Spots and characterization attributes. Hot Spots, their characterizations, and other research products play a role in the CCSU implementation process. This process is a guide for project professionals to implement the findings of this and other CII CCSU research holistically within a project context. The authors created the process to make the research results from this and previous research more accessible and implementable for CCSU managers. Finally, a validation review of the Hot Spot characterizations was conducted by external industry experts. Greater detail on the methodology for each of the aforementioned research steps is given hereafter.

Table 2. Hot Spot identification survey participant background information

Category	Subcategory	Value
Organization type	Owner	7
	Construction contractor	5
	Software contractor	1
	Service contractor	2
	Total organizations	15
Industry sectors represented	Petrochemical/oil and gas	6
	Pharmaceutical	1
	Metals manufacturing	1
	Multisector contractors	7
Individuals	Total	49
	Average per organization	3.27
Years of industry experience	Total	1,286
	Average per individual	26.2
Years of CSU experience	Total	748
	Average per individual	15.3

Table 3. Hot Spot characterization interview participant background information

Category	Subcategory	Value
Organization type	Owner	10
	Construction contractor	3
	Software contractor	1
	Service contractor	5
	Total organizations	19
Industry sectors represented	Petrochemical/oil and gas	4
	Chemical process	2
	Pharmaceutical	2
	Power	2
	Multisector contractors	9
Individuals	Total	23
	Average per organization	1.2
Years of CSU experience	Total	433
	Average per individual	18.8

CCSU Hot Spot Identification Methodology

In order to identify Hot Spot activities, panel members, along with other CCSU experts from their organizations if possible, were asked to complete a survey to come up with a short list of 4 to 10 of the activities listed in the CCSU activities flowchart that were problematic for their company (i.e. their corporate Hot Spots). More specifically, Hot Spots were defined as

- CCSU activities with unclear responsibility assignments, or
- CCSU activities with recurring problems or deficiencies, or
- CCSU activities that often fail to deliver on expectations.

In a few instances, panel members also invited experts from other organizations outside the panel to participate in the survey. In total, 15 organizations were represented in the survey, with 49 individuals participating—an average of just over 3 per company. Survey participants had a cumulative total of 1,286 years of industry work experience, and 748 years of CSU experience. Further background information on survey participants is provided in Table 2.

Survey participants were given the opportunity to write a justification as to why each activity they selected was a Hot Spot for their organization. These comments were later used as part of the Hot Spot characterizations. Once survey responses had been collected, activities were ranked and tabulated by the number of organizations that indicated them as Hot Spots. Most organizations submitted a single survey response, but also provided the authors with the number of employees who provided input for the response. In the few cases in which individuals from the same organization submitted separate responses, the individuals were considered separately, but were considered only as a single organization when their responses coincided. Where closely related activities had both been selected by multiple organizations, they were merged into a single Hot Spot. Most Hot Spots, however, connected to only a single activity. Activities/groups of activities selected by three or more organizations were included in the final list of 20 Hot Spots. The number of individuals represented by those selecting organizations was used as a secondary tie-breaker when activities were selected by the same number of organizations. (Table 5 provides the final ranking of Hot Spots, including the number of organizations and individuals that selected them.)

The authors conducted a difference-of-means hypothesis test to justify limiting the list of Hot Spots to only those with three or more selecting organizations. This constituted a one-tailed, two-sample t-test (assuming unequal variances), with an alpha level of 0.01. Because the surveys were conducted based on CCSU activities, each activity was considered as a single data point. The sample size for Hot Spot activities was 23; the sample size for non-Hot Spot activities was 101. Together the samples represent the full set of 124 CCSU activities included in the CCSU activities flowchart.

CCSU Hot Spot Characterization Methodology

Characterization fields for each Hot Spot include project context/example scenarios; alleged common deficiencies; causal factors; qualitative impacts/threats to success; prevention/mitigation strategies; responsible, accountable, consulted, and informed (RACI) designations; and CSU critical success factors. An example of a Hot Spot characterization can be found in Figs. 2–4. Once the form for characterizations was settled on, interview solicitations were sent to industry CCSU experts. Potential industry expert interviewees were identified by our panel of industry practitioners, from a previous study on CSU, and from two professional conferences. Experts indicated willingness to participate in interviews by returning solicitations indicating which of the 20 Hot Spots they felt were the most common. Seventeen of the 23 experts interviewed (74%) were from different organizations than the members of the industry panel, ensuring that multiple industry sectors, companies, and perspectives would be represented. Interviewees had a cumulative total of 433 years of CSU experience, with an average of 18.8 years of experience per individual. Background information on interviewees is provided in Table 3. Interviews lasted between 20 and 45 minutes, and covered questions on the seven characteristics. Each Hot Spot was characterized by at least two interviewees; in most cases interviewees were interviewed on Hot Spots that they had indicated as common on the interview solicitation form, ensuring that they had experience with those particular problems. Interviewees were invited to view and fill in characterization forms before the interviews, with additional notes added during the interview.

Each Hot Spot characterization went through five iterations:

1. An initial compilation of comments from the Hot Spot identification survey into the seven characteristic categories;
2. A first review by one panel member to edit, clarify terms, and make additions/subtractions;
3. A second review by a different panel member for the same purposes;
4. Addition of comments from interviews with two or more industry experts; and
5. A final edit by the authors, with content changes approved by the panel.

Individual Hot Spot characterizations had between 10 and 31 contributors, including the authors, members of the panel, interviewees, and Hot Spot identification survey respondents.

Hot Spot Characterization Analyses Methodology

The authors conducted an analysis of 3 characteristics across all 20 Hot Spot characterizations. These were causal factors, qualitative impacts/threats to success, and prevention/mitigation strategies. After reviewing the discrete statements for each of the 3 characteristics over all Hot Spots, the authors sought out patterns, commonalities, trends, or alignments of opinion. Several common themes emerged during topical qualitative coding. Each theme was judged to be either present or not in the discrete characteristic statements for each Hot Spot. The authors ranked the themes according to those present in the characterizations of the greatest number of Hot Spots.

Logistic regression analysis was performed on the sets of themes across the three Hot Spot characteristics. Binary data indicating the presence of a theme was used for the tests; logistic regression is an appropriate test for binary data for a categorical independent variable (the Hot Spots). The purpose of performing these tests was to show whether there was a significant difference in the likelihood of the more and less frequently detected themes being present. If a significant difference were found, it would justify the ranking of themes. For each of the three characteristics tested, the most frequent theme was used as a baseline. For any themes found to be significantly different from the baseline, the difference in likelihood of being present was also calculated. This was done by exponentiating the estimated increase in log odds of an outcome, then subtracting that value from one.

The final characteristic for each Hot Spot characterization listed factors found to be critical to CSU success (CII 2015) which applied to that Hot Spot. A tabulation of the frequency of links to critical success factors across the Hot Spots is provided in the section "Results and Analyses."

Implementation Process Methodology

An implementation process was created in the form of a flowchart, outlining the major tasks for implementing research findings from major studies on CSU. Its focus is on research from the current study (CII 2017), but references are also made to two other studies on planning for CSU (CII 1998) and CSU critical success factors (CII 2015). Thus, the flowchart references some research results and products that are not within the scope of this article. However, explanations of these elements are given in the section "Results and Analyses" to provide the reader with an understanding of how research findings can be implemented in the context of existing industrial CCSU knowledge.

The implementation process began as a simple list of tasks; it was later converted into a flowchart with interconnectivity between activities shown mapped across project phases. Seventeen tasks are listed in total. Five draft versions were cycled through by the authors, with each draft receiving comments and modifications by the authors and the panel of industry practitioners. The sixth and final version contained only formatting changes.

Validation Review Methodology

Validation of the Hot Spot characterizations was conducted by 11 industry CCSU experts. Reviewers had a total of 320 years of industry experience, with an average of 29.1 years per individual. They also had a total of 152 years of CSU experience, with an average of 13.8 years per individual. Background information on validation reviewers is provided in Table 4.

Reviewers individually assessed the accuracy of Hot Spot characterizations. They were asked to respond with comments addressing any critical content that was missing or any significant corrections that were needed. Reviewers made suggestions to add characterization statements, delete repetitive statements, and adjust RACI assignments. In total, over 100 comments suggesting changes were submitted. Some suggested changes would have narrowed the applicability of characterizations to a reviewer's sector and so were not made. The authors and the panel made changes judged to be valid and applicable within the general context of industrial sectors and projects.

Table 4. Hot Spot characterization validation reviewer background information

Category	Subcategory	Value
Organization type	Owner	7
	Construction contractor	1
	Service contractor	1
	Total organizations	9
Industry sectors represented	Petrochemical/oil and gas	4
	Pharmaceutical	1
	Power	2
	Multisector contractors	2
Individuals	Total	11
	Average per organization	1.2
Years of industry experience	Total	320
	Average per individual	29.1
Years of CSU experience	Total	152
	Average per individual	13.8
Participation in project CSUs	Total	169
	Average per individual	15.4

Results and Analyses

CCSU Hot Spots

In the initial Hot Spot identification survey, about two-thirds of all the possible CCSU activities to choose from were selected as potential Hot Spots by at least one company. This indicates a large amount of variation in the CCSU activities that organizations experience problems with. This variation was not unexpected because of the wide variety of projects performed by organizations in disparate industrial sectors. The authors chose three selecting organizations as the cutoff for inclusion in the Hot Spot list. The choice of selecting organizations rather than individuals favored a diverse representation of organizations and sectors; the authors sought to put forward a set of Hot Spots that was as representative as possible of the current situation across industrial sectors. The choice of three selecting organizations as the cutoff was the result of practical constraints on the research as well as the desire to include activities that had been identified by more rather than fewer organizations. A higher cutoff gives greater credibility to the Hot Spots selected as being commonly problematic. For these reasons, this list of 20 Hot Spots is suggested as a starting point from which CCSU practitioners can work. A complete list of CCSU activities and the number of surveyed organizations that identified them as potential Hot Spots are included in Table S1.

The set of 20 Hot Spots identified by the survey is provided in Table 5, along with descriptive information about each. These Hot Spots represent the most commonly problematic CCSU activities across industrial capital projects. More specifically, as indicated in the section "Research Methodology," Hot Spots are activities with unclear responsibility assignments or recurring problems or deficiencies, or that often fail to deliver on expectations.

A one-tailed, two-sample t-test (assuming unequal variances) indicated that the mean value of the number of organizations selecting the activities included in the final list of Hot Spots was significantly greater than the mean value of activities not included

Table 5. CCSU Hot Spots

Number	Hot Spot	Number of selecting organizations (percentage of 15 total)	Number of selecting participants (percentage of 49 total)
1	Mobilize resources and facilities for precommissioning, including necessary subject matter experts (SMEs) and third-party participants	7 (47)	25 (51)
2	Perform preservation through all phases and execute equipment preservation plan	7 (47)	21 (43)
3	Transition to CSU system–based execution (from area- or discipline-based)	7 (47)	20 (41)
4	Perform cleaning, passivation, and drying of piping and ducts (including steam blowing and pigging)	5 (33)	21 (43)
5	Identify and communicate construction punch list items critical for precommissioning, commissioning, and startup	5 (33)	13 (27)
6	Plan for and manage CSU schedule recovery	4 (27)	15 (31)
7	Ensure correctness and completeness of as-built, commissioned drawings and documentation	4 (27)	15 (31)
8	Complete collaborative inspection walkthrough of tags and systems by commissioning manager, construction contractor, and operations	4 (27)	12 (24)
9	Procure CSU materials, including spare parts	4 (27)	12 (24)
10	Confirm availability of utilities needed for precommissioning and commissioning	4 (27)	11 (22)
11	Conduct construction-CSU alignment meeting on execution plan	4 (27)	8 (16)
12	Define system construction turnover packages	4 (27)	8 (16)
13	Initiate maintenance procedures	3 (20)	10 (20)
14	Identify and integrate key operations and maintenance personnel and supporting organizations	3 (20)	10 (20)
15	Familiarize operations personnel with equipment during FAT or on-site	3 (20)	9 (18)
16	Conduct loop checks and input/output point-to-point checks	3 (20)	9 (18)
17	Conduct system walkdowns for turnovers	3 (20)	9 (18)
18	Verify closure of HAZOP action items	3 (20)	8 (16)
19	Finalize approval of commissioning operation test procedures	3 (20)	6 (12)
20	Conduct construction-CSU team building	3 (20)	5 (10)

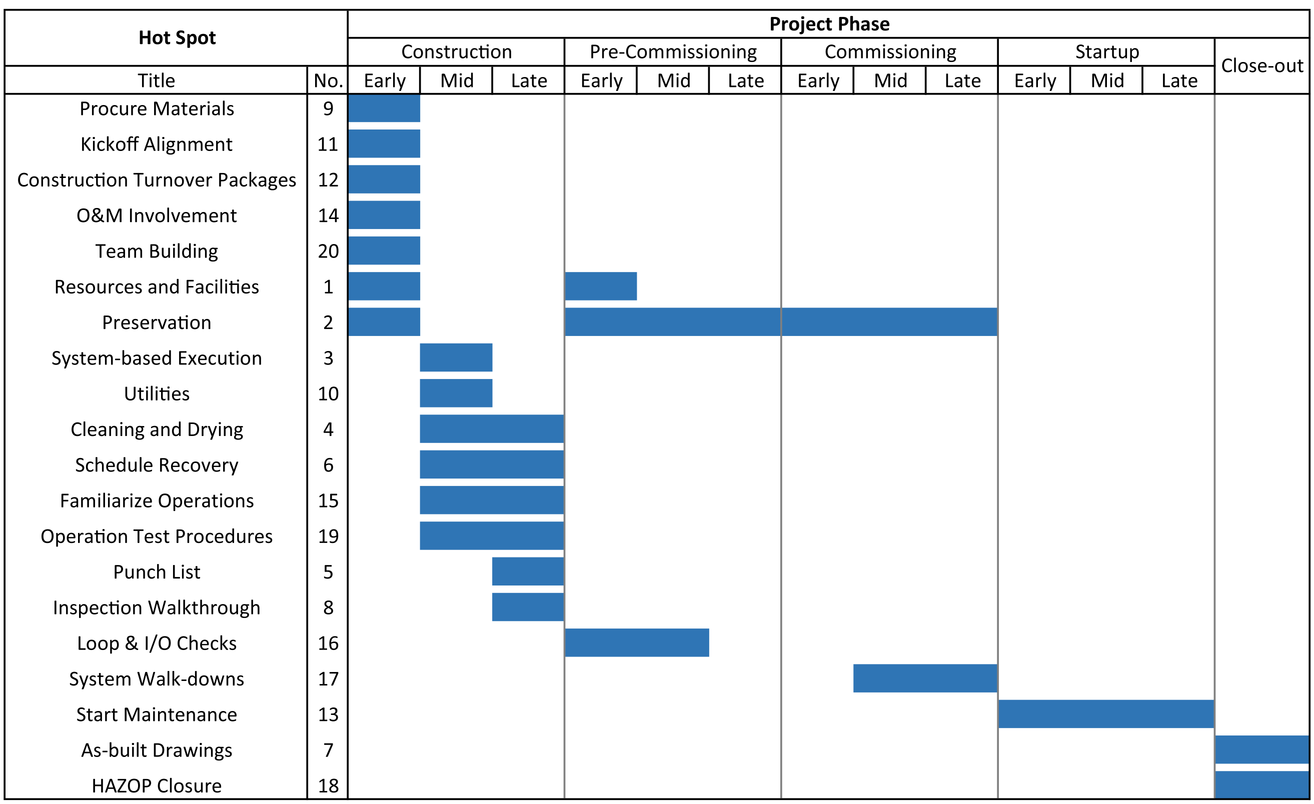

Fig. 1. Phase timing for CCSU Hot Spots.

in the final list. The difference between means demonstrated by the test justified the threshold of three selecting organizations for inclusion in the final list of Hot Spots. The complete set of data used for the test is provided in Table S1. The alpha level used was 0.01.

Notably, 15 of the 23 activities (65%) making up the Hot Spot list occur during the construction phase. This large proportion is indicative of a need for early attention to CCSU activities. Phase timing for Hot Spots is shown in Fig. 1 as a Gantt-style chart; it is also indicated in respective Hot Spot characterizations. As a reminder, Hots spots 1 and 2 have more than one activity each, which explains the spread of execution timing. Also note that the Hot Spots in Fig. 1 are arranged not in rank order but in schedule order. Further, the relative schedule duration of phases is not to scale. For reasons of practicality and brevity, only abbreviated Hot Spot names are shown.

Several parallels between Hot Spots and problematic activities mentioned in the literature can be drawn. Hot Spots 1 and 9 have to do with procuring and mobilizing resources and facilities, especially early in the CCSU process. The involvement of operations and maintenance personnel is part of Hot Spots 14 and 15. Hot Spots 8, 12, and 17 are parts of handover or turnover. Hazard management shows up in Hot Spot 18 with the closure of HAZOP items. Team building is the subject of Hot Spot 20. Hot Spots 16 and 19 relate to testing and checks, with loop and I/O checks specifically part of Hot Spot 16. Construction QA/QC relates to Hot Spots 2, 4, 5, and 8. New technology implementation is not specifically mentioned as a Hot Spot activity; however, in the case of new technology being implemented on a project, several Hot Spots could easily encounter greater difficulty (Hot Spots 2, 6, 9, 12, 13, 15, and 19).

CCSU Hot Spot Characterizations

Hot Spots are characterized according to seven characteristics, along with descriptive information such as number, name, flowchart activity number(s), and phase timing. An example Hot Spot characterization is shown in Figs. 2–4. The complete set of characterizations is extensive and cannot be fully provided in this article. However, characterizations for all 20 Hot Spots can be fully accessed via CII (2017).

Horsley identified a total of six underlying causes for the 20 typical CCSU problems that he listed (1998). For each of the 20 Hot Spots, this research identifies an average of more than six causal factors. Table 6 provides a quantitative summary of the characterizations, which represent much more specific information on industrial CCSU problem activities than has been collected as part of any other research. Each Hot Spot has multiple common deficiencies, causal factors, impacts, and solution strategies. This multiplicity will arm project personnel with the adaptability to determine the present (or future) causes of their problems and to implement the solution strategies that fit their project context. The detail of each characterization goes down to the phase timing of Hot Spot activities and suggested responsibility and accountability assignments for them.

Hot Spot Characterization Analyses

The Hot Spot characterization themes discovered for causal factors, impacts/threats, and prevention/mitigation strategies are provided in Tables 7–9. Logistic regression results are also provided in Tables 7–9, with values indicating how much less likely themes are to be present for a Hot Spot than the baseline theme (the highest-frequency theme). A numeric value in the logistic regression column indicates that that theme has a frequency significantly lower than the baseline, at an alpha value of 0.05. Each of the three characteristics has themes with frequencies significantly lower than the baseline. Each one also has themes not found to be significantly less frequent than the baseline. This variation tends to justify the theme ranking. Not only are themes present for the three characteristics; they are present in varying degrees. For themes found to be significantly less frequent than the baseline for each characteristic, logistic regression further shows how much less likely they are to be present for a Hot Spot. The unique findings of these analyses indicate that further research exploring Hot Spot characteristic themes may be warranted.

Hot Spot #1 | # Contributors: **31**

Resources and Facilities for Pre-Commissioning

Mobilize resources and facilities for Pre-Commissioning, including necessary SMEs and third-party participants

Flowchart Activity # 14, 53

Timing

Construction: Early (Activity #14)

Pre-Commissioning: Early (Activity #53)

Project Context/Example Scenarios

- Most projects today do not conduct on-site instrumentation/control valve bench tests, set-ups, and functional checks with wrenches and screwdrivers. The same work is now done with software (AMS) diagnostics in Pre-Commissioning or Commissioning by an SME. This important work cannot be skipped over. Failure to mobilize these resources in a timely fashion (whether due to cost-cutting, schedule-cutting, or for any other reason) will cost far more in schedule and budget during Startup.
- Technology today for new plants includes smart equipment with self-diagnostic tests and checks available to SMEs for quick verification during Pre-Commissioning or Commissioning. At least 98% of projects now buy and install this new capability; however, few take full advantage of it.

Alleged Common Deficiencies

- Timing the mobilization of CSU resources and personnel correctly is difficult, and often occurs too late.
- Vendors and SMEs are not involved enough because of cost-cutting and the extra coordination required.
- It is difficult to persuade project managers of the necessity of staffing a few Commissioning personnel no later than full execution funding.
- Startup personnel do not have a complete understanding of the process design.
- Too few experienced personnel are on site at the time of Pre-Commissioning, Commissioning, and Startup.

Causal Factors

- Vendors and SMEs are not sufficiently involved in Commissioning because of cost-cutting.
- Commissioning is not well understood by most in industry. This lack of understanding often causes unreasonable time constraints and cost pressures to be imposed on Commissioning.
- Since Commissioning always occurs at the end of a project, it inherits the leftover budget, schedule, and execution problems from all previous work.

Fig. 2. Hot Spot 1 characterization: Part 1 of 3. (Reprinted from CII 2017, with permission.)

Data showing which themes are present for each of the three characteristics and 20 Hot Spots is provided as supplementary data in Table S2.

As part of the Hot Spot characterizations, contributors identified links and associations between the Hot Spots and CSFs. An example is shown in Fig. 4. Upon tabulation of CSF frequency across the Hot Spots (provided in Table 10), three critical success factors stood out as linking to 50% or more of them. These CSFs are thus particularly applicable to common problem activities in CCSU execution. Those deserving special attention from CCSU managers are CSFs 4, on alignment; 9 on the CSU execution plan; and 11, on check sheets, procedures, and tools.

Implementation Process

The implementation process flowchart was created by the authors, with input from the panel of industry practitioners in order to give CCSU decision makers a concise procedure for implementing the research findings in the context of the industrial CCSU body of knowledge. It is relatively simple, with only 17 tasks listed, making it practical for project personnel to use in understanding how research results can be used in their CCSU execution plan. The implementation process is shown in Fig. 5.

Hot Spot #1 | # Contributors: **31**

Causal Factors *(continued)*

- Commissioning is not treated as a stand-alone discipline, and thus gets subordinated to construction.
- Startup personnel are often brought in from other facilities because of staffing constraints.
- Extreme winter working conditions and remote job sites can make it difficult to mobilize resources (human and other).

Qualitative Impacts/Threats to Success

- Lack of timely Vendor/SME support ends up costing more than was saved by not hiring them. Doing verification testing right the first time with an SME/Vendor present is cheaper than doing it wrong and being delayed. An SME may be needed to help solve the problem in the end anyway.
- Commissioning without proper staff/resource support will result in a frustrated, overworked Commissioning team that is forced to respond to emergencies, rather than preventing them. Even if construction finished on time or ahead of schedule, that time will be lost during extended commissioning. These working conditions will lead to more mistakes.
- Lack of necessary resources will lead to delays in Startup.

Prevention/Mitigation Strategies

- Allocate appropriate budget for successful commissioning, especially for the timely inclusion of SMEs and vendors.
- Educate company executives and estimators on the importance of commissioning, as well as the schedule and budget requirements for successful commissioning.
- Create a fully integrated construction-commissioning schedule with system-based milestones.
- Development of a vendor/SME plan including a schedule and regular updates.
- If the construction schedule slides, do not reduce the scheduled time for Commissioning. This will only result in further delay because of rushed Commissioning.
- Identify and involve the Commissioning team in the Design phase, giving them adequate time to review the scope of commissioning, and plan for staffing accordingly.
- Involve Startup personnel in the pre-Startup safety review.
- Commissioning and Startup personnel should not report to the construction contractor, but rather to the project manager.
- This hot spot can be prevented or mitigated with the following Innovative CSU Technology [CII 2015]: Asset Data Management/Wireless Instrumentation.

Fig. 3. Hot Spot 1 characterization: Part 2 of 3. (Reprinted from CII 2017, with permission.)

Hot Spot #1 | # Contributors: **31**

RACI Designations

Responsible: Commissioning and Startup Management

Accountable: Project Management

Consulted: CSU Personnel Coordination (Staffing); CSU SMEs/Engineering Support

Informed: HSE Management; Project Management; Construction Management; Plant Operations Management; HSE/Safety/SIMOPS Coordination; Security (e.g., site, personnel, cyber); Systems Completions Database and Support; CSU Cost Estimation and Controls; CSU Planning, Progress Tracking, and Schedule Control

Hot Spot #1 — **CSU Critical Success Factors** (from IR312-2, Volume I)

CSU Critical Success Factor	Indicators of CSF Achievement
1. CSU Value Recognition	1.1 CSU manager is on the project organizational chart at the start of front end engineering.
3. Adequate Funding for CSU	3.1 By the end of front end engineering, the CSU budget has been derived from knowledge of CSU strategy and scope of work, and if needed CSU resources, not simply a percentage of TIC.
4. Alignment among Owner PM, Operations, CSU, Engineering, and Construction	4.1 The CSU philosophy/strategy/execution plan has been reviewed/approved by all stakeholders, and signatures are affixed.
	4.2 Repeated confirmation of alignment is achieved.
	4.3 Critical CSU input has been acquired for engineering design reviews, engineered equipment purchases, construction sequencing, and schedules.
5. CSU Leadership Continuity	5.1 A CSU manager was assigned at the start of front end engineering and remained with the project through to initial operations.
	5.2 The qualifications and the planned tenure of the CSU manager were well-defined by early front end engineering.
12. CSU Team Capability	12.1 Project operational objectives were well documented and well understood among CSU team members.
	12.2 CSU team members understood the links between their actions and the technical metrics for project success.
	12.3 CSU progress was regularly assessed with management metrics.

Fig. 4. Hot Spot 1 characterization: Part 3 of 3. (Reprinted from CII 2017, with permission.)

The first steps shown in the implementation flowchart are recognizing the importance of CSU, understanding CSU contract strategy, and planning for CSU—topics covered by previous research. Next, multiple tasks are listed for completion during the detailed design phase, prior to construction. Two of these have to do with implementing the aforementioned list of 16 CSU critical success factors and their indicators. Several tasks address assigning specific responsibility and accountability for all applicable CCSU activities listed in the flowchart. The CCSU RACI matrix tool gives suggested RACI assignments for all 124 CCSU activities (CII 2017). CCSU managers should tailor the general information provided by these research products to the specific situation and needs of their projects. Several other tasks deal with creating a CCSU organization chart and ensuring that all staff positions are filled.

Some of the most critical flowchart tasks deal directly with the findings presented in this article. CCSU managers should review the list of 20 Hot Spot activities presented and identify which ones are likely to be problematic on their current project. Managers can review the other flowchart activities to find project-specific problem activities. Plans should be made to utilize the prevention/mitigation strategies for each Hot Spot identified as likely to be problematic for the project, as appropriate. Responsibility and accountability for implementing these strategies as necessary should be assigned. Plans to prevent or mitigate problems should consider the timing of each Hot Spot, common deficiencies, causal factors, and anecdotal examples—all attributes detailed in the Hot Spot characterizations. The negative impacts of unaddressed Hot Spots are listed as part of the characterizations as well. Foreknowledge of

Table 6. Hot Spot characterization quantitative summary

Characteristic	Metric	Value
Alleged common deficiencies	Total	87
	Average per Hot Spot	4.4
Causal factors	Total	133
	Average per Hot Spot	6.7
Qualitative impacts/threats to success	Total	75
	Average per Hot Spot	3.8
Prevention/mitigation strategies	Total	178
	Average per Hot Spot	8.9

these impacts can help persuade project executives to invest in appropriate prevention/mitigation strategies.

Once Hot Spots likely to be problematic have been identified, and solution strategies chosen from among those listed in the Hot Spot characterizations, plans to implement those strategies should be included in the project's CCSU execution plan.

Conclusions

Fulfillment of Research Objectives

Research results and analyses fulfilled the objectives of this research in the following ways:

Table 7. Hot Spot trends analysis: causal factors

Tag	Theme	Frequency across Hot Spots (percentage of 20 total)	Logistic regression
A	Unclear or unbalanced roles/responsibilities	11 (55)	Baseline
B	Construction/CSU/operations staffing problems (including lack of experienced personnel)	10 (50)	—
C	Unreasonable time and budget constraints/pressure	9 (45)	—
D	Lack of alignment	8 (40)	—
E	Construction-CSU interface problems	6 (30)	—
F	CSU activities not properly planned for	6 (30)	—
G	Lack of understanding about importance/complexity of CSU	5 (25)	0.78
H	Problems with systems definitions and handover to commissioning (late, wrong order, etc.)	5 (25)	0.78
I	Problems with CSU documentation	4 (20)	0.84

Table 8. Hot Spot trends analysis: qualitative impacts/threats to success

Tag	Theme	Frequency across Hot Spots (percentage of 20 total)	Logistic regression
A	CSU schedule delay	19 (95)	Baseline
B	Increased CSU cost	16 (80)	—
C	Deteriorating relationships between individuals/organizations	7 (35)	0.99
D	Increased health, safety, and environment (HSE) risk	7 (35)	0.99
E	Increased downtime/decreased production poststartup	7 (35)	0.99
F	Technical complications during CSU	6 (30)	0.99

Table 9. Hot Spot trends analysis: prevention/mitigation strategies

Tag	Theme	Frequency across Hot Spots (percentage of 20 total)	Logistic regression
A	Align on major CSU issues	13 (65)	Baseline
B	Ensure detailed CSU requirements are included in contracts	11 (55)	—
C	Assign specific tasks to specific people	11 (55)	—
D	Involve CSU and O&M teams early	10 (50)	—
E	Document CSU meticulously	9 (45)	—
F	Involve subject matter experts and original equipment manufacturers	7 (35)	—
G	Plan for CSU	7 (35)	—
H	Resource-load CSU	6 (30)	0.80
I	Conduct rigorous QA/QC program	6 (30)	0.80
J	Focus on systems	6 (30)	0.80
K	Educate/train personnel of all levels on CSU	5 (25)	0.85
L	Analyze, mitigate, and manage risk	5 (25)	0.85
M	Communicate openly and frequently	4 (20)	0.89

Table 10. Links between CCSU Hot Spots and CSU critical success factors

Factor (ordered by frequency)	Frequency across Hot Spots (percentage of 20 total)
Alignment among owner project management, operations, CSU, engineering, and construction	17 (85)
Detailed CSU execution plan	10 (50)
Definition of CSU check-sheets, procedures, and tools	10 (50)
CSU team capability	7 (35)
Adequate funding for CSU	6 (30)
Recognition of CSU sequence drivers	5 (25)
Integrated construction/CSU schedule	5 (25)
System milestone acceptance criteria and deliverables	4 (20)
Transition to systems-based management	4 (20)
Collaborative approach to construction-CSU turnover	4 (20)
Critical interfaces on brownfield projects	3 (15)
Accurate as-built Information	3 (15)
CSU value recognition	2 (10)
CSU leadership continuity	2 (10)
CSU system engineering during front-end engineering and design	2 (10)
System-focus in detailed design	2 (10)

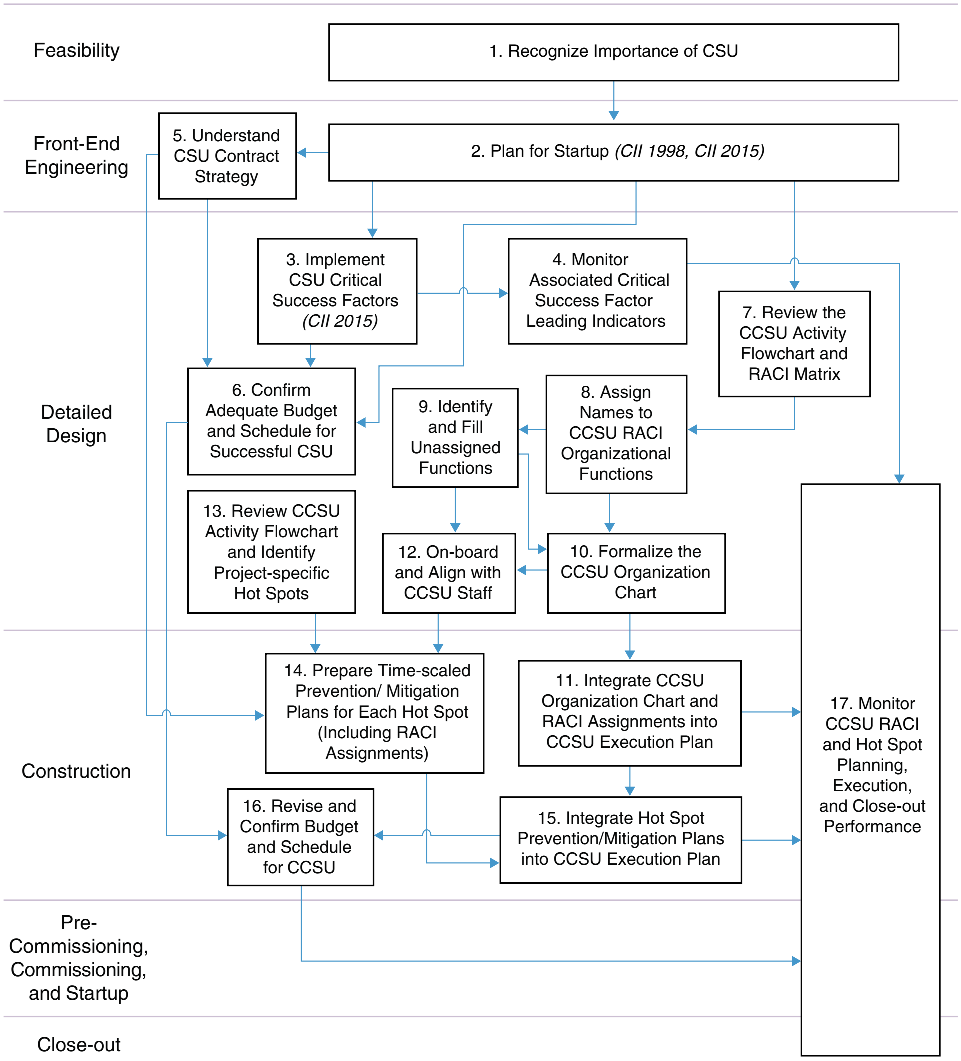

Fig. 5. CCSU implementation process. (Adapted from CII 2017, with permission.)

- The most common problematic CCSU activities were identified as Hot Spots from among the activities on the CCSU activity flowchart via a survey of industry experts.
- Hot Spot characterizations provided insight into seven distinct characteristics, including common deficiencies, causal factors, and impacts.
- Each Hot Spot characterization includes RACI designations to clarify responsibility and accountability assignments. The implementation process flowchart indicates when RACI assignments to specific individuals should be made.
- An average of more than eight prevention/mitigation strategies were identified for each Hot Spot.
- Trends were identified by analyzing three characteristics across the Hot Spots.

Key Findings

This research has identified 20 of the most common problematic CCSU execution activities and characterized them. Major conclusions drawn from this research include the following:

- Certain activities are generally problematic across industrial capital projects. These Hot Spots provide project teams with focal points for advancement.
- CCSU Hot Spot trends provide more insight into causal factors, qualitative impacts/threats to success, and prevention/mitigation strategies.
- Hot Spot analysis further reinforces the importance of the CSU critical success factors identified in prior research.
- Many Hot Spots occur during the construction phase. Early focus on CCSU execution from the beginning of the construction phase is recommended.

Industry Application

Implementation of the research findings, explained in the "Results and Analyses" section, represents an advance beyond current industry practice. The academic literature has identified scattered problematic activities and some solutions to those activities. The key findings of this research focus project personnel attention on the activities that are most likely to be problematic (Hot Spots) and their potential solutions. The identification of these common problems and solutions from among myriad CCSU activities can save project professionals much time and effort. Application of the findings provided here should enable a shift in CCSU culture from reactive to preemptive.

The authors conducted an ex post facto comparative case study on the CCSU of twin offshore spars constructed in the Gulf of

Mexico (CII 2017). As part of a design-one, build-two strategy, these project were uniquely suited to this purpose. CCSU management from the owner firm took the lessons learned from problematic activities on the construction of the first spar, and planned for the prevention and mitigation of those same problems on the second spar. After both projects were completed, owner management identified six of the 20 Hot Spots (30%) as particularly problematic on the first spar that they prepared to ameliorate on the CCSU of the second spar. A comparison of final project metrics showed a 58% decrease in CSU person-hours from the first project to the second. Additionally, the first spar exceeded its CSU schedule by 80%, while the second spar finished 40% ahead of its CSU schedule.

Contributions

The CCSU Hot Spots and their characterization represent significant contributions to industrial construction knowledge. While some literature addresses a few problematic activities, this is the most comprehensive collection of commonly problematic activities and their most detailed and systematic characterization, including phase timing, example scenarios, common deficiencies, causal factors, qualitative impacts, and prevention/mitigation strategies. The Hot Spots and their characterizations will aid project managers in the identification of CCSU problems in time to prevent or mitigate them. Other contributions include an analysis of themes recurring among the characterizations and a model for implementing research findings.

Data Availability Statement

All data generated or analyzed during the study are included in the published paper. Information about the *Journal*'s data-sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

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Supplemental Data

Tables S1 and S2 are available online in the ASCE Library (www.ascelibrary.org).

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