Assessing Circular Information Flow in Industrialized Construction: a framework for evaluating data for circular construction

J Berglund-Brown1,2, F Kedir1, A Riabova1 and D Hall1

1Chair of Innovative and Industrial Construction, ETH Zurich, HIL F 27.1 Stefano-Franscini-Platz 5 8093 Zürich Schweiz
2Building Technology Program, Department of Architecture, Massachusetts Institute of Technology, 77 Massachusetts Ave, Bldg. 5-418 Cambridge, MA 02139

E-mail: jbbrown@mit.edu, kedir@ibi.baug.ethz.ch, ariabova@student.ethz.ch, hall@ibi.baug.ethz.ch

Abstract. A circular economy offers a solution for improving both the efficiency and environmental impact of the built environment. As the construction industry transitions to a circular economy, adequate information flow is necessary to keep products in the value chain for as long as possible. Industrialized construction firms show high potential for a successful transition to a circular economy because of optimized information flow through the use of product platforms, the use of information communication technologies, and the integration of actors. However, there is no current framework to assess whether construction firms using industrialized construction methods have a circular information flow. In this research, four characteristics are identified as main descriptors of a circular information flow framework: Completeness, Availability, Accessibility, and Incorporation of Information into Business Strategy. Using the framework, industrialized construction firms are asked to self-assess their performance through pre-defined survey questions. The findings from sixteen industrialized construction firms reveal the need for more complete data about recyclability potentials of products and unique materials and product identifiers, with 47% of firms indicating they have insufficient information. The survey of companies also indicates a need for more feedback about the reuse, recycling, and remanufacturing phases to be available, with only 20% of firms gathering feedback about reuse, 13% about recycling, and 20% about remanufacturing. The stakeholders with the most consistent access to information about design and materials of a project are the manufacturer, engineer, architect, and assemblers. 13% of firms employed RFID tags. More accessibility of information is needed for actors outside of the firm. Additionally, only 13% of firms implemented a take-back strategy, emphasizing the need for incorporating these business strategies within the firm. 17% of firms, however, had CE in mind during strategic development, demonstrating the potential for CE adoption in industry. Finally, the paper discusses future opportunities for circular information flow, such as employing blockchain technology.

Keywords: building firms, literature review and survey, circular information flow, industrialized construction firms, circular construction, circular data
1. **Introduction**

The building sector is a major contributor to global carbon emissions [1]. There is an urgent need to reduce carbon emissions globally, and to transition to a circular economy (CE) is one strategy to do so [2, 3]. The concept of a CE aims to decouple economic activity from the consumption of finite resources. In the built environment context, CE principles manifest through four resource strategies: narrowing, slowing, closing, and regenerating the lifecycle of building products and projects [4]. In order to achieve CE in the built environment, a better understanding of the entire building life cycle and the construction value chain is needed [5]. Designing for a CE involves a holistic shift in generating and processing data [6]. This shift can be achieved through improvements to develop better circular information flow (CIF).

CIF refers to the development, management, and exchange of CE-relevant data [7] throughout the lifecycle of an asset in the built environment. The current construction industry has several challenges to achieve CIF, including the disjointed nature of information and data flow in the construction industry today [4]. Despite an extensive amount of data being generated throughout the lifetime of a building, the adoption of big data analytics has been slow and limited [4]. There is a need for “Infusing technology and innovation” to achieve adequate information flow and ensure the right data flow between all actors [8]. Such digitalization can improve data production and management [9].

The traditional construction industry is not currently equipped for the transition. That being said, approaches such as modularity in construction and industrial practices have been found to help promote the transition [7, 10, 11, 12]. Industrialized Construction (IC), referring in this case to concepts such as modular building, prefabrication, robotics, and off-site manufacturing, offers tremendous opportunities for reducing environmental impact [7, 13]. IC provides many opportunities for a shift towards circularity. This is due to the use of product and process platforms, digitization, and the integration of many actors into the building process. Additionally, these attributes have the potential to facilitate a CIF in construction [7, 10]. Adopting IC practices is one strategy that has the potential for successfully embracing CE through the proper incorporation of CIF [5].

However, the synergies between IC and CIF are not sufficiently studied [7]. This could partially be attributed to an undefined set of information about what circular information flows are, and how industry can ensure their firms are equipped to implement CIF. There are several gaps in understanding information flow in the built environment for circular data: 1. What characteristics does this information have? 2. How does the industry use this data? 3. How do we evaluate how the industry incorporates this information into their business strategy?. To answer these questions, this paper conducts a systematic literature review to define CIF and the set of fundamental characteristics necessary for CIF. Next, the paper evaluates several industrialized construction companies across each attribute to understand how they compare. A survey is conducted for 16 IC companies across different markets. Next, from the survey analysis, the paper identifies the gaps and barriers in circular information flow. This paper contributes through a better understanding of circular information flows and develops an framework for circular information flow in IC Firms.

2. **Background**

2.1. **Circular Information Flow**

In order to be able to assess CIF in IC Firms, it is imperative to first establish a working definition for CIF. CIF is the information created, shared, and stored throughout the life cycles of a product that helps implement circular economy practices [14]. Information, in this case, follows the same definition used in other circular information flow literature, derived from information quality literature. For the purpose of this paper, “information” is defined as structured data about a product [15]. Because of this definition, information and data are occasionally used interchangeably. “Information flow,” therefore, refers to the exchange and path of said structured data between actors and life cycle phases. Tracing and tracking this information is an important component of circular building strategy [4]. Hunhevicz et al. [16] identified two different types of information flow: technical information, defined as property and
material data relevant for use and reuse phases, and commercial information, which is information during the construction.

2.2. **Defining Characteristics for CIF**

For the purpose of this paper, CIF in IC firms can be defined by four characteristics, described in Figure 1: *Completeness, Availability, Accessibility, and Business Strategy Incorporation.*

2.2.1. **Completeness.** Completeness of data is an integral component to the nexus of circularity and information management because of how essential the condition and properties of material objects are for CE practices [15]. After a construction project, data is often incomplete and low quality [16]. Incomplete information is often left that way, and when information is updated, it is often delayed, leading to rework or the inability to use data in different life cycle stages [16, 17]. Hunhevicz et al. 2020 identifies “completeness” as a necessary attribute for a high-quality dataset. Completeness is also mentioned in literature pertaining to “data sheets,” which are “pre-defined ways of stating the properties of a construction product” [9]. A data sheet, in this case, is not considered a data sheet until the information pertaining to product properties and related values are marked complete [9]. In summary, “complete data” is data that contains all necessary information for reuse about properties of building materials and components. This includes technical data about size and dimensions, building physics, chemical composition, biological safety, safety hazards, recyclability, and unique material products and identifiers [14].

2.2.2. **Availability.** Data availability poses as a challenge to CE adoption and is integral to CIF [18]. Before the level of “completeness” of a data set can be assessed, the question of the existence of the data must first be asked. That is, what information is being generated by a company? The difference between completeness and availability are as follows: completeness asks, “are there values missing for certain parameters?” whereas availability questions if the company generates and collects information about parameters in the first place.

2.2.3. **Accessibility.** Accessible data is data that can be obtained or examined by many different stakeholders at all stages of the life cycle. Questions about accessible data also pertain to how data is retrieved. An industry study conducted by Box, a secure cloud content sharing platform, found that construction firms have the highest rate of work shared with outside parties [19]. With that in mind, understanding who has access to data is essential. The flow of information to all relevant actors on a project is imperative [20] and cannot happen without accessible data. Circular product certification schemes such as Cradle to Cradle(C2C) identify the need to make instructions for how to cycle the product publicly accessible [21]. Additionally, accessibility plays a significant role in what data is used in engineering projects [22]. If actors don’t have easy access to certain types of data about reuse or a building life cycle, they are less likely to use it or actively incorporate CE into their work.

---

**Figure 1.** Circular Information Flow Characteristics.
2.2.4. Business Strategy Incorporation. The fourth and final CIFC identified is incorporating and considering data in an IC firm’s business strategy. In order to incentivize complete, available, and accessible data, firms must incorporate processes and mechanisms that promote CE in their business strategy. For example, the absence of mechanisms to trace properties of materials pose a barrier to reuse [23]. Having mechanisms in place, such as RFID tags or number tags, could enable reuse. The CE transition requires new business models [4] and allows for the retention of value of circular assets [23]. Circular Business Models (CBMs) allow for the creation of value while practicing CE principles [24, 25]. CIF, as previously described, is a crucial aspect of CE principles, and therefore must also then be considered in CBMs and business strategy in general.

2.3. Industrialized Construction and Circular Information Flow
IC has a potential for optimized information flows. One reason for this is the use of product platforms which consists of technical and process platforms. A technical platform is defined as a set of common components, modules, or parts from which a stream of derivative products can be efficiently developed and launched for a building project [26]. A process platform, includes a systematic collection and organization of subprocess, working methods, structure for information handling, performance measurement approaches, collaboration, and planning methods [27]. As a result, comprehensive and organized data about the building as a product, building components, and processes can be created, tracked, and shared. This attribute can be very beneficial for emerging CIF tools such as material passport (MP) [7]. A MP is made up of data describing characteristics of materials within a product, system, or, in this case, a building [28]. MPs are a helpful tool for implementing CE in construction as it allows data to be tracked throughout the product and building life cycle.

Another marker for successful CE transition and optimized CIF in IC is digitization. Lessing developed a nine-category framework with constructs that make up industrialized house building (IHB) [27]. Among the nine categories is information and communication technology (ICT). IC’s predictable processes require “reliable information, supported by suitable information and communication technologies that enable effective structuring and management of digital materials” [27]. The incorporation and consideration of information management in IC practice is an indicator for successful CIF. Of these framework categories, also notable in relation to information management is the long-term relationships between participants and logistics integrated into the construction process. IC’s emphasis on relationships and integration of actors also lends itself to having potential for superior information flow. Adequate information flow is necessary for advancing sustainability and CE in construction. Because of the advantages of product and process platforms, ICT, and actor integration, IC firms have the potential to be equipped for this change.

3. Methodology
The research followed two primary research methods, a literature review, and an industry survey to understand the current state of information management in IC Firms.

3.1. Literature Review
To identify the characteristics of CIF, a systematic literature review was conducted that identified literature falling into the intersection of IC, CE, and information management [14]. A total of 83 papers were analyzed, leading to the development of a requirements table specifically in the IC value chain [14].

From these requirements, a survey was developed to understand the information procurement, storage, and exchange across different life cycles of products in IC firms [14]. From this survey and requirements table, four characteristics were identified as particularly essential when considering circular information flows in IC Firms: data completeness, data availability, data accessibility, and the integration of data into business models. The characteristics have been structured in a 3+1 model, with two describing attributes of the information, and one referring to how the firm interacts and incorporates said data. After the characteristics were identified, another supplemental, informal literature review was
conducted to define each characteristic and its use. A summary of these characteristics are provided above in subsection 2.2.

3.2. **Industry Survey Development**

After each circular information flow characteristic (CIFC) was outlined, there was a need to understand their application in an industry context. A survey was distributed to over 26 IC firms between February 2021 and September 2021, 16 responses were collected from firms spanning Europe, USA, UK, and Canada. The companies were identified through keyword internet search, LinkedIn network, and Industrialized Construction Forum speakers. The companies themselves operate primarily on the design and construction side of the building life cycle, while having some involvement in operation. The product of the companies range from volumetric and complete housing solutions, prefabricated construction systems, digital platforms, panelized building components, to reconfigureable housing units. The survey sought to understand the current status of information flow management in IC firms and to collect data on the information flow management in IC firms in the context of the information requirements for the circular practices. The survey questions and responses were then grouped by CIFC category and can be found outlined in Figure 2.

**Table 1.** Survey questions sorted by CIFC.

| Circular Information Flow Characteristic (CIFC) | Question                                                                 | Question type and possible answers                                                                 |
|-----------------------------------------------|--------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| Data Completeness                             | How would you assess the completeness of information on building materials/products properties you receive from suppliers? | Rank the following on a scale of (Sufficient, Well-organized, Sufficient Not well-organized, Not sufficient, No Information): Physical, Building type, Chemical, Biological, Health and safety, Recyclability, Certifications, Unique Materials/product identifiers |
| Data Availability                             | Does your firm create assembly instructions for the products? If yes, who creates them? | Y/N, Fill in the blank                                                                              |
|                                               | Do you create other, circular economy related information about your products? (Ex: LCA of your products) | Y/N, Fill in the blank                                                                              |
|                                               | From which phases in the life cycle do you gather feedback about the performance of your products? | Design, Manufacturing, Logistics, Assembly, Use, Maintenance, Demolition, Reuse, Remanufacturing, Recycling |
| Data Accessibility                            | Across design, manufacturing, maintenance, and end of life phases, who has access to the detailed design model or BIM model of your product? | Sales agent, Architect, Engineer, Material Supplier, Manufacturer, Project Manager, logistics, Assembler, Facility Manager |
|                                               | Across design, manufacturing, maintenance, and end of life phases, who can access information created and stored by your firm about the building materials? | Architect, Engineer, Material Supplier, Manufacturer, Project Manager, Logistics, Assembler, Facility Manager, Demolition company, Reuse agent, Remanufacturer, Recycler |
|                                               | What information are you ready to share with a demolition company or a remanufacturer at the end of the intended lifecycle of your product? | Component design, BIM Model, Material properties, Certification, Current condition, Life cycle history |
|                                               | Do you use a take back strategy for your products?                        | Y/N                                                                                               |
Integration of CIF into Business Strategy

| Question                                                                 | Y/N |
|-------------------------------------------------------------------------|-----|
| Do you have a strategy to remanufacture your products?                  |     |
| Do you have circular economy in mind during your strategic development?  |     |
| Which programs and technologies do you employ to track the locations of your products from manufacturing to assembly? |     |

In addition to the questions outlined above, the survey also collected data pertaining to stakeholder involvement, market area, and barriers to CIF in their firms.

4. Results

4.1. Completeness

The survey asked IC firms to rate the extent to which they believed their data was complete (from Sufficient, Well-organized, to No Information) across varying parameters. The resulting input from IC firms (outlined in Figure 3) details how overall, across all firms, the most complete information was about physical building characteristics, with 60% of firms indicating their physical data was both sufficient and well organized. There seemed to be more complete data about health and safety, with 40% of firms indicating having sufficient and organized information, and only 7% having no information on Health and Safety of data. The least number of firms indicated that they had sufficient and well-organized information about unique materials and product identifiers, with 47% of firms having insufficient information, which emphasizes the need for better product identifiers for the circular economy transition.

![IC Firms Self Assessment of Completeness of Building Data Across Parameters](image-url)

- Unique Materials/Product Identifiers
- Certifications
- Recyclability
- Health and Safety (hazards)
- Biological (safety)
- Chemical (composition)
- Building Physics (hydrothermal performance)
- Physical (dimensions, weight)

Legend:
- Sufficient, Well-organized
- Sufficient, Not well-organized
- Not Sufficient
- No Information
4.2. Availability
The survey sent out to construction firms covered three questions pertaining to information availability, one asked whether assembly instructions are created in firms, the other asked if other CE related data (such as LCA) is created, and the third asks at which stage in the building life cycle there is performance feedback collected. The survey yielded results indicating (in Figure 2) that 87% of firms reported they obtained feedback about product performance in the design phase of the life cycle and 73% of firms gathered feedback during the manufacturing, assembly, and use phases. The minority of firms (20%, 20%, 13%, respectively) gathered data about the life cycle's reuse, remanufacturing and recycling phases. The other two survey questions in this category asked if assembly instructions and other CE related data are generated. 93% of firms reported that assembly instructions are available, whereas 60% of firms reported that other CE-related data is available.

4.3. Accessibility
In the assessment of how accessible data is on the firm level, we examined who has access to information about building materials and BIM models. The results are demonstrated in the figures below. The stakeholders with the most consistent access to detailed design models and building material information across firms are the manufacturer, engineer, architect, and assemblers, whereas there is little to know access given to demolition, remanufacturing, and recycling companies.
4.4. Business Models

The survey sent to IC Firms found that 53 percent of firms employed Bar/QR codes, and only 13% employed RFID tags. In order to better understand the current state of the industry, firms were also asked whether they employ take-back strategies and strategies to remanufacture. Only 13% of firms indicated they use a take-back strategy, and the same amount indicated the presence of a strategy to remanufacture. 73% of firms declared they keep the circular economy in mind during strategic development.

Figure 3. Results from survey questions pertaining to data availability and accessibility.

Figure 4. Results from survey questions pertaining to incorporation of data into business models.
5. Discussion
From these results, four key takeaways emerge: 1. There is a need for more complete material and product data available to IC firms. 2. More data is needed in the realm of reuse, recycling, and remanufacturing in IC firms. 3. There is a need for larger consideration of CIF in business strategy in IC firms. 4. Firms are aware and thinking about CE during strategic development.

The Completeness assessment category revealed the lack of complete data across IC firms. In general, the parameters where the largest number of firms reported their data was sufficient and organized were physical and health and safety hazards. This makes sense as complete physical characteristics (such as dimensions and weight) are necessary for construction. Health and safety hazard data must also be complete for the well-being of the occupants. Complete data about recyclability of a building product is significantly lacking, in addition to unique material data and unique product identifiers. Material passports offer a potential solution for more complete information in these areas, and more complete data about recyclability is necessary for CE. In terms of availability, the majority of companies create assembly and other CE related data (i.e., LCA), which is promising for a CE transition. That said, while analyzing information availability across lifecycle stages, more available data in the reuse, recycling, and remanufacturing fields are necessary. Accessibility revealed that firms provided little to no access to material data to remanufacturers, recyclers, and demolition companies. These parties are often outside of the firm, and therefore little access to information is is provided to these actors. The lack of information shared outside the firm signifies the need for better information exchange between actors. Based on these results, there is a clear need for a larger consideration of CIF in business strategy. While firms may not currently implement take-back and remanufacturing strategies, the survey revealed this incorporation is certainly on the horizon. It is promising that the majority of companies have CE in mind during strategic development, which demonstrates an understanding of the importance of CE adoption. While it is positive that companies are thinking about CE, the next step is implementation, and CIF will aid in this process.

5.1. Research limitations and future directions
This exploration developed one method of assessing circular information flows in IC firms. That said, this evaluation approach can certainly be supplemented by characteristics about data structures and how information is exchanged. Additionally, the survey was developed based on the current state of the firms surveyed. Because of the absence of certain actors and strategies in firms, they were not included in the survey. For example, this is the reason actors such as demolishers were not considered in the availability category, and why disassembly instructions were not included in the completeness strategy. As the industry makes strides towards a CE, there is potential for new categories and questions throughout the survey. The survey also yielded a limited number of respondents, with 16 firms contributing to the survey. Because of this limitation, there is room for surveying additional firms to obtain a more holistic view of IC value chains.

Furthermore, the survey that was sent out was a qualitative, self-assessment by the IC Firms. There is potential and opportunity for more quantitative assessments of CIF. There are quantitative evaluation systems that currently exist for circular products [29], but none directly for construction and building products. Another potential future direction examines current certification systems for circular products and draws comparisons and avenues for applying said assessments to the built environment and building products.

Finally, another promising research area emerged during the analysis for availability and business models. Blockchain technology, a “distributed peer-to-peer system for value transactions without any intermediation from a central authority” [30] offers a way to enable material passports [4] and enable peer to peer transactions to create a flow network, an essential component to information flow [30]. A platform is necessary for actors to communicate design and material information [4], and Blockchain technology can provide a governance structure for doing so.
6. Conclusion
The synergies between IC and CIF are promising and IC provide great opportunity for enhancing CIF. That said, in order to implement CE principles into IC Firms, there is a need to better manage circular data, which refers to any data relevant to CE and the sustainable transition. This paper sought to understand the characteristics of information flow in firms, how IC firms use data, and how to evaluate how firms incorporate IC into their business strategy. This paper revealed the necessity to enhance the completeness of material data, the availability of reuse, remanufacturing, and recycling data, and the incorporation of CIF and tools that aid CIF into business strategy. Finally, the paper demonstrates the immense potential for CE adoption in IC firms, particularly due to the firms enthusiastic, self-reported interest. The framework developed in this paper aids in the broad understanding of data characteristics that are necessary for a circular transition.

References
[1] UN Environment Programme 2019 2019 Global Status Report for Buildings and Construction Sector
[2] Masson-Delmotte V et al 2018 Global Warming of 1.5°C (IPCC)
[3] Ellen Macarthur Foundation Circular Economy Introduction - Overview
[4] Çetin S, De Wolf C and Bocken N 2021 Circular Digital Built Environment: An Emerging Framework Sustainability 13 6348
[5] Munaro M R, Tavares S F and Bragança L 2020 Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment Journal of Cleaner Production 260 121134
[6] O’Connor F 2018 Circular thinking in design Designing for a Circular Economy (Routeledge)
[7] Kedir F, Bucher D and Hall D 2021 A Proposed Material Passport Ontology to Enable Circularity for Industrialized Construction European Conference on Computing in Construction
[8] Barbosa F, Woetzel J, Mischke J, Ribeirinho M J, Sridhar M, Parsons M, Bertram N and Brown S 2017 Reinventing construction through a productivity revolution
[9] Mêda P, Sousa H and Hjelseth E 2020 Data Templates—Product Information Management Across Project Life-Cycle Sustainable Materials in Building Construction Building Pathology and Rehabilitation ed J M P Q Delgado (Cham: Springer International Publishing) pp 117–33
[10] Ellen Macarthur Foundation and McKinsey Center for Business and Environment Growth Within: a circular economy vision for a competitive Europe
[11] Luseure L and Mulhhall D 2018 Circularity information management for buildings Designing for a Circular Economy (Routeledge)
[12] Minunno R, O’Grady T, Morrison G, Gruner R and Colling M 2018 Strategies for Applying the Circular Economy to Prefabricated Buildings Buildings 8 125
[13] Kedir F and Hall D M 2021 Resource efficiency in industrialized housing construction – A systematic review of current performance and future opportunities Journal of Cleaner Production 286 125443
[14] Riabova A 2021 Bringing circularity to industrialized construction with the help of information management MSc Thesis Eigenössische Technische Hochschule, Zürich
[15] Zeiss R 2019 Information Flows in Circular Economy Practices 27th European Conference on Information Systems - Information Systems for a Sharing Society pp 1–17
[16] Hunhevicz J, Schraner T and Hall D M 2020 Incentivizing High-Quality Data Sets in Construction Using Blockchain: A Feasibility Study in the Swiss Industry Proceedings of the 37th International Symposium on Automation and Robotics in Construction pp 1291–8
[17] Jylhä T and Suvanto M E 2015 Impacts of poor quality of information in the facility management field Facilities 33 302–19
[18] Brimacombe L Thinking life-cycle in a circular economy Designing for a Circular Economy (Routeledge)
[19] Bouck W 2014 Mapping the Information Economy: A Tale of Five Industries Box Blog
[20] McGraw Hill Construction 2013 Information Mobility: Improving Team Collaboration Through the Movement of Project Information

[21] Cradle to Cradle Products Innovation Institute 2021 Circularity Data Report

[22] Fidel R and Green M 2004 The many faces of accessibility: engineers’ perception of information sources Information Processing & Management 40 563–81

[23] Carra G and Nitesh M 2017 Circular Business Models for the Built Environment

[24] Ferasso M, Beliaeva T, Kraus S, Clauss T and Ribeiro-Soriano D 2020 Circular economy business models: The state of research and avenues ahead Business Strategy and the Environment 29 3006–24

[25] Peters M, Ribeiro A, Oseyran J and Wang, K 2017 Buildings as Material Banks and the Need for Innovative Business Models (Buildings as Material Banks)

[26] Meyer M and Leonard A 1997 The Power of Product Platforms (The Free Press)

[27] Lessing J and Stehn L 2019 Industrialised house building Offsite Production and Manufacturing for Innovative Construction pp 86–110

[28] Luscuere L M 2017 Materials Passports: Optimising value recovery from materials Proceedings of the Institution of Civil Engineers - Waste and Resource Management 170 25–8

[29] Cradle to Cradle Products Innovation Institute 2021 Cradle to Cradle Certified® Version 4.0

[30] Hunhevicz J J and Hall D M 2020 Do you need a blockchain in construction? Use case categories and decision framework for DLT design options Advanced Engineering Informatics 45 101094

[31] Chen K, Lu W, Peng Y, Rowlinson S and Huang G Q 2015 Bridging BIM and building: From a literature review to an integrated conceptual framework International Journal of Project Management 33 1405-16