Summary for CIFE Seed Proposals for Academic Year 2019-20

Proposal number	2019-08
Proposal title	A Comparative Study of the Ecosystems for Prefabrication: Europe and the US
Principal investigator and department	Martin Fischer – Civil and Environmental Engineering (SDC)
Research staff	Wilfrido Martinez-Alonso
Total funds requested	$ 57,229
Project URL for continuation proposals	**N.A.**
Project objectives addressed by proposal	**Buildable**
Expected time horizon	**2 to 5 years**
Type of innovation	**Breakthrough**
Abstract	**The problem:** After talking to CIFE members who prefabricate building components in Europe and the US, we noticed that Europeans see advances in the US they find difficult to implement, and vice versa. **The proposed solution:** Compare ecosystems for prefabrication in Europe and the US with respect to: design, fabrication, and assembly/construction processes; decision-making procedures (decisions made when, by whom, on what basis, how often); criteria to differentiate between good and bad designs; scope of the type and number of design options considered (e.g. mostly product-focused, or also process- and organization-focused); project participant's understanding of "design"; knowledge and skills of project participants; effort expended, timeline and calendar time; information and knowledge density over time; VDC approach used (if any); tools used and disciplines involved (when, how); amount of project-specific and project-independent information and knowledge; differences with the ship building industry. **The proposed research approach:** Case studies with four pioneering partners (two in Europe, two in the US) using significant amounts of prefabricated building components to develop a comparative study of their ecosystems.

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1. Engineering/Business Problem

Prefabrication of building components, sub-systems, and modules is not new. Firms have taken different approaches to prefabrication, with discrete motivations, and an evident discrepancy between European and US companies. For example, in the CIFE community, Ryan Companies has had the capacity to build and deliver custom buildings in shorter periods than traditional construction can offer since the 1970s [1]. They ship their panels on a single flat-bed truck. Germany-based GOLDBECK developed product lines for industrial buildings, offices and multi-story car parks in 1988 [2], an element-based approach. They started making steel components for industrial buildings, and then included concrete components. In 1996 IKEA and Skanska introduced building blocks with prefabricated modules through BoKlok in Sweden [3]. Also in Sweden, NCC has owned a subsidiary that develops prefabricated concrete shafts since the mid-aughts [4]. They have plans to move this sourcing in-house. Around the same time in Denmark, Ramboll started using prefabricated concrete and metal elements in their ducts [5]. Mortenson first introduced prefabrication to their projects in 2012, using exterior panels, bathroom pods, multi-trade racks, and head walls [6]. DPR Construction started to use prefabricated light gauge structural frames (LGSF) panels in 2015 [7]. They had already used prefabricated wood-frame structures. During the same year, French Bouygues Construction gave its first step towards prefabrication by partnering with Techniwood to develop high energy performance prefabricated wood panels [8]. Founded in the 2010s, Digital Building Components' (DBC) projects use load-bearing panelized structures, fully-finished panelized exterior walls, and advanced panelized interior walls [9]. DBC produces their components directly from a 3D model [10]. In 2017, MT Højgaard, a Norwegian company, used prefabricated façade elements, balconies, chimneys and ventilation rooms for the first time [11]. There are other companies that have explored the use of prefabricated building components. Clark Pacific started offering prefabricated concrete modular buildings in 1973. Today they use prefabricated concrete for penalization, scheme, architectural details, finishing and connections [12]. The European firm LLENTAB incorporated their own automated production line to produce steel profiles from hot-dip galvanized coils in 1987 [13]. Nowadays they deliver fully prefabricated steel buildings in seven European markets. Established in 2008, Project Frog is trying to automate design and workflows in their practice, through a kit-of-parts procedure [14].

After talking to CIFE members who prefabricate building components in Europe and the US, we noticed that Europeans see advances in the US they find difficult to implement, and vice versa. A major reason could be they have singular developments, and because construction does not encourage collaboration nor knowledge sharing between companies [15, 16, 17], there are unanswered questions whose resolution could facilitate the European adoption of US advancements (and the other way around.) For example, how are design, fabrication and assembly/construction systems different? Are there similarities in these systems? What are the major differences? What decision-making procedures (e.g. decision maker, timeliness, frequency, and basis) do companies follow?

Are there company-specific design criteria (i.e. definition of what makes a design good or bad)? How does the type and number of design options considered introduce variability (e.g. product-focused, or also process- and organization-focused)? Is there a defined format for design iteration cycles? What do project participants' understand by "design"? Is their understanding mostly circumscribed to their own personal experiences? Has the extent of their knowledge and skills been surveyed or classified? Do companies measure the effort spent on projects and timelines? Does the presence of abundant, non-connected tools (e.g. types, uses,) and disciplines involved (e.g. when, how) can contribute to create inefficient work? Is there a mechanism to measure this work inefficiency? To the extent of our knowledge no prefabrication company has structured platforms or databases to make information and expertise available over time. Without this, is it possible to discern between amount of project-specific and project-independent information and knowledge in their projects? Are prefabrication companies taking advantage of Virtual Design and Construction (VDC)? If so, to what extent?

Existing research in the prefabrication industry focuses on individual or small-scale aggregates of case studies or theoretical frameworks to think about prefabricated construction companies [18]. This translates in research mostly analyzing isolated, non-generalizable cases and developing rigid frameworks. This makes it difficult to inspect the differences between prefabricated construction methods in Europe and the US [16], and generates a weak understanding of the adaptability of prefabricated construction advancements to different scenarios. Additionally, there is a lack of research on the impact networks and organizational structures have in the industry, and their effect on project systems. Stephen Pryke provides a good point of departure, but his analysis did not consider the particularities of prefabricated construction, and addressed the context of European companies only [19]. Thus, a critical analysis comparing the ecosystems for prefabrication in Europe and the US with focus on the companies' organization and workflows, and the type of prefabricated building components they use is necessary to: (i) evaluate the efficiency of prefabricated systems developed in contrasting environments (Europe and the US) based on the baseline for process, product, and organization established in the preliminary research stage; (ii) understand the use of information and data to mitigate risks (variability) in prefabricated construction; (iii) outline how projects implementing advanced prefabrication techniques unfold; (iv) apply or adapt the VDC framework to optimize prefabrication workflows; (v) consolidate design guidelines and cycles in prefabricated construction systems; and, (vi) map the organizational structure of companies using significant amounts of prefabrication.

2. Theoretical and Practical Points of Departure

We will build on extensive research developed at CIFE, and integrate it. Relevant CIFE research has explored prefabrication and supply chain management strategies (Lepech and Suck; Fischer, Flagger, Hamamji, and Havelia; Fischer and Flagger; Levitt) to optimize schedules (Fischer, Lee, and Wilson,) but found there is still significant variability in the plan execution over the project course (Garcia-Lopez, Schütz, and Fischer.) It has also explored the use of bill of materials for made-to-stock materials (Fischer and Song,) used by advanced prefabrication companies. Organizational and networking structures have also been explored (Fischer, Lepech, and Russell-Smith; Levitt; Levitt, Ashcraft, and Hall) in the context of traditional construction. Statistical techniques have been employed to optimize design and reduce uncertainty (Fischer, Iccarino, Welle, and Druzgalski; Fischer, Choo, and Garcia-Lopez; Jain,) as well as to improve decision-making processes (Fischer, Kam, Khalessi, and Senarata.) CIFE developed frameworks to track construction flow (Fischer, Levitt, and Lopez,) bring 3D printing to construction (Fischer, Bazjanac, and Mrazovic,) and improve digital design manufacturing of façades (Fischer, Billington, Bazjanac, and Mrazovic.) Use of tools to deliver high-performance projects has also been investigated (Fischer and Schütz; Levitt and Gasparro,) as well as the use of look-ahead planning and feedback loops to use current project data in the planning (Fischer and Garcia-Lopez; Fischer and Schütz; Levitt and Gasparro.) VDC has been researched extensively at CIFE.

- **<u>Prefabricated Construction Status in Europe and the US</u>**

In the US prefabricated construction has only gained mainstream adoption in the last five to ten years [16]. This momentum was created by a combination of, among others, rising labor costs and proliferation of unskilled labor, the irruption of Building Information Modelling (BIM,) rising demand for sustainable, buildable, operable and usable buildings that do not require trade-offs between constraints, and global trading trends allowing for international shipping [15, 16, 20, 21]. An example of this trend is Marriot International Inc. launching the "Modular Initiative," targeting to employ prefabricated construction in 25 percent of hotels in their pipeline within five years [22]. They are currently planning for a 26-story hotel in NYC, which will be assembled in a Polish factory. It is expected the hotel will rise in 90 days, developed by Concord Hospitality. Guerdon Modular Buildings built an AC Hotel (a Marriot brand) in Oklahoma City in the context of this initiative, while across the street a contractor was building a Hyatt Hotel with a traditional approach [23]. This provided an opportunity to draw a particularly direct comparison (Table 1) between construction methods as much of the external project variability was removed. Results show that permit was issued four months later for AC's hotel, but it managed to opened three months earlier than Hyatt's hotel.

Table 1: Hotel Comparison: Key Comparable Metrics. Two similar projects using different construction approaches delivered in Oklahoma City.

Hyatt Hotel	vs	AC Hotel
128	**Rooms**	142
5	**Stories**	5
III	**Type**	III
90,184	**Area**	86,560
22	**Months**	15

In Europe, prefabricated construction started to attract widespread attention in the early aughts, after being shunned due to criticism on the technical quality [24]. Of particular importance is the influence the European Single Market brought. Factories could now be located across EU countries [2] and both National and EU Governments engaged to activate the industry [25]. For instance, the EU introduced BIM guidelines to "stimulate economic growth and competitiveness while delivering value for public money" [26]. This is important as variability in building codes and other requirements across every municipality in the US, attempting to standardize and then automate prefabrication practices is non-trivial [16]. In order to overcome this issue, some prefabrication companies in Europe decided to integrate design, production, and assemble/construction. This vertical integration allows them to have a better control of their supply chain (SC) and "own" the design cycle. On the one hand, owning the design cycle has permitted, for example, the exploration of parametric tools to efficiently enable design automation [16]. Bryden Wood and the University of Cambridge have developed parametric process flows where interdependencies between multiple processes can be simulated [27]. On the other hand, command over the SC allows companies to better control their processes and reduce risks. For example, GOLDBECK developed a planning strategy based on their calibrated SC (Figure 1a) which permits them to keep an impressive delivery record[1], avoiding burdens present in traditional projects' supply chain (Figure 1b) [28]. This addresses research calls to rearrange existing structures for SCs to be effective in the construction industry [19, 28, 29, 30]. A logical question is whether vertically integrated companies in the US have similar practices, and if not, what are the key differences. We consider a comparative study could help answer this question.

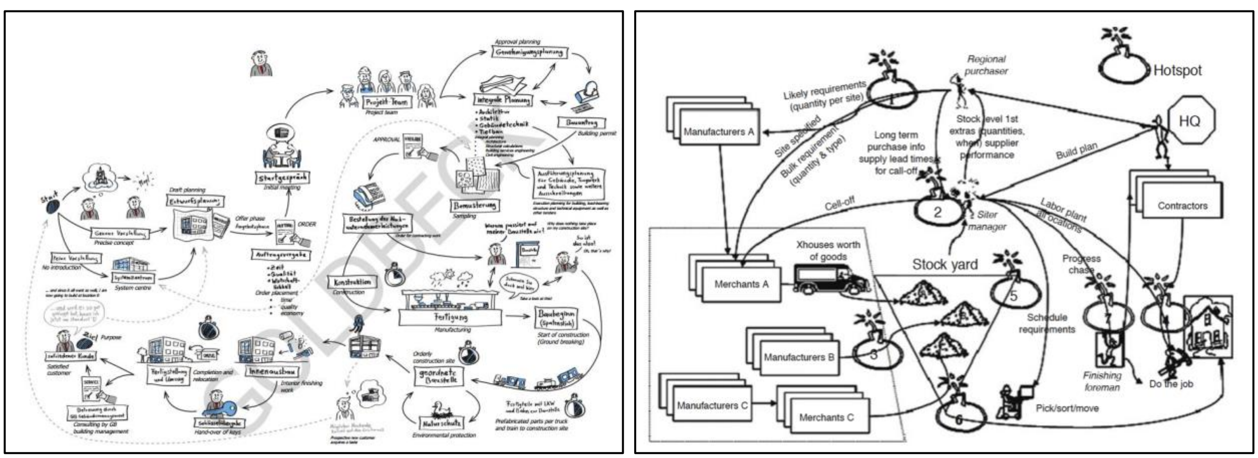

Figure 1: From Left to Right: a) GOLDBECK Project Workflow [Courtesy: GOLDBECK]; b) Representation of Traditional Supply Chain "Hot Spots." (1) Little use of market knowledge; (2) lack of integration; (3) no time compression strategy; (4) inability to rapidly reconfigure; (5) excessive waste; (6) no space buffer; and, (7) excessive human resource [Adapted from 28].

[1] A PM at GOLDBECK told the authors he has never missed a delivery deadline during his 7-year tenure.

- **Other Industries**

While developments in the construction industry are often compared to those in the automotive industry [15, 16, 18, 31], we think the shipping industry could afford more objective analogies [31]. There are two reasons: (i) size, complexity, and singularity of construction projects are more akin to building ships than to assembling automobiles; and, (ii) the shipping industry used to be behind the world standard for productivity, but is now above the average [32]. The later point was achieved through the use of BIM to reduce construction cycle times. The industry is starting to use BIM to explore opportunities for modularization [31, 32]. Importantly, they introduced the "percentage of total modularization" metric to measure the "percentage of work that can be modularized beyond conventional methods" in different trades [33]. Findings suggest most sectors of labor can be modularized up to 80 percent, cutting labor hours by 23 percent [31], reducing budget overruns and delayed deliveries. Furthermore, both prefabricated construction and ship building companies have baseline designs, which are almost always modified to accommodate clients' demands [1, 2, 12, 31, 33]. Both industries have different styles to manage variability, but these design changes seem to have a larger impact in the construction industry. By comparing them we could identify and import valuable ship building risk-management practices to prefabricated construction.

3. Research Methods and Work Plan

The three traditional research strategies are experiment, survey, and case study [34]. Case studies are an appropriate research strategy when there is little known about the topic of interest [35]. The proposed phases in this research effort to perform a critical analysis comparing the ecosystems for prefabrication in Europe and the US are four: (i) preliminary research; (ii) case studies and data collection; (iii) data analysis; and, (iv) framework development.

i) PRELIMINARY RESEARCH

Research, structure and consolidate current knowledge state in the prefabrication industry. We will use it to establish a baseline for process, product, and organization for prefabrication companies.

ii) CASE STUDIES & DATA COLLECTION

Run case studies with four pioneering partners: two in Europe and two in the US. We will use them to identify areas of opportunity and draw parallels between them. Methods for data collection will include direct observation, interviews and surveys, and documentary analysis [35]. We expect to structure and collect historical data from partners as studies in machine learning suggest more often than not data volume rules over algorithm sophistication [36, 37].

ii.i) Proposed Structure for Case Studies

We plan on analyzing our partners' processes with respect to one of their products (e.g. warehouses.) Within a product there are two types of building components: self-performed or outsourced (i.e. subcontractors.) We expect to focus on a selected group of object types each of them supply (e.g. columns, beams, façade.) We are going to examine, among others, information flow, design iterations, and variability in the cost, time, and quality by comparing planned to actual product. We intend to gather data from these studies, but also collect historical data from our partners. This all will help us find correlations and differences between our partners' practices.

iii) DATA ANALYSIS

We look for three key concepts: reliability, validity, and representativeness [35]. We will employ advanced statistical techniques (e.g. machine learning) to identify triggers and root-causes for variability, and parameters enhancing operations.

iv) FRAMEWORK DEVELOPMENT

Propose a framework, which based on best practices found during the case studies, facilitates to advance the implementation of prefabrication methods, including companies' organizational structure. The framework will include advice on how to create platforms to integrate company and project information across projects. It will also suggest metrics to track company and project progress, and keys to successfully adopt or boost VDC.

4. Expected Results: Findings, Contributions, and Impact on Practice

This research seeks to study similarities and differences between prefabricated construction companies in Europe and the US. As an starting point we will research, structure and consolidate the current knowledge state in the prefabrication industry. We will use it to establish a baseline for our partners' (two from Europe, two from the US) process, product, and organization as well as to identify potential opportunities for improvement. In particular, we want to compare ecosystems and draw parallels between them, and develop a framework where these ecosystems can learn from each other. Once we have a general idea of our partners' practice, we expect to:

- ✔ Profile their design, fabrication and assembly/construction processes.
- ✔ Analyze their decision-making procedures: decisions made when, by whom, on what basis, and how often.
- ✔ Research their criteria to differentiate between good and bad designs.
- ✔ Consider the scope of the type and number of design options they consider (e.g. mostly product-focused, or also process- and organization-focused.)
- ✔ Investigate what do project participants understand by "design."
- ✔ Examine the knowledge and skills of project participants.
- ✔ Measure the effort expended, timeline, and calendar time.
- ✔ Study their information and knowledge density over time.

- ✔ Explore, if any, the VDC approach they use.
- ✔ Quantify inefficiency created by the use of abundant, non-connected tools (including classification of types and uses,) and disciplines involved (when, how.)
- ✔ Compare the amount of project-specific to project-independent information and knowledge.
- ✔ Contrast the prefabricated construction industry with the shipping industry.

After completion, we will be in a position to evaluate how these points impact their practice. We plan to provide them with guidelines and strategies for best practices in the prefabrication industry that allows them to optimize their organizational structure and prefabrication processes. We also intend to help partner companies to enhance their understanding of their own practice and aid their VDC implementation. Finally, we hope to aid partners develop and select metrics allowing them to strengthen their project delivery and organizational structure.

5. Industry Involvement

We are looking for four pioneering partners (two in Europe, two in the US) using significant amounts of prefabricated building components to develop a comparative study of their ecosystems. CIFE members and other industry partners involved would ideally have a good record of employing prefabricated building components in their practice, and be in a position to give us access to study their structure (i.e. organizational systems.) We trust our access to projects using compelling levels of prefabrication would allow us to gain a better understanding of workflows and decision mechanisms through their processes. We are hopeful this collaborative effort will allow us to develop a database from which insights on best practices are gained, and frameworks to advance the implementation of prefabrication methods developed. We are confident we can help our partners enhance their understanding of their own practice based on their similarities and differences with respect to other partners. We are also optimistic in our ability to help partners introduce (or advance) VDC to their organization, with focus on finding metrics to measure and bolster their performance across projects. As of now, we have maintained contacts with GOLDBECK (Germany) and DBC (US.)

6. Research Milestones and Risks

Proposed milestones to gauge the researchers' progress are outlined in Table 2.

Table 2: Seed Proposal Milestones. Timeline for delivery of actionable items.

#	Milestone	Delivery Date
1	Research, structuring and consolidation of current knowledge state in the prefabrication industry.	December 2019
2	Case Study 1: Data collection and process mapping for Company A (Europe.)	March 2020
3	Case Study 2: Data collection and process mapping for Company B (US.)	June 2020
4	Preliminary analysis of companies A and B.	July 2020
5	Case Study 3: Data collection and process mapping for Company C (Europe.)	October 2020
6	Case Study 4: Data collection and process mapping for Company D (US.)	December 2020
7	Presentation at *CIFE Industrialized Construction Forum 2021*.	February 2021
8	Statistical implementation based on collected and volunteered data.	April 2021
9	Framework for advancing the implementation of prefabrication methods.	July 2021
10	Co-joint workshop with partner companies on *Best Practices for Prefabricated Construction.*	September 2021
11	Deliver report to partners.	September 2021

Identified risks that could hinder the progress of this research effort are as follows:

a) **Availability of Projects.** Timeliness and smooth progress of case-study projects will set the pace of our findings' evolution.

b) **Data Acquisition.** Willingness of prefabrication companies to share (and allow us to collect) data will depend on our continuous carefulness in the handling of these confidential data.

c) **Resemblance of Organizational Systems.** Reciprocity between prefabrication companies' structures, processes, and systems could accelerate the researchers' progress – and vice versa.

d) **Statistical Implementation.** Execution of advanced statistical techniques providing a competitive edge finding parameters aiding successful implementations and root-causes for variability could prove technically challenging.

e) **Company Involvement.** It is our experience receptive and communicative partners facilitate the introduction of new concepts, expedite their adoption, and amplify their impact.

7. Next Steps

We expect to develop a framework for the advancement in the implementation of prefabrication methods by developing four case studies. We are looking for two more partners (one in Europe and one in the US.) Our next step would be to deliver a report with our findings to our partner companies. Then, validate and enhance the versatility of our framework through continuous collaboration with our pioneering partners and the inclusion of other industry collaborators. A key possible extension is the integration of VDC to companies using significant amounts of prefabricated building components and the incorporation of powerful, integrated tools (e.g. IoT.)

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