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EXPLORING HOW LEAN PROJECT DELIVERY SUPPORTS CARBON CAPTURE, UTILIZATION, AND STORAGE FOR INDUSTRIAL RETROFITS

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ABSTRACT

The "lean construction ideal" is to maximize stakeholder value, minimize waste, and emphasize collaboration throughout the design, construction, and operating stages of a building project. In practice, lean construction relies on methods such as the Integrated Project Delivery (IPD) system to align stakeholder interests and share risks throughout the project lifecycle. IPD effectively enfranchises various project stakeholders as parties to one agreement, integrating their involvement throughout the design and construction process. While lean construction methods are evidenced to enhance project efficiency in cost and schedule while improving quality, the collaboration fostered by IPD also creates a project environment conducive to innovation and the adoption of new technologies. To that end, lean construction environments, and IPD projects in particular, may offer an opportunity to increase the adoption rates of more environmentally-conscious design alternatives, particularly as the construction industry continues to trend in a more sustainable direction. This paper explores how the lean project delivery system supports incorporating innovative design options on retrofit construction projects (i.e., on existing facilities), and leverages incorporating carbon capture, utilization, and storage (CCUS) systems on cement plants as a proof of concept.

KEYWORDS

Sustainability, environment, collaboration.

INTRODUCTION

Literature from the International Group for Lean Construction (IGLC) confirms that often, the leanest path to "green" is to retrofit an existing building rather than demolish it and begin from scratch (e.g., (Ladhad and Parrish 2013; Ding and Parish 2019; Soliman-Junior et al. 2022). Research from outside of lean construction further supports this claim. For example, Jagarajan et al. (2017) discuss the need to retrofit the existing stock of buildings and industrial facilities in order to achieve climate goals. Perhaps more relevant to this study is the nexus of lean and green shifts within manufacturing processes and facilities, e.g., Huang et al. (2022), a study that discusses the necessity of retrofitting manufacturing plants, equipment, and processes to ensure that production is as lean as possible (i.e., minimal labour, material, and time waste) and that the manufacturing process limits environmental impact to the extent possible. Mellado and Lou (2020) discuss the importance of lean project delivery systems for creating an environment

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where sustainability can thrive; they argue that leveraging building information modelling in a lean project team with sustainability goals is the best environment for BIM, lean, and sustainability goals to be achieved. This paper, similarly, argues that a lean project delivery system, and a team committed to lean, provides the right environment for green retrofits, and CCUS retrofits of cement plants specifically.

BACKGROUND

LEAN PROJECT DELIVERY SYSTEM

Figure 1Figure illustrates the lean project delivery system, first introduced by Ballard (2000), and updated in 2008 (Ballard 2008). This system illustrates collaboration across project phases (i.e., project definition, lean design, lean supply, lean assembly, and use) as well as across project stakeholders, evidenced when triangles for different phases overlap, i.e., the "Design Concepts" node represents collaboration of owner representatives, designers, engineers, and contractors involved in project definition with the stakeholders involved in lean design. Such a system supports implementation of lean throughout the project lifecycle.

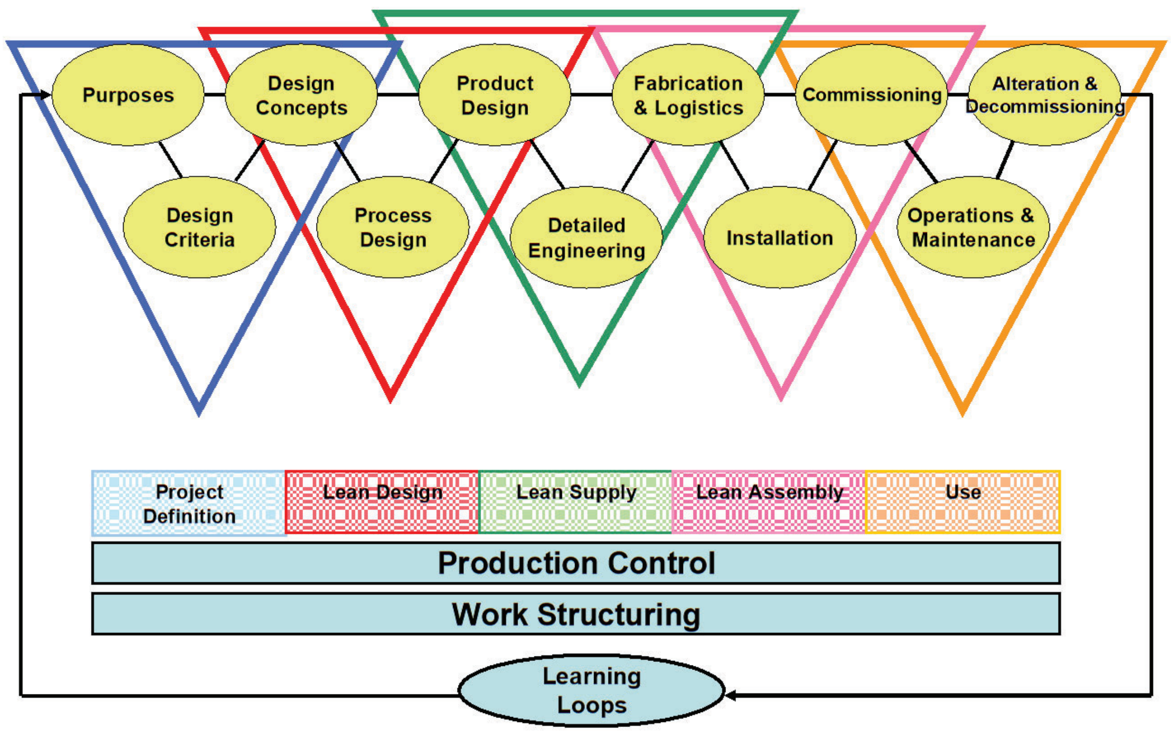

Figure 1: Lean Project Delivery System (Ballard 2008)

CCUS

Carbon Capture, utilization, and storage, or CCUS, refers to technologies that capture CO_2 from large point sources, i.e., industrial facilities, and then transport and utilize or store the CO_2 (IEA 2023). The number of retrofit construction projects involving CCUS installation will increase substantially over the next ten years. By the end of 2021, the global CCUS project pipeline contained 135 facilities, including 27 fully operational plants (Global CCS Institute 2021). The pipeline contained 51 facilities in 2020, with 21 operational (IEA 2023). Attaining the climate goals of the 2015 Paris Agreement requires construction of an additional 70-100 CCUS facilities globally, each year (Global CCS Institute 2021). CCUS represent the only group of technologies which at once abate end-of-pipe carbon emissions and offset past emissions. Given their capture capacity per area, CCUS technologies are the most direct path to a negative carbon effect.

For this reason, CCUS features prominently on sustainability roadmaps to net-zero and beyond (e.g., (GCCA 2022). Attaining net-zero in hard-to-reach sectors like power generation or cement and steel production is virtually impossible without CCUS technologies. Reflected in their sustainability commitments, Heidelberg Cement's carbon neutrality roadmap (Lenz 2023) features immediate and widespread integration of carbon capture technologies to reduce cement process emissions followed by intense development of capture and utilization technologies (Lenz 2023). Heidelberg showcases the retrofit of the Heidelberg Materials cement plant in Brevik, Norway as a first of a kind full-scale carbon capture demonstration (Brevik CCS 2023).

RESEARCH HYPOTHESES

Based on the background presented above, the authors developed the following research hypotheses:

> The collaborative nature of lean project delivery supports project teams' ability to implement CCUS technologies in industrial facility retrofit projects

> The lean project delivery system supports inclusion of innovative design alternatives in retrofit construction projects

METHODS

Testing the aforementioned hypotheses would require exploring a large number of "similar" retrofit projects, some delivered via LPDS and others not. Ideally, in order to conduct tests for statistical significance between the projects delivered with LPDS compared to those delivered without it, the authors would collect at least 30 projects delivered with each delivery system, for a total of at least 60 projects. Given that the total number of fully operational CCUS plants at the end of 2021 was 27, such a study is not feasible at present. Moreover, not all of the 27 operational plants represent retrofits, adding further difficulty to this experimental approach.

Given the limitations outlined above, the authors opted instead to illustrate how LPDS *could facilitate* the inclusion of sustainable design alternatives in retrofit projects. More specifically, the authors explore how the LPDS environment supports inclusion of one such sustainable design alternative, CCUS. To do so, the authors present the barriers to CCUS technology implementation and discuss how lean project delivery, and lean tools may be able to address these barriers. The barriers themselves are derived from a recent interview study conducted by the first author. The authors then suggest lean tools that may address these barriers based on IGLC and other lean construction literature.

INTERVIEW PROTOCOL

The authors developed the interview protocol to elucidate barriers in 2021 (Table 1), and conducted interviews from April 2022 – December 2022. The authors map each question to the most applicable phase of the LPDS, in order to best contextualize results.

The authors conducted interviews with 21 practitioners that spanned fields of basic research, applied research, technology development, innovation management, life-sciences, geophysics, civil engineering, construction materials, cement and concrete technologies, energy infrastructure, and innovation policy. The authors were transdisciplinary in their approach so they could learn about how innovative and sustainable design alternatives were developed and deployed in the cement industry. As important, they could understand the science that underpins

CCUS technologies and how these scientific considerations impact CCUS adoption in the cement industry (e.g., how the chemical process of producing cement impacts the feasibility of deploying various CCUS technologies in cement plants).

Table 1: Interview Protocol

Number	Question	LPDS Phase
1	What types of new cement materials or technology have you worked with and how often do you work with them?	Lean Design
2	What needs to improve for the cement materials and technologies in use today?	Lean Design
3	What are some of the drawbacks of the green cement materials and technologies you have worked with so far?	Lean Design
4	What project delivery methods are best suited for green/regenerative projects or projects with novel technologies?	Lean Assembly
5	What are the impacts to cost (budget/schedule/productivity) when a new cement material or technology is brought on to a project?	Lean Assembly
6	What are the risks and benefits for taking on regenerative/green projects?	Project Definition
7	What innovations are most successful in the cement industry?	N/A
8	What innovations are most needed in cement materials and technologies?	N/A
9	When considering an innovation portfolio decision, what data and inputs are most useful?	N/A
10	What barriers do you perceive to innovation with cements and what would you suggest to overcome them?	N/A
11	What makes a regenerative or green innovation easier to adopt or spread within the industry?	N/A
12	What effect do sustainability and climate goals have on shaping your innovation portfolio?	Project Definition

All interviews were conducted via zoom. Interviews were recorded with the participant's consent (all participants consented to being recorded). The authors used the zoom transcripts for coding (Frey and Fontana 1991; Wengraf 2001). Specifically, the authors coded the responses for themes related to barriers to adopting innovative technologies in the cement industry. For the purposes of this paper, only barriers related to CCUS are presented.

RESULTS

Based on the interviews, the following barriers to CCUS implementation in the cement industry emerged:

Limited utilization potential for captured CO_2: Participants indicated that finding a local use for captured carbon was a challenge to achieving circular economy. Moreover, responses indicate that natural processing of CO_2 seems to favour storage, e.g., carbon deposits under the ocean floor.

Evaluation of technology readiness can impede implementation: Respondents discussed the Technology Readiness Level, or TRL, which influences those technologies that can be, and are, considered for inclusion in a capital project. In the context of the cement industry, the technologies with high TRL may not yet be cost effective over the expected lifetime of the plant.

Indeed, traditional cost assessments and their analytical methods do not accurately depict risks, costs, and benefits of CCUS projects in current and future markets. These evaluation models assess the cost of a CCUS install as a function of capital expenditures (CAPEX) and effects on operating costs (OPEX), accounted for in cost per unit of CO_2 captured. Analysis includes baseline assumptions about the operating requirements of the carbon capture equipment, such as power requirements, maintenance, cost of compression, transport, and storage, and effects on plant productivity during and after construction (e.g., (Liang and Li 2012). Baseline assumptions rely on outdated performance data, typically from amine-based capture processes relying on coal-fired heat and power generation with overstated power requirements and carbon capture efficiencies around 70 to 80% of total plant emissions (Liang and Li 2012). Assumptions also incur oversized effect to indirect costs, such as technology readiness level (TRL) impacts on contingency planning costs (Gardarsdottir et al. 2019) and production impacts from simulated process flow models (Liang and Li 2012). Outside-the-gate factors assume fixed estimate rates for variable factors like future carbon pricing and energy supply types (Liang and Li 2012). Traditional assessments may also ignore market specific conditions like the availability of carbon transport and storage infrastructure or potential revenues for captured CO_2.

Cement plants that are "new" are less likely to undergo an intensive retrofit: Given the relatively young age of cement plants discussed by interviewees, the interviewees indicated that taking on a capital-intensive retrofit would be unlikely unless such a retrofit was mandated by a local/state/national policy.

Cement plants have typical service lives of 30 to 50 years (Gardarsdottir et al. 2019). With the average age of plants in the U.S. at just under 20 years (IEA 2023), many existing plants could be considered for potential CCUS retrofit, provided they can sustain operations for the 20 to 25-year payback period (Gardarsdottir et al. 2019). CCUS installation can raise the costs of clinker production 50-90% (Gardarsdottir et al. 2019). The cost of captured carbon is a function of the cost of clinker divided by the total capture capacity of CO_2 emissions. Cost of captured carbon varies widely according to the capture efficiency of each technology and the specific plant deploying it (Gardarsdottir et al. 2019). Total plant costs with carbon capture compared to potential revenues and incentives in each market determines the economic justification for retrofit.

DISCUSSION

The authors discuss herein how the barriers listed in the “Results” section can be addressed by lean project delivery.

LIMITED UTILIZATION POTENTIAL FOR CAPTURED CO_2

It is not immediately clear how lean tools, or the lean project delivery system, can address this barrier. However, one possibility would be to conduct a root cause/5 Whys analysis to understand exactly why the utilization potential is low. The authors do not expect that this analysis will yield a clear solution. Rather, the authors posit that this analysis will clearly frame future research directions that provide clarity about what makes utilization difficult. For instance, is the issue that there is not enough demand for CO_2 in the marketplace? This would seem reasonable, as many ongoing efforts work to reduce the CO_2 created, rather than use CO_2. If this is the root cause, then perhaps solutions for CCUS should focus more on storage of the captured carbon, without trying to develop a case for using the CO_2. If, however, the issue is that once carbon is captured, the transport to the utilization site (e.g., a soda plant) “costs” more CO_2 emissions than the CO_2 capture and utilization avoid, there is a clear opportunity to site new users of CO_2 proximate to cement plants with CCUS technologies installed. Indeed, the authors research suggests that if CO_2 has to be transported more than 100 km, the net CO_2 emissions are higher than if the CO_2 had simply been released at the plant.

EVALUATION OF TECHNOLOGY READINESS CAN IMPEDE IMPLEMENTATION

As discussed, evaluation of technologies and their applicability for a given plant should not be considered “one size fits all.” Lean philosophies recognize the unique nature of construction sites and support developing the best approach for that specific site. Of particular note for evaluation is set-based design (e.g., (Ward et al. 1995; Sobek et al. 1999; Rekuc 2005; Parrish et al. 2007; Parrish et al. 2008a; Parrish et al. 2008b; Parrish 2009), which allows project teams to consider multiple design options longer than would be typical in a point-based design scenario. For the case of CCUS retrofits for cement plants, set-based design may involve considering multiple CCUS technologies, regardless of their technology readiness level. Indeed, the goal would be to allow each CCUS technology to persist in the design process until the last responsible moment, when failure to make a decision delays the overall project (Parrish et al. 2007). Project teams may elect to consider various CCUS technologies and explore their fitness for the cement plant at hand, in terms of leveraging incentives, meeting local/state/national or organizational CO_2 emissions reduction goals, and supporting site-specific production cost metrics, e.g., $\$/t_{CO2}$. When design alternatives are developed, project teams can make data-driven decisions about which CCUS technology is most appropriate using Choosing By Advantages (e.g., (Suhr 1999; Parrish and Tommelein 2009; Arroyo et al. 2015). CO_2 emissions reductions can be expressed as a ‘must’ or a ‘want’ criterion, depending on the requirements of the city or region where the plant is located.

NEWER CEMENT PLANTS ARE UNLIKELY TO UNDERGO A RETROFIT

The “Project Definition” and “Lean Design” phases of the LPDS offer clear opportunities to address this barrier. While it is understandable that a cement plant owner may not want to make a large capital investment in their relatively new plant, climate-related legislation and goals may warrant making such investments earlier than originally planned. Similar to the “evaluation barrier” described above, this barrier can be addressed by thoroughly understanding the context for the project. Assuming that a plant *must be retrofit* to comply with internal or external CO_2 emissions reduction plans, then lean project delivery offers the full project team an opportunity to collaboratively brainstorm potential solutions and assess them as a team. To address this barrier, a “big room” may be helpful (Ballard 2008). However, instead of using the big room during the design phase, the authors recommend implementing a big room meeting during an ownership meeting; that is, the plant owners could invite multiple designers and engineers to one of their routine meetings where they discuss plant operations. This big room would essentially offer a platform for brainstorming feasible CCUS solutions for each plant in the owners' portfolio. Then, the project teams can leverage set-based design and Choosing By Advantages to evaluate the most appropriate CCUS option for each site.

BROADER CONTEXT: EXISTING FACILITY RETROFITS

While this paper has focused on the barriers to implementing CCUS in cement plants, the barriers are likely not all that different than barriers facing any facility retrofit. As concern about the climate grows, and policies begin to be implemented that limit CO_2 emissions and mandate energy performance across sectors (e.g., (State of California 2018; New York City 2019), many facility owners will face a need to retrofit their facilities. The LPDS, and specific tools that enable it, can help owners identify the appropriate potential retrofits for their facility and decide from among these alternatives.

CONCLUSIONS

This paper explored how the lean project delivery system can support CCUS implementation in the cement industry. The authors highlighted specific barriers to CCUS implementation in the current marketplace, including limited utilization potential for CO_2, evaluation of CCUS technology, and unwillingness to invest in a relatively new asset. The authors discuss how the LPDS, and lean tools like set-based design, Choosing By Advantages, and big room meetings can help owners to overcome barriers associated with CCUS implementation. Indeed, the authors argue that these results extend beyond CCUS implementation in cement plants, and extend to any facility that requires a retrofit.

As discussed in the "Methods" section, the authors did not have enough data about enough projects to compare project outcomes for those projects using the LPDS versus those that did not. Such a study would be welcome in future research by the IGLC community.

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