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DOI
10.3390/su17020638

Publication date
2025

Document Version
Final published version

Published in
Sustainability

Citation (APA)
Davis, A., van Bortel, G., & Martí Audí, N. (2025). Circular Industrialised Housing: Insights from Solar Decathlon Europe 2022. *Sustainability*, *17*(2), Article 638. https://doi.org/10.3390/su17020638

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Circular Industrialised Housing: Insights from Solar Decathlon Europe 2022

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Abstract: The latest policy and research recommendations focus on advancing transition of housing to the circular economy framework to tackle environmental and affordability challenges. A key strategy for this is industrialised construction, which combines controlled manufacturing methods with strategies that facilitate future disassembly, allowing for adaptations, maintenance, and material reuse. Despite its importance, long-term housing solutions that integrate both industrialised construction and disassembly remain rare. This study obtained insights into circular industrialised housing from the Solar Decathlon Europe competition through interviews and observations with fifteen participating teams in Wuppertal, Germany, in 2022. The competition's build challenge provided a unique opportunity to examine the practical application of both industrialised and disassembly approaches, where teams developed highly energy-efficient, affordability-conscious, and scalable housing systems. On-site interviews with team members from diverse disciplines took place midway through the competition's assembly phase. These were further informed by observing team Azalea's housing disassembly in Spain, which took place shortly before reassembly in Germany. Thematic and content analyses were conducted using a predefined framework based on holistic factors and lifecycle processes. Our results reveal the critical impact of Cultural factors, particularly during the (re)design process and provide new data to aid our understanding of the (dis)assembly process. This study contributes towards the development of a circular industrialised housing framework.

Keywords: circular housing; design for disassembly; industrialised construction; qualitative research; framework

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Academic Editor: Aliakbar Kamari

Received: 27 November 2024
Revised: 8 January 2025
Accepted: 10 January 2025
Published: 15 January 2025

Citation: Davis, A.; Bortel, G.v.; Martí Audí, N. Circular Industrialised Housing: Insights from Solar Decathlon Europe 2022. *Sustainability* **2025**, *17*, 638. https://doi.org/10.3390/su17020638

1. Introduction

The current lack of sustainable and affordable housing has escalated into a wide-scale crisis in the EU and globally [1,2]. Significant numbers of people lack access to decent housing in both developed and developing countries, and the planet's resources are being consumed at an alarming rate, perpetuating biodiversity loss and water stress [3,4]. Construction activities notoriously cause some of the greatest negative environmental impacts. They consume half of the raw materials extracted globally each year, which is expected to double in the next forty years [5,6]. Cement, a key ingredient in concrete, is a major source of greenhouse gas emissions. Additionally, sand is extracted for construction purposes at unsustainable rates [5]. Furthermore, recent research also suggests that carbon sinks, upon which EU climate policies in countries such as Finland rely on heavily, may not be sufficient to achieve urgent net zero targets [7].

Environmental sustainability and housing affordability are so-called ‘wicked problems’ that are often in tension with each other [8]. Additional homes and renovations are required to meet housing needs, yet construction activities significantly contribute to crossing planetary boundaries such as climate change and resource scarcity [9,10]. Within this context, sustainable circular housing solutions, though often erroneously perceived as more expensive compared to business-as-usual approaches, are essential for reducing negative environmental impacts. This is particularly relevant for residential buildings, which account for approximately 75% of the EU building stock, therefore playing an even more critical role in this twin crisis [11,12].

A circular economy approach to housing can theoretically simultaneously improve both affordability and sustainability. This relies on a long-term vision and whole-lifecycle outlook, considering impacts post-building completion during both the use phase and the beyond End-of-Life (EoL) phase. Fundamental to this paradigm is the reintroduction of previously used materials within housing, coupled with ensuring that newly produced building parts in turn facilitate future reuse. The European Commission is committed to the transition of the built environment to a circular economy through policy instruments such as the Circular Economy Action Plan [13] and the Waste Framework Directive [14] under the European Green Deal [15] and alongside the EU Level(s) framework. Recent top-down guidance emphasises the need to utilise prefabricated and standardised building parts that integrate Design for Disassembly (DfD) to support repairs, reuse, and building adaptations. Most notably, this includes the European *Circular Economy Principles for Building Design* guidelines, the Level(s) framework, and ISO standard 20887 [16–18].

The circular transition of housing is increasingly supported by developments in industrialised construction (IC), which goes beyond basic prefabrication to include digitalisation, robotics, and automation to manufacture standardised yet customisable housing at scale under controlled conditions [19]. This fosters the continuous improvement of building products and construction systems, rather than the production of one-off housing projects [20].

Despite recent advancements and incentives in support of *circular* industrialised construction within the housing sector, disassembly and reuse are rarely implemented in permanent housing and such practices remain largely theoretical. The long timespans inherent to the housing lifecycle, amongst other factors, create challenges in applying circular economy principles to housing produced using IC, with few built examples demonstrating disassembly and reassembly processes for replacement, adaptations, and subsequent use cycles.

A growing body of academic literature clearly demonstrates the opportunities to improve both the environmental and economic sustainability of housing through the integration of industrialised construction (IC) with circular economy (CE) principles [21–24]. However, significant gaps remain in the academic literature regarding their practical application to affordable, energy-efficient, and scalable housing systems [25]. Existing research often focusses on the technical aspects of IC, such as prefabrication methods, digitalisation, and quantifying embodied carbon, while neglecting the integration of non-technical socio-economic implications [26–28]. Numerous theoretical frameworks support the IC and CE transitions [29–31], although these two concepts are often not fully integrated with each other or tailored to the housing sector. Although industry-developed scalable building systems, such as WikiHouse, have been analysed and tested by the academic community [32], the literature does not sufficiently capture the experiences of a range of stakeholders with primary experience in delivering highly efficient, prefabricated housing designed for disassembly. Bridging these gaps requires empirical studies exploring both the technical and non-technical barriers to and enablers of adopting circular and industrialised practices in housing, offering insights relevant to all lifecycle stages.

The Solar Decathlon competition provides a unique opportunity to observe and collect empirical data on the execution of the disassembly and reassembly of 'circular housing', based on off-site or prefabrication methods that additionally incorporate digital strategies. The housing competition requires university teams to collaborate with industry partners to relocate a highly energy-efficient house across countries, showcasing how the future disassembly of building components and materials can be integrated within planning, design, manufacturing, delivery and removal processes. This serves to extend the lifespan of housing by facilitating maintenance, adaptations, reuse, and supporting sustainable EoL scenarios. This study uses the Solar Decathlon Europe 2022 competition as a case study to explore lessons learned and best practices derived from interviews with fifteen teams during the two-week assembly phase in Wuppertal, Germany.

The teams were primarily composed of undergraduate and master's students, guided by university staff and researchers and collaborating with industry partners. Through these partnerships and their substantial investment of time and hands-on effort to complete the design and build challenges, students gain valuable knowledge on IC and DfD. By delivering sophisticated and highly energy-efficient housing solutions—often applying the latest technologies—student team members acquire practical insights reflective of innovative and real-world practices in industrialised circular housing. To capture insights from diverse perspectives, interviews were conducted with interdisciplinary team members, whose collective expertise offers holistic insights into the opportunities and challenges encountered across the building lifecycle.

This study builds upon a prior systematic literature review carried out by the authors, which retrieved 347 articles, of which 46 relevant studies were analysed [33]. The review examined the relationship between distinct circular processes and hypothesised that barriers and enablers vary across lifecycle stages. It proposed a framework outlining four lifecycle processes and identified 6 emergent holistic factors influencing circular industrialised housing (Figure 1), along with 15 recurring themes and 35 sub-themes. Whilst the review sought to gather practical examples of the disassembly process, the systematic search predominantly yielded theoretical studies, with relatively few practical examples. This highlighted a significant gap in the literature on circular industrialised housing, particularly regarding applied knowledge and experience within academic research.

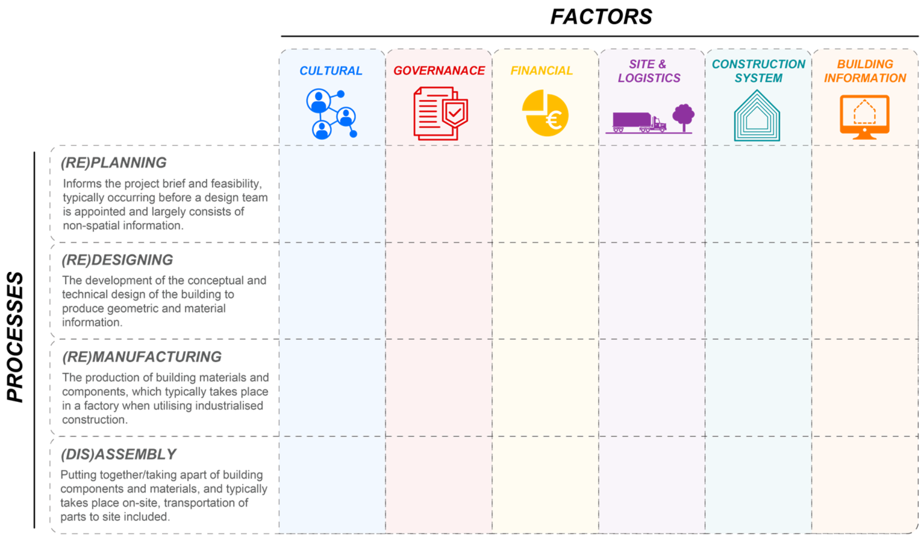

Figure 1. Circular industrialised housing framework established by previous study—factors represented by six distinct colours.

The Solar Decathlon study serves as an exemplary case study, providing an opportunity to collect empirical data on barriers and enablers that are underrepresented in the existing scholarship. These include factors such as site and logistics considerations, as well as the identification of new emerging themes and sub-themes. These research objectives aim to further refine and expand the circular industrialised housing framework that forms the foundation of this study.

This study is based on the following research questions:

1. What insights can be gained about the enablers of and barriers to circular industrialised housing in relation to building processes from the Solar Decathlon Europe competition?
2. What can we learn about the disassembly, assembly, and reassembly of circular industrialised housing that is not addressed in the existing literature?
3. Which themes and sub-themes emerge from the interviews that complement or expand upon the literature review findings?

1.1. The Competition

Solar Decathlon is a university competition where student-led teams undertake the challenge of designing and constructing a highly innovative and environmentally sustainable house. These are fully functional and built to scale, and are referred to by the Solar Decathlon organisation as a House Demonstration Unit (HDU). The competition was initiated by the United States Department of Energy; as such, it has historically placed great emphasis on energy efficiency rather than resource efficiency [34,35]. Since the first Solar Decathlon in the USA in 2002, the competition has expanded its reach to Africa, China, Europe, Latin America, and the Middle East.

This study is based on data gathered from the Solar Decathlon Europe (SDE) 2021/22 edition, hereafter referred to as SDE-2022. This was the fifth European competition event and was hosted by the University of Wuppertal in Germany. This remains the most recent European edition due to the cancellation of SDE-2023 in Bucharest, Romania, and the next edition is forecast to take place in 2026, but confirmation of the host city remains pending [36,37]. The build challenge was held in Wuppertal at the competition site known as the Solar Campus (Figure 2), on land owned by the host university. Sixteen teams participated, eight of which, located to the west side of the Solar Campus, were pre-selected to remain on site for an additional 3 to 5 years as living labs. This meant the teams to the east side would need to dismantle and remove their HDUs at the end of the competition.

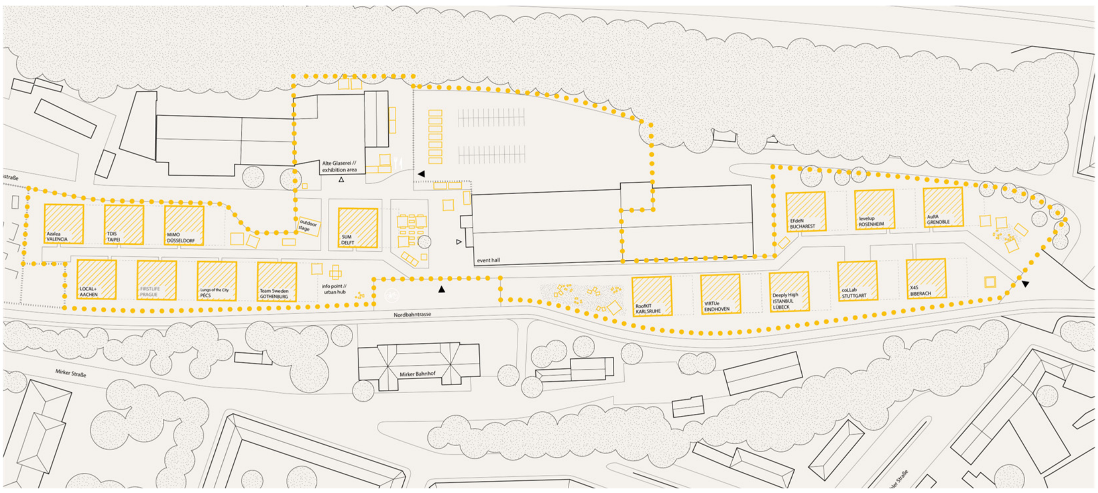

Figure 2. The Solar Campus in Wuppertal, Germany, contains building plots for 16 HDUs [38].

Although the competition's design challenge primarily focussed on minimising operational carbon, participating teams were also tasked with exploring ways to achieve a climate-neutral building stock. The build challenge required teams to design prefabricated building systems, assemble their HDU at a site in their home country, disassemble it, and finally transport and reassemble it within two weeks at the Solar Campus. The integration of DfD, IC, and circularity are therefore integral to the competition, making it a unique opportunity to demonstrate how permanent housing—as opposed to temporary or emergency housing—can be designed so that its constituent parts can be systematically removed without causing damage to the connecting parts. In practice this would facilitate replacements, reuse and building adaptations during a period of several decades and eventually preventing demolition at the EoL phase, but the competition condensed such activities into a matter of weeks.

The competition is based on ten contests that strive to cover all issues related to dwelling in the immediate future, calling for a response to a range of environmental and social aspects in addition to energy efficiency [39]. Housing designs are restricted in terms of building area, being required to fit within a Solar Envelope (Figure 3): a truncated pyramid with a base of 18 m × 18 m that narrows to a 10 m × 10 m area limited to 7 m in height. The maximum permitted building footprint was 70 m^2 for a single-storey building or 110 m^2 for two storeys [39]. A designated operations area was provided directly beside the Solar Envelope within each building plot on the Solar Campus.

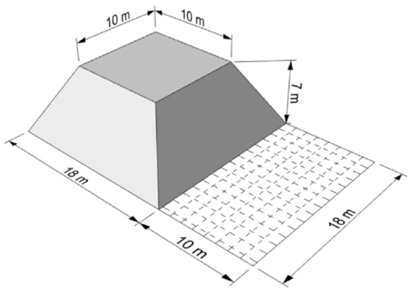

Figure 3. The Solar Envelope dictates the competition's spatial constraints in three dimensions [39].

Competing teams comprising undergraduate and masters' students were supported by supervising faculty staff; some teams had additional support from university research groups. The competition encourages teams to gain sponsorship from industry partners such as product suppliers and contractors. The students acquire valuable knowledge and experience in DfD and industrialised methods throughout the competition, while collaborating industry practitioners, companies, and local councils have the opportunity to test novel products for climate-resilient and socially responsible building systems.

The theme underpinning SDE-2022 was *SDE Goes Urban!*, calling for teams to respond with one of three urban situations: a horizontal extension, an additional storey (top-up), or an infill solution aimed at 'closing the gaps'. The theme therefore echoed the need for sustainable, highly energy-efficient solutions dealing with both new-build and existing building stock. Sixteen teams hailing from Czechia, France, Germany, Hungary, the Netherlands, Romania, Spain, Sweden, Taiwan, and Turkey took part in the build challenge. Ten teams responded with top-ups, four with closing the gaps, and one with a horizontal extension (Table 1) [25]. The winner of SDE-2022 was team RoofKIT from Germany [40], second place was awarded to team VIRTUe from the Netherlands, followed by teams SUM and AuRA in joint third place from the Netherlands and France, respectively. Table 1 is organised in order of points awarded. FIRST LIFE from Czechia is not included in this study as the team was unavailable for interview.

Table 1. Overview of the fifteen teams interviewed at SDE-2022 [41].

#	Team	Urban Situation	Prefabrication Methods			
			3D Modules	**Internal Pods**	**2D Panels**	**Framing System**
1	RoofKIT	Additional storey	√			
2	VIRTUe	Additional storey		√	√	√
3	SUM	Additional storey	√		√	
4	AuRA	Horizontal extension	√		√	
5	MIMO	Additional storey		√	√	
6	LOCAL+	Closing the gaps	√	√		
7	levelup	Additional storey	√	√		
8	Azalea	Closing the gaps		√	√	√
9	coLLab	Additional storey		√	√	√
10	EFdeN	Additional storey		√	√	√
11	TDIS	Closing the gaps		√	√	√
12	X4S	Additional storey		√	√	
13	Deeply High	Additional storey	√		√	√
14	Lungs of the City	Closing the gaps		√	√	√
15	Team Sweden	Additional storey		√	√	√

[1] Karlsruhe Institute of Technology, Germany. [2] Eindhoven University of Technology, the Netherlands. [3] Delft University of Technology, the Netherlands. [4] Grenoble School of Architecture, France. [5] Düsseldorf University of Applied Sciences, Germany. [6] Aachen University of Applied Sciences, Germany. [7] Rosenheim Technical University of Applied Sciences, Germany. [8] Polytechnic University of Valencia, Spain. [9] University of Applied Sciences Stuttgart, Germany. [10] Ion Mincu, University of Architecture & Urbanism Bucharest, Romania. [11] National Yang Ming Chiao Tung University, Taiwan. [12] Biberach University of Applied Sciences, Germany. [13] Istanbul Technical University, Turkey and the Technical University of Applied Sciences Lübeck, Germany. [14] University of Pécs, Hungary. [15] Chalmers University of Technology, Sweden. √ Indicates the prefabrication methods used by each team.

1.2. Industrialised Construction Aspects

The competition mirrors trends in industrialised, dry, and lightweight construction, requiring teams to assemble their builds at the competition site within an extremely short time-period. Each competing team demonstrated varying aspects and degrees of industrialised construction. Prefabrication is a prerequisite of the competition, as the HDUs must be pre-built before being transported to the Solar Campus and constructed within the stipulated 14 days [25]. Most teams used a hybrid of prefabricated methods that included structural 3D volumetric construction, in addition to non-structural 3D internal pods (used for modular technical/plant rooms, bathrooms, and kitchens), 2D panelling, and framing systems (Table 1). Three teams produced their HDUs under factory-controlled conditions using the facilities of partnering off-site housing construction companies. These included teams SUM, coLLab, and RoofKIT, who partnered with off-site construction companies from the Netherlands, Germany, and Austria, respectively. Another key element of industrialised construction demonstrated by the teams included digitalisation. Each team was required to use Building Information Modelling (BIM) and submit a complete model of their HDU prior to participating in the build challenge, which were utilised to carry out environmental simulations and assessments.

1.3. Circular Construction Aspects

Circular construction was integrated both in terms of the environmentally conscious design and economic viability of the HDUs and the concepts underpinning them. Contests of note within the competition in this regard are ‘Sustainability’ and ‘Affordability and Viability’. Although the innovative one-off prototype homes are built at considerable cost, the affordability contest assesses the market viability and integration of the concepts into social housing policies, encouraging teams to consider real-world application, scalability, and sensitivity to gentrification. Resource efficiency and disassembly are embedded in the criteria for the 'Architecture' and 'Engineering and Construction' contests within SDE-2022, for example, the use of local resources and optimisation for assembly and disassembly. The 'Sustainability' contest was updated for the SDE-2022 edition to integrate a lifecycle approach to housing with the inclusion of two sub-contests, 'Circularity' and 'Sufficiency, Flexibility and Environmental Sustainability'. A mandatory lifecycle assessment (LCA) promoted a quantitative and whole-lifecycle approach that encouraged the inclusion of bio-based and reused building materials. In addition to the LCA, each team was required to calculate the Urban Mining Index (UMI) for their HDU. The UMI is an assessment method developed at the University of Wuppertal to quantify the reuse and disassembly potential of a building, which also considers the economic viability of reuse scenarios [39,42]. Overall, the SDE-2022 teams are considered to have demonstrated exceptional innovation and sensitivity to circularity and the closing of material loops in comparison to previous editions of the competition [25].

2. Materials and Methods

This study is based on the analysis of primary data collected from interviews with university team members from various disciplines who took part in the SDE-2022 competition, who possessed technical expertise and experience in circular industrialised housing. This was supported by on-site observations of disassembly, assembly, and reassembly. The methodology consists of five main steps, illustrated in Figure 4, aiming to provide results with relevant implications for industry practitioners and policymakers, which are described in the Discussion section. The analysis employed a semi-inductive approach, using a predefined outline framework to deductively organise and relate the interview data to processes and overarching factors. This was followed by an inductive process to identify emerging themes and sub-themes, which were subsequently categorised as either barriers or enablers. This layered analysis approach allows for the identification of the most critical barriers, enablers, and sub-themes within each process.

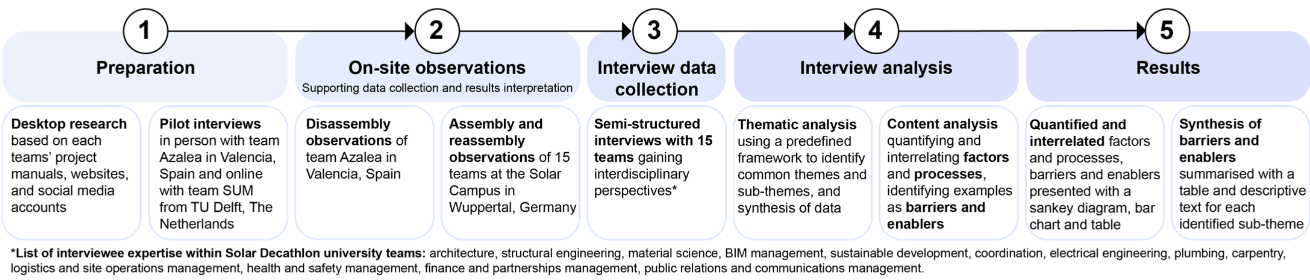

Figure 4. Overview of methodology composed of five main steps.

2.1. Preparation

Detailed information about each team's HDU was studied by the authors prior to attending the assembly period at the competition's Solar Campus. This included mandatory project manuals submitted by each team and uploaded to the Solar Decathlon's open-source Knowledge Platform [43], while the teams' websites and social media accounts provided the latest developments with video and photographic information. Interview questions were piloted with two teams prior to visiting the Solar Campus in Wuppertal to test and refine the questions. This pilot testing was conducted in-person with several members of team Azalea from the Technical University of Valencia (UPV) in Spain in early May 2022. A second pilot interview was conducted online with a member of TU Delft's team SUM in the Netherlands later the same month.

2.2. On-Site Observations

First-hand observations during the disassembly (shortly before the competition with team Azalea) and midway through the assembly period for all fifteen teams at the Solar Campus in Wuppertal strengthened the authors' understanding of the teams' experiences [44]. This enhanced their ability to ask pertinent follow-up questions and improved the later interpretation of the data. The development of the predefined interview questions was further informed by in-person observations and conversations with team Azalea in Spain over a period of two weeks during the disassembly of their HDU. This occurred shortly after their inauguration event at the UPV campus and before attending the competition in Wuppertal.

Subsequently attending the competition midway through the two-week assembly period in Wuppertal ensured that the HDUs would be partially constructed, exposing the building layers [45]. This meant that observations of the interfaces between the façade, structure, building services, and internal elements would be possible, facilitating well-informed follow-up questions to be addressed to all teams. Both the exteriors and interiors of all fifteen HDUs were visually inspected together with the interviewee(s) either shortly before or after the interview. Further information was gathered from informal conversations with various teams during work breaks. Photographs documented the disassembly and reassembly processes, with particular attention given to connections and materials (Figure 5).

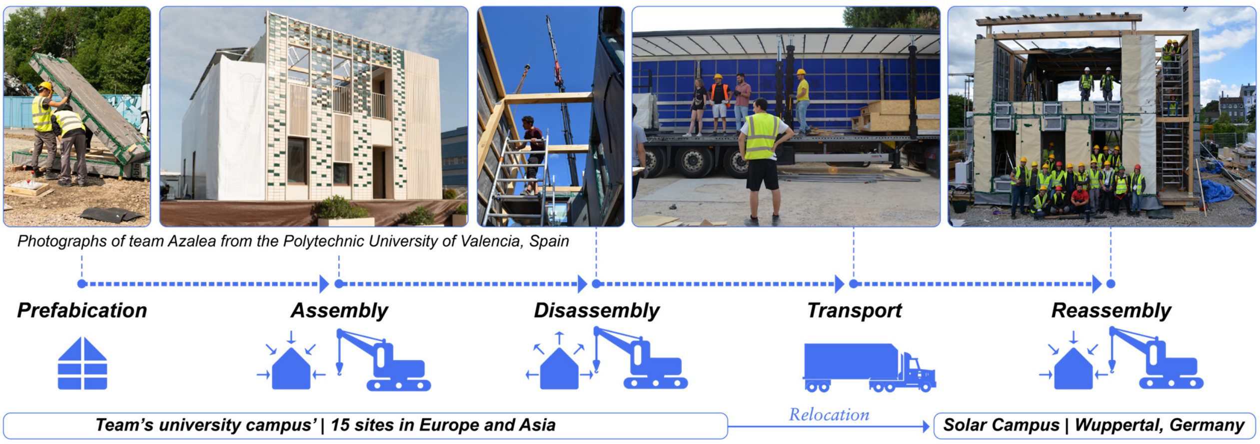

Figure 5. Build challenge overview—interviews supported by on-site observations (source: primary author. Note: The two left-most photographs are courtesy of team Azalea's social media).

2.3. Interview Data Collection

Semi-structured interviews were used to gain insights across the building lifecycle, drawing upon the interviewees' experiences during the pre-construction, assembly, disassembly, transport, and reassembly phases, and were carried out with fifteen teams hailing from nine countries. Twenty interview questions were prepared to guide the discussion towards aspects such as design, sustainability, affordability, and collaboration with industry experts. Where appropriate, follow-up questions were asked to provide additional depth and insights. A minimum of one interviewee per team was required, and where possible, several teammates participated in a group interview to provide diverse perspectives across disciplines.

The interdisciplinary university teams included students and professors from the fields of architecture, structural engineering, building services engineering, project management, and BIM management, in addition to members trained in energy simulations, LCA, costing, and communication management (e.g., marketing and social media). This diversity allowed for multiple 'stakeholders' to contribute insights, offering a holistic overview of IC and DfD successes and challenges in circular housing applications. A list of the interviewees' expertise is included in Figure 4. Although largely consisting of university students, the team members learned valuable lessons in circular industrialised housing, having delivered fully functioning homes in collaboration with industry partners. These homes aligned with local building codes from their respective countries while meeting and exceeding the latest sustainability practices.

Interviewees were selected based on their technical understanding of the project; participants with in-depth involvement from the start of the project since 2021, such as student team leaders, were particularly desirable. A total of 3.5 days at the Solar Campus was deemed sufficient to make observations and conduct the interviews, which were anticipated to last approximately one hour.

2.4. Interview Analysis

A predefined analysis framework was used to categorise and interrelate the factors presenting opportunities and challenges to circular and industrialised housing among key processes throughout the whole building lifecycle. Figure 6 illustrates the six holistic factors (left) and four lifecycle processes (right) defining the framework. This was developed based on the findings from a previous systematic literature review conducted by the authors [33].

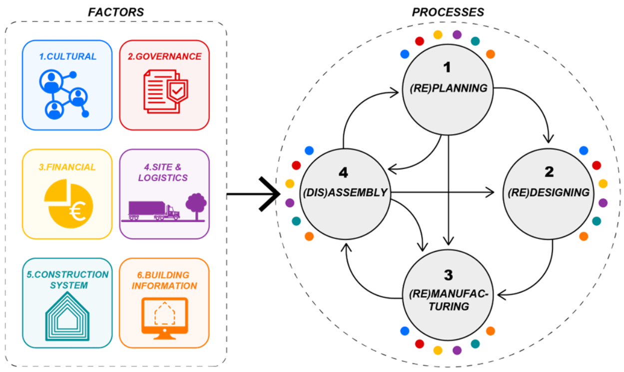

Figure 6. Analysis method based on defined factors and building processes (source: primary author).

The study identified six broad factors, which were integrated into the framework to analyse the interview data. These were Cultural, Governance, Financial, Site and Logistics, Construction System, and the Building Information. The four processes, which are based on the European Norm and methodology for LCA and the RIBA *Plan of Work* [46,47], relate to all activities occurring, or re-occurring, throughout the building lifecycle, resulting in the physical alteration of the building.

The four processes are defined as follows:

1. **(Re)planning:** Informs the project brief and feasibility, typically occurring before a design team is appointed and largely consists of non-spatial information.
2. **(Re)designing:** The development of the conceptual and technical design of the building to produce geometric and material information.
3. **(Re)manufacturing:** The production of building materials and components, which typically takes place in a factory when utilising industrialised construction.
4. **(Dis)assembly:** Putting together/taking apart of building components and materials, which typically takes place on-site, including the transportation of parts to/from the site.

Crucially, these processes may (re)occur in varying sequences throughout the building lifecycle and during transitions to different End-of-Life scenarios. The processes within the framework are applicable to the creation or modification of housing, which includes new construction, renovations, maintenance, additions or adaptations, deconstruction, or relocation. This is indicated by the arrows illustrated between the processes on the right-hand side of Figure 6.

This Solar Decathlon study therefore contributes valuable primary data towards the continued development of the circular process framework, which aims to support stakeholders involved in the delivery of circular industrialised housing throughout the building lifecycle.

The analysis followed a semi-inductive approach, categorising emergent themes and sub-themes within the framework's factors based on the interview transcripts. This was achieved using thematic analysis; themes and sub-themes were revised iteratively until saturation was reached, whereby suitable and meaningful descriptions were defined [48]. The synthesis of the successes and challenges experienced by the fifteen teams was structured around the factors and the emergent themes and sub-themes to provide contextualised examples. A content analysis was employed to quantify the interview data according to the predefined factors and processes. This allowed for the identification of relationships between factors and processes and hot-spotting of barriers and enablers amongst the sub-themes, as well as an overview of trends, gaps, and missing information. Each excerpt was coded with four categories: factor, sub-theme, process, and whether it represented a barrier or enabler. In some cases, excerpts were coded as both a barrier and an enabler, reflecting the complexity of the data. Coding was performed using Atlas.ti software version 23.1.1.

3. Results

Interviews were conducted on site between 25 and 28 May 2022, except for two interviews conducted online after the competition due to time constraints. The primary author spoke to all teams on site and visited all fifteen HDUs, including tours of the interiors. Interviewees were from different fields and included both students and professors; most interviewees were student team members. Between one and three people were interviewed per team, totalling twenty-five participants. The interview length ranged from 50 min to 2 h. Approximately one-third of the teams had previously assembled their HDUs, one-third had partially assembled, and a third had not previously assembled their HDU in their home country. Irrespective of previous assembly experience, all teams contributed highly insightful information encompassing all circular processes.

3.1. Content Analysis—Relationship Between Processes and Factors

Following the interview data collection approach detailed in Section 2.3, semi-structured interviews were conducted on site using 20 pre-determined questions. Full transcripts of the interviews were subsequently analysed and coded through a thematic analysis, incorporating predefined factors as well as emerging themes and sub-themes, as outlined in Section 2.4. Additionally, transcript excerpts were assigned codes corresponding to one of four circular processes and categorised as barriers, enablers, or both. A content analysis was employed to quantify the frequency of the assigned codes, thereby identifying which sub-themes and related processes presented the most significant barriers or enablers.

The results of the coding exercise and quantitative frequency analysis, illustrated in Figure 7, show the relationship between the factors (left) and the circular processes (right) within the interview data. Barriers and enablers were most frequently related to the (re)designing process, accounting for 44%, followed by (dis)assembly at 27%; (re)manufacturing accounted for 17%, and (re)planning processes were the least frequently related at 12%.

The interview data were most frequently related to the Construction System across all four processes (33%). Cultural factors (29%) were almost equally as critical according to the decathletes. As illustrated by the breakdown included on the right-hand side of Figure 4, Cultural factors were the most influential aspect experienced by the teams in SDE-2022 for both the (re)designing (38%) and (re)planning processes (41%).

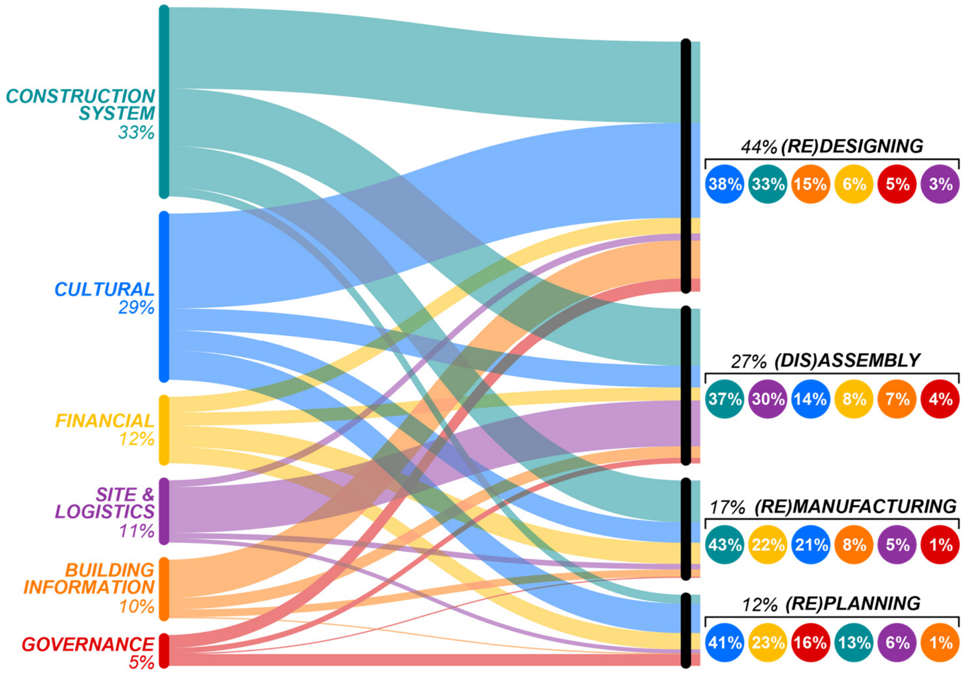

Figure 7. Content analysis results illustrating the quantity and relationship of data related to factors (**left**) and processes (**right**) (source: primary author).

3.2. Emergent Sub-Themes and Identification of Barriers and Enablers

A thematic analysis of the interview data yielded 14 common themes and 39 sub-themes within each of the 6 predefined factors, described in Table 2.

Table 2. Emergent sub-themes within each factor category (source: primary author).

Factor	Theme	Sub-Theme	Description
Cultural	(1A) Knowledge	Education Collaboration Skills and Experience Project Management	Institutional knowledge and support Knowledge generation through co-creation Expertise and previous experience Organisation of team and tasks
	(1B) Values	Cultural Norms Priorities	Currently accepted practices Conflicting aims and trade-offs
Governance	(2A) Regulation	Competition Rules Land Regulations Building Regulations Site Regulations	Design and construction constraints Restrictions for land use Design and performance restrictions or requirements Restrictions for site operations
	(2B) Policy Initiatives	Government Partnerships Policy Creation	Founding partnerships with local housing authorities Impact through policy creation
	(2C) Legal	Ownership	Building and product owners
Financial	(3A) Building Costs	Material Costs Labour Costs Transport Costs Factory Costs	Building materials costs Design and construction labour costs Costs to transport building elements to site Factory set-up and production costs
	(3B) Business Models	Circular Business Models Funding Housing Models	Whole lifecycle approach to financing Obtaining financing from partners and sponsors Financial plan shaping access for residents

Table 2. *Cont.*

Factor	Theme	Sub-Theme	Description
Site and Logistics	(4A) Logistics	Transport Constraints Supply Chains Site Operations	Restrictions caused by vehicle type and infrastructure Delivery of materials and building parts Lifting and handling of building elements
	(4B) Site Conditions	Storage Space Ground Conditions Weather	Material storage either on or off site Coordination between site and construction system Impacting weather or climatic conditions
Construction System	(5A) Design	Theoretical Design Technical Design Materiality Connections	Design concepts informing spatial design Technical design and construction information Type of building materials used Connection at the product level
	(5B) Production	Supporting Equipment Industrialised Approach Supplier Products	Specialist machinery used off and on site Building in parts such as components or 3D modules Products provided by external companies
	(5C) Building Performance	Testing Energy Strategies	Previous testing of assembly performance Passive and low in-use demand for energy
Building Information	(6A) Data Storage	Digitalisation Information Type	Digitalisation of building information Detailed material and building information
	(6B) Data Analysis	Assessments and Simulations Strategic Delivery	Quantified environmental and financial impacts Strategic dismantling and logistics planning

Themes are coded with a number and letter in brackets to distinguish and organise the synthesis of sub-themes, as described in Section 3.3.

Figure 8 presents a bar chart illustrating the relationships between coded factors and processes, categorised as either barriers or enablers. Overall, more enablers (449) were mentioned than barriers (407). Barriers were most concentrated in Cultural factors during the (re)designing process, followed by Site and Logistics factors during the (dis)assembly process. Enablers were most frequently associated with Construction System factors, particularly in the (re)designing, (re)manufacturing, and (dis)assembly processes. Detailed information on the results, including a breakdown of the barriers and enablers for each sub-theme and lifecycle process, is provided in the Supplementary Information.

Table 3 outlines the most frequently mentioned barriers and enablers across the four stages of the circular building process, classified according to the established sub-themes. Barriers primarily relate to Cultural factors, particularly ‘Skills and Experience’ and ‘Cultural Norms’. In contrast, enablers are mainly associated with Construction System factors, such as ‘Theoretical Design’ and ‘Industrialised Approach’, alongside Cultural factors, particularly ‘Skills and Experience’.

Table 3. Frequently mentioned sub-themes identified as either barriers or enablers across the lifecycle processes.

Process	Barriers	Enablers
(Re)planning	• **Education:** Lack of support from university/course integration • **Project Management:** Lack of communication • **Cultural Norms:** Tension with economic development and profit	• **Cultural Norms:** SDE itself creating positive change • **Housing Models:** Concept integrates CE and affordable rent • **Theoretical Design:** Top-up system adapts to different contexts
(Re)designing	• **Cultural Norms:** Lack of applied research into DfD CE theory • **Skills and Experience:** Lack of interdisciplinary experience • **Digitalisation:** Lack of BIM strategy and common software	• **Theoretical Design:** Strategic layering design approach • **Collaboration:** Frequent development with industry partners • **Skills and Experience:** Previous disassembly/prefab experience

Table 3. *Cont.*

Process	Barriers	Enablers
(Re)manufacturing	• **Material Costs:** Expensive and fluctuating material prices • **Supporting Equipment:** Intricate design requires manual work • **Skills and Experience:** Industry partners unfamiliar with DfD	• **Materiality:** Reused (and recycled) local materials • **Supporting Equipment:** Factory-precise construction • **Industrialised Approach:** Prefabricating all parts and interfaces
(Dis)assembly	• **Transport Constraints:** Working to vehicle constraints • **Connections:** Waterproofing and airtightness issues • **Weather:** Unexpected adverse rain and wind conditions	• **Connections:** Simple, reversible, and fewer joints • **Industrialised Approach:** Pre-equipped large 3D modules • **Skills and Experience:** Preassembly experience of the system

Colours represent the six factors: Cultural (blue), Governance (red), Financial (yellow), Site and Logistics (purple), Construction System (green), Building Information (orange).

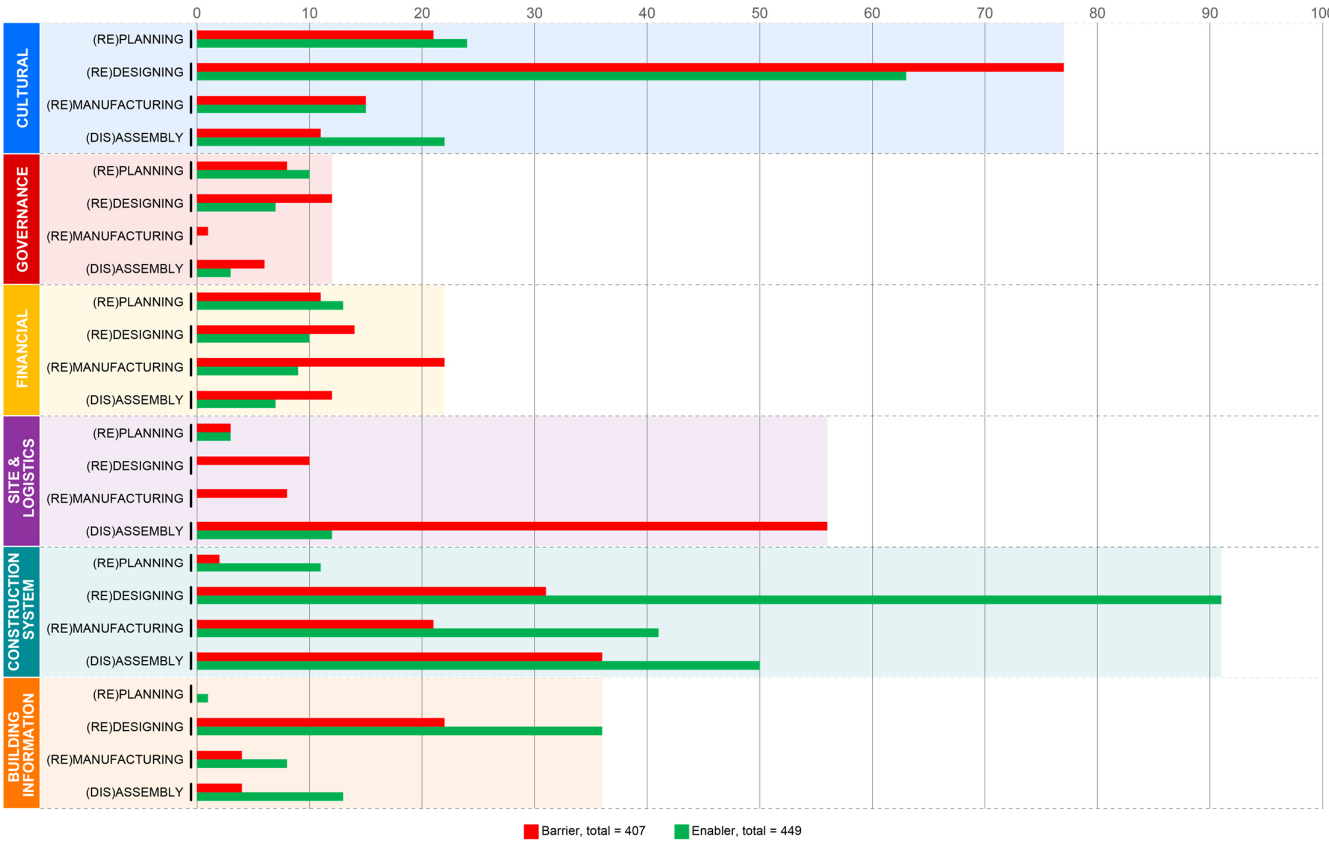

Figure 8. Bar chart—frequently analysis of barriers and enablers breakdown across factors and processes.

3.3. Synthesis of Experiences per Sub-Theme

In the following sub-sections, a synthesis of the barriers and enablers identified by the interviewees provide examples of all sub-themes described. These sub-themes, shown in bold, underlined text, are organised in the same order as Table 3 and grouped according to the relevant factor and theme.

3.3.1. Cultural

1A Knowledge

Education: Whether the teams put circularity at the heart of their concept and integrated disassembly practices early on was dependent on the teaching culture at their home university. Architecture students were particularly critical of current traditional education, which, according to whom did not sufficiently prepare them for the Solar Decathlon, which requires a sophisticated response in a range of contest areas. Teams that had the competition integrated within their curriculum and had an existing culture of cross-departmental teaching were at an advantage both in terms of human resources and time. University culture influenced disassembly research approaches and the choice of information sources. Most teams relied on trial and error, advice from professors, and external experts. The winning team RoofKIT relied more on literature resources, such as the *Manual of Recycling*, authored by researchers from the University of Wuppertal who were also involved in the competition's circularity tool UMI [49].

Collaboration: Interdisciplinarity within teams was crucial. Teams composed of students specialising in Mechanical Electrical and Plumbing (MEP) systems, structural engineering, and sustainability, rather than being heavily architecture-led, had fewer design and delivery issues from the outset. For example, teams levelup and EFdeN benefitted from early cross-collaboration with technical schools where students generally had greater construction expertise in these areas. While being part of an international team was largely positive, language proved to be a barrier in some cases, hindering communication. Cross-border collaboration was denoted as both the greatest strength and barrier for team Deeply High, who uniquely consisted of both German and Turkish universities. Interdisciplinary group problem solving was vital during the design phase and was actively promoted by teams EFdeN and coLLab. Teams Deeply High and Azalea highlighted the close relationship developed with the crane operators, tapping into their wealth of experience to resolve critical assembly issues together on site, although earlier input during the design/manufacturing processes would have prevented assembly issues.

Skills and Experience: Teams greatly benefitted from circular construction experience in previous Solar Decathlon competitions. Contractors from industry provided a wealth of relevant expertise, particularly those specialising in timber construction. Teams TDIS and RoofKIT benefitted from previous experience in Solar Decathlon competitions and research projects with the same contractors, therefore building upon shared experience. Azalea's issues coordinating the construction system with the foundations highlighted the overall lack of industry professionals skilled in disassembly and dry construction, who require less precision when working with more common concrete and masonry structures. Although BIM was a competition requirement, the interviewees expressed a digital literacy skills gap among both students and industry collaborators, who were generally unfamiliar with software such as Revit. Deeply High disclosed that younger students within their team possessing experience in companies have valuable applied digital skills, which is closing this gap. Product suppliers who were conscious of circularity and disassembly were an invaluable resource according to LOCAL+. External industry experts were also necessary for most teams to complete the assembly, who were involved in areas such as roofing, drainage, and electrical systems.

Project Management: Team continuity was an issue for numerous teams, although there were usually core members from the project outset, some experienced a large loss of members, significantly impacting the development of the design concept and the commitment to circularity. The COVID-19 pandemic further negatively impacted team member commitment and internal communication. Effective management strategies were allocating specific tasks to individuals, ensuring all members understood the interface between their scope with others, and developing the project together with industry experts with regular, interdisciplinary meetings.

1B Values

Cultural Norms: Despite a general awareness of circular building and disassembly theories such as building in 'layers', particularly among architecture students, it was not intentionally applied to the HDUs in several cases. Most teams used common-sense approaches such as ‘Learning-by-Doing’ and ’Research-through-Design’, but interviewees agreed that circularity would have been improved if it had been researched beforehand. Traditional construction companies struggled to adapt to the disassembly concept, unlike those specialising in prefabrication. Many teams acknowledged a cultural rejection of structural timber, both by governmental institutions and industry. This meant few off-site factories were set up for timber construction. Students collaborating with contractors had to overcome an industry culture of addressing unresolved problems on site rather than “on paper”, thus hindering precision manufacturing. Interviewees emphasised the cultural shifts required of architects; teams AuRA and EFdeN struggled to reconcile the traditional context-based architectural approach to one that is industrialised, while RoofKIT suggested architects must also be flexible and open to last-minute changes to incorporate Urban Mining and reuse. Regarding end users (residents), team LOCAL+ and their industry partners questioned the acceptance of safety for visible connections to facilitate future disassembly, which might be tampered with, particularly building services. Overall, the teams found SDE-2022 supported a positive change in cultural norms with several teams reporting that contractors and product suppliers were seeking out more circularity applications as a result.

Priorities: Several teams cited the prioritisation of building aesthetics over building execution and performance. In one case, this resulted in a whole project redesign. This prevented preassembly before attending the competition site and thus represents a missed opportunity to gain additional experience. LOCAL+ found that basing their concept on the architecture complicated the achievement of their affordability and sustainability goals and advised centring the concept around critical questions such as “What’s the target group? What’s the budget? What do you want to achieve?”.

3.3.2. Governance

2A Regulation

Competition Rules: Solar Decathlon imposes competition-specific rules during both the design and build phases. For example, prior to assembly, a BIM model and logistics plan must be submitted. Such rules are considered positive for improving skills while reinforcing industry trends towards industrialisation. Constraints such as health and safety rules and restrictions for deliveries that requires teams to book time slots also reflect real-world conditions. However, numerous teams found some rules onerous or unrealistic. Teams also found it particularly difficult to adapt to rule changes once the design process had begun; this included updates to the BIM guidelines and the boundaries of the Solar Envelope. Such changes are commonplace in industry but have a greater knock-on effect for IC systems. The predefined positioning of the Solar Envelopes on site affected how the HDUs could be orientated, highlighting the importance for circular industrialised housing to factor adaptations to planning boundaries in different contexts. Although the competition encouraged a holistic and lifecycle design response through varied contests, several teams revealed that they had focussed most on the *Architecture* contest rather than championing circularity. This was later evidenced by the competition results where the highest points were awarded within the Architecture contest across the competition [41].

Land Regulations: Disassembly was an integral solution for vacant or underutilised infill sites specific to Taiwanese urban renewal strategies, providing a key opportunity to prove that circular concepts can also be integrated into medium-term housing solutions. Land regulation dictates material availability and construction expertise; as Taiwanese forests are protected, there is, therefore, no mass timber industry, which is instead imported from the EU, Canada, and Japan.

Building Regulations: The teams considered adapting their building systems to meet regulations in different European contexts. This proved more difficult in regions with significantly different climatic conditions; TDIS's HDU was earthquake-resistant as per Taiwanese regulations. However, overengineering to meet these regulations required more materials than would be necessary in most European contexts. Team LOCAL+ highlighted strict local German design codes, requiring adaptations to the local vernacular and performance criteria. EFdeN commented on further complexities arising from conflicting building regulations at the local and national levels in Romania.

Site Regulations: The competition imposed strict health and safety rules and penalties such as time-outs or deducted points for non-compliance. These measures were more difficult to adhere to for teams for whom this is less strictly regulated in their home countries, causing further delays during (re)assembly. Site inspections were difficult to coordinate during the two-week assembly, which was significantly faster for teams using 3D volumetric construction; in such cases, documenting all site processes with photos was a necessary compromise.

2B Policy Initiatives

Government Partnerships: Several universities were in conversation with local authorities to apply the prototype solutions to social housing initiatives locally. The Swedish local authorities even demonstrated openness to using the novel bio-based 3D printing technology.

Policy Creation: The competition creates significant publicity for the teams, particularly through the awarding of contest prizes. TDIS had previously leveraged this to co-create a national policy in Taiwan using their 2014 HDU. The SDE competition and exemplary projects are therefore a valuable platform to showcase the potential for circular industrialised construction and foster integration within policy for systems change.

2C Legal

Ownership: The project concepts considered the legal complexities inherent to realising top-up and infill solutions, which would involve multiple ownerships when handling renewal of entire housing blocks or renovation of a single building. Students raised the issue of ownership within the competition itself. In several cases there was uncertainty around the fate of the HDUs post-competition. It was speculated that responsibility ultimately deferred to Wuppertal University, who owned the Solar Campus site and would therefore need to ensure a sustainable EoL.

3.3.3. Financial

3A Building Costs

Material Costs: Material costs were higher for bio-based materials and these were more difficult to source, especially for the structure, in contrast to concrete and steel. Therefore, both the type of material and the need for additional material due to the doubling of prefabricated structural elements caused higher material costs. Teams faced price fluctuations due to supply chain issues, forcing them to either redesign at the manufacturing and disassembly stages or to pay more for the same products and materials to avoid changes. The use of novel and high-spec technical equipment is an additional affordability barrier.

Labour Costs: The teams recognised the higher labour costs associated with innovation and circular solutions, requiring longer planning and design periods and higher upfront costs. Suggestions to combat this were standardisation, 'low-tech' solutions, and greater experience to reduce labour/time costs. Construction labour intensity is another major financial barrier associated with disassembly practices. Team coLLab's efforts to be resource efficient by using their manufacturer's wood off-cut 'waste material' was time-consuming to sort and reuse, particularly when dealing with very small pieces, which cannot be handled by current machinery. In response to asking how affordability could be improved, team VIRTUe advised that the number and type of connections are key to apprehend "how many and how tough it is, because in the detail it looks easy, you know you place five bolts, but it takes me two hours". Alongside time constraints, preassembly proved too complex and therefore expensive for some teams to attempt, such as MIMO, whose climate grid would have required paying for external assistance. Some teams could not afford to bring their HDUs back after the competition despite having permissions for site relocation in place, which illustrates the pertinence of financial barriers and labour costs. One proposed solution was to sell the HDU for a token euro, thus donating Urban Mining material, with the new owner solely needing to pay for transport costs.

Transport Costs: Transport was found to be a considerable expense, especially to relocate an entire building or assemble it far from the production site, as experienced by team TDIS, who used shipping containers to transport the materials from Taiwan by air and land. This highlights that disassembly and remanufacturing should be carried out as locally as possible to make it viable, while limiting embodied transport emissions.

Factory Costs: The teams were confident that applying economies of scale to their concepts could improve affordability. Teams also discussed various barriers linked to factory production, citing high upfront costs, difficulties in changing factory set-ups, and switching to bio-based materials. Incorporating the Buildings As Material Banks (BAMBs) [21] concept was also considered necessary to make circular industrialised housing work on a large scale. Although such measures are possible using existing technologies, these changes require investors to divert from standard methods of house building, therefore opening them up to taking on more risk.

3B Business Models

Circular Business Models: The teams based their HDU concepts on a lifecycle costing approach to ensure long-term affordable rents and future material recovery benefits. The implications of lifecycle costs were generally less clear for teams compared to environmental lifecycle considerations. For example, LOCAL+'s investigation into green façades unexpectedly revealed the high long-term costs for specialist maintenance with worse environmental outcomes. Teams also applied cost-saving measures to the build challenge. Effective strategies included using locally salvaged materials and renting building products and scaffolding for the competition. However, team VIRTUe expressed caution over using Product-as-a-Service (PaaS) due to reliance on one producer in the long-term; therefore, "general" second-hand companies were considered more trustworthy compared to companies producing specialised or proprietary products. Teams MIMO and Deeply High commented on the inherent high upfront cost of the innovative and circular products and construction methods used, which go against normal practices.

Funding: A lack of finance and sponsors affected most teams' ability to deliver or gain access to professional expertise to improve circularity and construction efficiency. Investors and sponsors were of greater advantage when brought in early, although using specific products also restricted the teams. The competition in turn provided companies the opportunity to test products not yet on the market, helping to further industry innovation in the field of housing circularity while generating awareness among the general public, who were invited to the competition's opening events. The early stages of product testing also meant that some components were more fragile, such as team SUM's façade panels, which cracked during transport and handling.

Housing Models: All teams strived for realistic, affordable, and scalable concepts, though the teams acknowledged the considerable costs involved in creating a prototype of the HDUs and the use of expensive high-tech solutions. Deeply High pointed out that low-tech solutions would support the development of more affordable—and sustainable—housing solutions. Some interviewees suggested lowering specifications to improve housing affordability; however, this would prove problematic for circularity and ensuring longevity, which requires investment in high-quality materials. In terms of integrating affordability within housing models, all teams relied on the economies of scale concept to compensate for the costly design, manufacturing, and (dis)assembly processes inherent to circular construction. Several teams applied the financial benefits of alternative living arrangements, such as cooperatives and co-housing or 'cluster living' models with shared communal space to reduce costs/m^2 per person. RoofKIT's top-up factored cross-subsidisation as an anti-gentrification measure, and TDIS proposed their project as a social enterprise using rented government land and affordable rent to pay for construction costs. Teams such as LOCAL+ similarly considered leasing structures to reduce rents and setting-up of companies to realise their affordable housing concept in practice, in addition to embedding the Sharing Economy concept into resident facilities.

3.3.4. Site and Logistics

4A Logistics

Transport Constraints: The transport mode used by the teams responded to the infrastructure connecting the production sites to the Solar Campus; this constrained the type and size of appropriate vehicles and in turn impacted the sizing of prefabricated elements. Extra-large vehicles were not always available, nor possible, considering the narrow and winding streets leading to the Solar Campus in Wuppertal (Figure 1). Furthermore, police escort vehicles were not realistic and would restrict travel to weekends or night-time hours. Such constraints have considerable knock-on effects for Just-in-Time (JIT) delivery and storage. The dimensions of transport vehicles dictated the size of building parts, some of which were not tall enough to fit 3D volumetric elements required to meet building regulations for minimum floor-to-ceiling heights. Shipping containers were much more limiting according to EFDeN, who had previously used cargo ships for the Solar Decathlon competition in Dubai in 2018. To avoid damage, teams used the strategic and compact organisation of parts, bracing, and protective plastic wrapping. Despite these measures, some fragile and organic items such as clay or tiling needed space for movement to avoid cracking. Breakages and damage were more common with long elements or fragile glass parts, which were not always able to be transported vertically and with foils. Water damage occurred where plastic wrapping was perforated during handling and transport (or not well wrapped), enabling rainwater to enter during transit. Team levelup cautioned that elements made from ETFE, which had been damaged during transport and handling on site, should be built on site rather than prefabricated. Scuff marks were inevitable due to movement during transport and handling, requiring touch-ups on site. LOCAL+ cautioned bracing should be attached carefully and should not compromise waterproofing layers, as during their preparation for transport, some screws had penetrated through the foils.

Supply Chains: Shipping was comparatively high risk compared to land deliveries, which were easier to control and prevented delays. JIT deliveries were necessary for (re)assembly and students found that their main contractors had good experience in this domain. JIT did not always go to plan; misplaced orders called for make-shift solutions to meet the assembly deadline. This meant that, in some instances, parts had to be substituted with unsustainable alternatives. The restrictions on delivery slots available to the teams on the Solar Campus created additional logistical complications. Several unexpected disruptive events significantly impacted material availability and pricing during manufacturing and assembly. Students named the Ukraine war, Suez Canal blockage, and truck strikes in Spain as barriers, and advised factoring in additional buffer time to prepare for such events.

Teams such as EFdeN found put post-design that some materials or products produced too far from Bucharest could not be procured in the end.

Site Operations: Lifting caused damage to building parts where loading was not sufficiently considered. Despite using lightweight construction, timber elements and 3D modules were of too great of a weight for handling. Teams found it difficult to precisely connect heavy modules and elements that required assembly with a crane, which was much easier to achieve by hand. Smaller elements were also unexpectedly difficult to handle on site, such as LOCAL+'s insulation panels. Failures were due to using inappropriate lifting equipment and connection strategies; for several teams, using hooks at the top of modules did not provide enough support and these elements should have been lifted from below to prevent cracking.

4B Site Conditions

Storage Space: A lack of on-site storage put greater strain on JIT delivery and assembly strategies. Previous assembly strategies had to be adapted for reassembly due to comparatively limited space on the Solar Campus site. Disassembly is therefore less demanding as the order of removal is less pertinent compared to assembly and construction. In EFdeN's previous experience, a long period of storage during a prior edition of the Solar Decathlon caused moisture damage to parts, rendering them unsuitable for reuse.

Ground Conditions: Some teams visited the Solar Campus during the planning phase to better understand the context and ensure the design would be appropriate for the roads connecting to site. Although prefabrication can facilitate a reduction in project delivery time through parallel works off-site for groundworks, it is vital to ensure the foundations are precisely coordinated post-planning. Team Sweden and Azalea unfortunately needed to spend additional time rectifying the misalignment of the slab, which their design could not be adapted to, despite factoring additional tolerance in the footings. Furthermore, for the teams that had previously assembled their designs, realignment on-site was challenging, particularly affecting internal and external finishes. Local conditions regarding energy supply must also be considered to ensure appropriate building systems for different contexts. For example, levelup needed to later change their energy concept based on district heat to the absorption heat pumps of the Solar Campus, impacting their circularity strategy.

Weather: Most damage was due to wet weather during (dis)assembly rather than transport. Provisions for weather protection, such as large tarpaulins and pressure treating all structural timber with varnish or resins for waterproofing, were advised by interviewees. Teams with unfortunate timings experienced significant water damage and waterproofing issues during assembly in Wuppertal, causing additional delays and site works, requiring new solutions to rectify weather damage or replace parts. The wind also caused significant delays when assembling fragile building parts for teams such as coLLab who needed to assemble an intricate lightweight PVC grid façade.

3.3.5. Construction System

5A Design

Theoretical Design: Teams applied circular design theories such as standardisation, building in 'layers', component and layer lifespans, Urban Mining, flexibility, and adaptability measures, considering future maintenance and repair or reuse. For example, team levelup ensured all electrical and plumbing was accessible and replaceable from both the building interior and the exterior of the façade. Teams applying these concepts from the early stages were generally more confident during (dis)assembly. Most teams targeted a common building typology for retrofit to enhance scalability, such as team SUM's solution for post-war tenement flats. Levelup highlighted that centring the design around a high degree of standardisation and large 3D modules poses a danger to design quality and can result in monolithic cities if mass produced.

Technical Design: Circular and industrialised strategies required more materials, not only due to the doubling of modular structural elements, as some parts were also oversized to improve rigidity for precise alignment on site, and for robustness to avoid damage during lifting, transport, and storage periods. To improve rigidity, avoid damage, and ease assembly, EFdeN suggested using either Cross-Laminated Timber (CLT) for larger elements due to its larger mass, or a greater number of small modules. Circular construction can seem counter intuitive to resource efficiency goals as the technical requirements rely on using more materials, as expressed by AUrA who said that "this is one thing that we can say about assembly and disassembly, sometimes it needs more materials than would be needed to just build in a more conventional way". It is therefore necessary to strike a balance between using a lean design where possible and ensuring sustainable EoL scenarios are seen through. The technical design must be 100% resolved before assembly to prevent delays and issues on site, as experienced by several teams. Teams MIMO and EFdeN reflected that avoiding complex details improves the circularity potential and increases the likelihood of future (dis)assembly for replacements or adaptations. Teams found that translating circular design theory to technical design can require complex and unique details, such as the separation of the 'Skin' (building envelope) or 'Services' layers. SUM relied on collaboration with an off-site construction industry partner to resolve the details of a separate Skin and Structure layer around the building openings, which if designed incorrectly would compromise the building's performance. Levelup's separation of the technical/plant room from the exterior created further complexities, requiring more perforations within the building envelope, which increased the risk of air and water leakage. Regarding the technical integration with existing buildings, EFdeN found it challenging to design standardised modules and parts to align with the existing irregular geometry for their top-up solution for the existing Café Ada.

Materiality: All teams used a high degree of bio-based materials such as clay, cellulose, and timber to score well in the environmental sustainability criteria. All HDUs used timber for the primary structure, although it was generally not a locally available material for teams outside of northern Europe. Teams incorporated reused materials and products, such as salvaged windows and timber for both structural and non-structural elements. A range of recycled materials were integrated but these were generally sourced from commercial product suppliers. Teams were conscious of using local, salvaged, and recycled materials, such as Lungs of the City's recycled aluminium railings, which were made by a small, local Hungarian company. LOCAL+ used gravel as a building material on site to rebuild parts damaged from rain, and Deeply High salvaged waste materials from other teams to fit-out their rooftop garden.

Connections: Various effective reversible connections included tape, plates, bolts, screws, gravity joints with pin connectors, plug-and-play connectors for building services, carpentry joints, and overlapping or layered joints, to name a few. According to EFdeN, assembling the connections proved most challenging where the geometry was complex, requiring various fixings to be joined simultaneously. All teams avoided nails and rivets while some teams such as VIRTUe, RoofKIT, X4S, and others strictly avoided foam, glues, and adhesives. However, using some adhesive for waterproofing roofs was unavoidable. Teams SUM and VIRTUe used reversible adhesives that could be detached with either heat or alcohol, though assembling the roofing was still a complex task. Several teams commented on the difficulty connecting and waterproofing the external envelope's roof and façade rather than air-tightness issues. According to teams levelup and EFdEN, the building services were the most difficult aspect to connect. In particular, water pipes were deemed more complex compared to electrical cabling as they are connected and accessed less frequently.

5B Production

Industrialised Approach: Teams prefabricated as much as possible using 3D and 2D approaches, usually in a hybrid mode with components, pods, and framing systems (Table 1). Although using smaller parts increased flexibility, it increased assembly time due to the greater number of parts and made waterproofing and airtightness more onerous, as students needed to close more junctions on site. Students stressed that any building parts not prefabricated will need to be attached on site, leading to compounded problems and unpredictable solutions, ultimately comprising the circularity of the construction system. According to the experience of LOCAL+, non-rigid elements such as insulation were not suitable for prefabrication, which the team needed to remove and re-do on site. In contrast, the prefabrication of rigid elements such as windows and doors was advantageous. Teams coLLab and levelup commented that while the prefabrication of their façades was advantageous, manufacturing was highly time consuming, and the design should be simplified for mass production. Teams typically reserved wet finishes, such as grouting, to be carried out on site rather than prefabricating them to avoid damage. Post-preassembly, the industrialised approach was different as not all parts were disassembled for the second assembly.

Supporting Equipment: Constructing building parts made from timber was relatively easy for students to work with using university facilities, whereas metalwork required external companies with more specialist or heavy-duty equipment. The teams collaborating with off-site manufacturers had a great advantage due to their factory facilities and precision manufacturing capabilities, expertise, and weather protection during prefabrication, all of which ultimately aided assembly. A lack of storage facilities during manufacturing at the students' home universities constrained teams such as Azalea's prefabrication strategies, forcing them to use smaller components rather than 3D modules. Teams Sweden and levelup experimented with 3D printing/digital fabrication, although Team Sweden had major issues due to being unable to acquire the printing nozzle in time.

Supplier Products: There are various circular-friendly and cradle-to-cradle-approved products on the market designed for multiple use cycles, and many teams used products from suppliers specialising in circular timber construction solutions. Although numerous novel sustainable products are commercially available, team X4S warned it was difficult to ensure social sustainability was embedded in their production and that some products marketed as 'recycled' were in fact produced from virgin materials. LOCAL+ found the design process was "not clear enough" to use Urban Mining products from emerging reuse distributer companies. The teams would have benefitted from a greater choice of market-available disassembly friendly connection products, as most teams needed to create bespoke connections. In EFDeN's case, an off-the-shelf product intended for other uses failed when applied to connections.

5C Building Performance

Testing: Teams that had previously assembled their designs in their home countries benefitted from experience in (dis)assembly and were able to test buildability. However, each (dis)assembly risked breakage during lifting. Teams that had prefabricated their designs using more manual methods rather than utilising support from factories lacked precise dimensioning, causing alignment issues during assembly and reassembly. In fact, teams that had preassembled their designs without factory precision were at a disadvantage compared to the teams that were assembling their buildings for the first time, as their HDUs required greater corrective alignment works on site. Deeply High noted their partial preassembly in protected factory conditions was "easy" but did not fully prepare them for the assembly on site, where wind and rain created unexpected issues. Team levelup tested the energy performance during assembly to ensure airtightness with their own air pressure testing kit, prior to the competition's mandatory blower door test. Teams generally did not have the time nor the means to conduct extensive testing of building performance beforehand, which, in practice, should be invested in to speed up the continuous improvement of building systems. Further waterproofing, airtightness, and comfort testing during the living lab period for teams would provide valuable data on building performance.

Energy Strategies: All HDUs incorporated passive design energy strategies, demonstrating that high energy efficiency is possible to integrate into housing designed for disassembly and built using dry construction. This relied on a mixture of technical equipment such as solar panelling fixed to roofs and façades and heat pumps, in addition to low-tech techniques such as Trombe walls and solar chimneys. Team Deeply High stressed that the competition should promote low-tech "ancient" techniques in future editions to reduce embodied carbon due to building services equipment. EFdeN also noted the importance strategies to limit active heating and cooling as the climatic conditions in Bucharest are more challenging compared to those in Wuppertal, making adaptability to different contexts more difficult.

3.3.6. Building Information

6A Data Storage

Digitalisation: BIM, which is both a process and software, was a mandatory element of the competition and most teams used either Revit or ArchiCAD to fulfil the requirement. When successfully implemented, it proved useful for clash detection, communication with industry partners, and parametric design to adapt construction systems to potential new sites. Teams also utilised digital tools to convert drawings for production [50] and Revit plugins to model building services. There were interoperability issues between disciplines; students from the technical schools, such as carpentry and other trades, used software that was neither BIM nor CAD based, which made internal collaboration difficult. BIM management was challenging where more than one software was used to model, e.g., a combination of Revit and ArchiCAD, or to integrate several working models using the same software into one synchronised file. Teams AuRA and levelup overcame this issue by assigning one person control of the model. Despite it being more efficient, interviewees found this strategy hindered collaboration and interdisciplinarity. Although not used to its full potential, particularly during (dis)assembly, students were generally positive about BIM aiding circular construction.

Information Type: Most inventory information was documented both physically with markings on building parts and digitally. This was typically achieved using Excel data sheets, rather than being integrated within 3D models. Teams such as MIMO, SUM and RoofKIT more successfully applied the Material Passport concept by using tagged data sheets and linking photographic information within BIM models during both manufacturing and the (dis)assembly process, while RoofKIT contributed open-source data on their HDU to industry collaborators [51]. Teams found it difficult to update building information due to design changes during assembly as the mandatory BIM models had already been submitted. It is therefore possible the correct as-built information would not have been captured. This lack of data would negatively impact circularity, hindering in-use maintenance and the EoL stage, and creating additional barriers during the future re-planning process. According to team levelup, some building information for timber finishes could not be gained before assembly, thus highlighting the need for prior assembly testing, quality assurance measures, and as-built audits.

6B Data Analysis

Assessments and Simulations: Life Cycle Assessment (LCA) was a competition requirement that assisted the students' material choices. This was carried out using software and databases such as SimaPro, GaBi, and Excel. This was a demanding task for student teams that lacked training in LCA. The University of Wuppertal provided support to ensure calculations were carried out correctly. Students faced additional challenges with old or unreliable material database information and difficulty accessing product and material data from external companies, including from collaborating sponsors. Parametric modelling was used to test the feasibility of adapting designs to other geographic contexts at the planning stage, in addition to in-use simulations of energy consumption during the more detailed designing process. Teams EFdeN and Deeply High identified additional barriers to LCA during the manufacturing and (dis)assembly processes due to the difficulty of assessing waste and measuring material weights, recommending more robust protocols when using both industry (e.g., LEED) and Solar Decathlon assessments. A further challenge experienced was conducting a sufficient analysis of load weight for lifting prefabricated elements. Although this was necessary to avoid damage during the (dis)assembly process, many teams did not carry out these calculations. Teams also needed to complete the UMI assessment, provided by the University of Wuppertal, which was received positively as a means of promoting a whole lifecycle approach.

Strategic Delivery: The use of data to efficiently dismantle and manage logistics was an area that was underutilised by teams in comparison to assessments and simulations of the construction system in isolation. Team EFdeN recommended that this aspect should be integrated within the competition rules under the *Siteworks Operations Plan* section [39], which would support post-competition disassembly and future reconstruction. Furthermore, phasing information should be updated in real time to adapt to on-site changes and decisions. Teams utilised their 3D models, and in some cases, specialist software, to manage the project programme and logistics to disassemble, transport, and assemble their HDUs. This was highly advantageous in preparing for the (dis)assembly process, particularly when a time dimension was applied to create '4D planning' still images. Such methods were also used to ensure prefabricated building parts would fit within the physical dimensions of transport vehicles and could be loaded, unloaded, and stored in the correct order for JIT delivery. Some teams used CAD software or Sketchup, while others used BIM and specialist software. Surprisingly, not all teams used deconstruction plans, which could have eased site operations and helped avoid difficulties in locating building parts and equipment on-site. Post-competition, deconstruction plans would better ensure the safe removal of HDUs from the Solar Campus and enable future sustainable EoL processes, particularly as many student members were graduating from their universities and would therefore not be available in the future.

4. Discussion

This study builds upon a previous literature review, which identified an acute knowledge gap regarding disassembly and site activities in circular housing. By exploring the relationships between processes and thematic factors using the Solar Decathlon Europe competition of 2022 as a case study, this study contributes to addressing this gap and the development of a supportive circular housing framework. The fact that the SDE-2022 teams came from different contexts, often with ambitious plans for local implementation, provided rich data and offered insights into notable policy implications within each of their home countries. The decathletes and built HDUs have had a significant impact on research on circular industrialised housing among industry and governmental actors.

4.1. Applying Competition Findings to Housing

The experiences of the decathletes demonstrate the importance of systematically capturing hands-on experience and lessons-learned from long-term housing designed for disassembly. Asset owners and asset managers must effectively understand these lessons to adequately manage the necessary repairs and replacements during the use phase to extend the overall building lifespan. Industrialising construction proved necessary not only for the digitalisation of information to manage circularity in a systematic way, but to be able to disassemble and reassemble or replace parts with fewer issues and cost. A manufacturing approach ensures all issues related to building parts and their interfaces are resolved, avoiding last-minute on-site solutions that compromise circularity.

4.2. SDE Accelerator for Change

As circularity in housing is still unconventional and perceived as risky, the Solar Decathlon competition and similar research projects can help drive the transition to a circular economy in housing. Other built case studies, such as BAMB [21], WikiHouse [52], Waste House [53], and Circle House [54] are similarly having a positive impact amongst industry practitioners and policymakers. Such projects help advance Urban Mining, circular hubs/depots, second-hand markets, and circular business models. Industry partnerships in the SDE-2022 competition provided valuable opportunities to test novel circular construction methods that might otherwise be considered too risky or costly to trial. However, as demonstrated by the HDUs, a circular and industrialised approach requires more materials. This poses a risk for circular industrialised housing to cause greater material waste in the future if a sustainable EoL is not ensured, or if lean construction methods to account for this are not adequately incorporated.

4.3. Scalability

Promising start-ups have emerged from the SDE-2022 competition, including SUM+, founded by three members of TU Delft's team SUM, and Mede-Oprichter, born out of Eindhoven's team VIRTUe. It is important to ensure circular aspects are not lost during the scaling-up of these projects, due to the higher upfront costs associated with circular construction. Top-up solutions are a promising archetype for councils with existing stock, particularly in dense cities where land is scarcer. This was evident in SDE-2022, where most teams had responded with modular top-up solutions, several of which were developed in collaboration with their local authorities both during and after the competition.

4.4. Limitations

While Solar Decathlon offers valuable insights into circular industrialised housing, the controlled competition environment introduces limitations. The absence of real-world regulatory challenges, such as stringent planning restrictions, limits the applicability of the findings to commercial settings. Additionally, as the student teams are unpaid, the study overlooks labour cost considerations throughout the four processes, which would likely represent a significant barrier to implementation in industry. The teams did not need to resolve potential complex issues with multiple ownership structures—particularly relevant to top-up solutions—which can significantly affect planning and implementation. Although some teams partnered with off-site construction companies, the scalability of automated manufacturing processes in mainstream construction requires further investigation. Lastly, while housing disassembly is indicative of future replacements, adaptations, and End-of-Life scenarios for housing circularity, it does not provide empirical data on long-term use. Questions remain regarding the durability and adaptability of the HDUs over time and the number of reuse loops for building parts.

4.5. Future Research

The findings provide a strong foundation for advancing circular and industrialised construction and highlight several lines of research requiring further investigation. Future studies should address the limitations and extend this study by engaging with industry professionals and examining circular housing systems in real-world contexts, providing more robust and widely applicable insights.

Firstly, the results of this study should be compared with the findings of the previous literature review carried out by the authors, serving to further develop and validate universal themes and sub-themes across these studies. To achieve this, the emerging themes and sub-themes and barrier and enabler hotspots identified within this study and the previous literature review could be analysed more deeply. Future research could compliment this study with an analysis of the detailed project information for each of the fifteen HDUs within SDE-2022. These data are readily available in the open access Solar Decathlon Europe team project manuals on the Knowledge Platform [43]. Similarly, it would be beneficial for future studies to contribute towards the development of the circular process framework, focussing on addressing the gaps identified across the factors and processes. Collaborative research input and testing of the framework with industry practitioners and local governmental stakeholders would provide valuable development and validation, while ensuring its applicability to industry and local-level policy.

Further investigation into the role of industry professionals, built environment experts, and local policymakers involved in implementation is crucial for advancing circular industrialised housing. Studies extending this research could explore the role of collaborative partnerships between housing providers, off-site contractors, and local authorities in overcoming barriers to adoption. Interdisciplinary interviews with practitioners with experience in DfD, IC, and preferably the integration of both, are crucial to understanding new developments and current bottlenecks to circular industrialised housing. These investigations should provide a deeper exploration of the gaps in (re)planning and (re)manufacturing processes, particularly through engagement with housing providers, off-site contractors, and designers. Future studies should consider the influence of Governance, Financial, and Building Information factors on the adoption of circular construction practices and seek to overcome the Culture-related barriers. Additionally, incentives, subsidies, regulatory frameworks, ownership, and procurement will also be vital for fostering the wider adoption of circular industrialised housing practices and were under-investigated within this study. Furthermore, future research should engage with the housing sector in different regions to understand the unique challenges and opportunities in various countries and reveal how circular housing principles can adapt to local contexts. For example, needs and constraints may vary considerably across Northern and Southern Europe.

Further research should focus on the challenges and enablers of scaling up exemplary prototypes. This could include following up with the spin-off start-up companies founded by the SDE-2022 teams post-competition and built projects within the industry. This would contribute to addressing the need for longitudinal studies that track the performance of circular industrialised housing over time. Such studies could provide a greater understanding of emerging technologies, such as digital twin systems and the Internet of Things (IoT) for real-time monitoring, while also capturing developments in the maturing of the second-hand market for building products, thus supporting reuse.

5. Conclusions and Recommendations

5.1. Conclusions

The SDE-2022 competition has demonstrated that circular industrialised construction is a viable approach for delivering permanent, yet reversible, and highly energy-efficient housing. The findings of the study contribute valuable knowledge and lessons learned based on first-hand experience in disassembly, industrialised construction, and housing circularity strategies that can be transferred to industry practitioners, housing providers, and policymakers.

The interviewees confirmed that the incorporation of disassembly and dry off-site construction techniques not only facilitates long-term maintenance and adaptability but also ensures the production of high-quality housing. While challenges related to water and air tightness, site logistics, and weather conditions persist, these technical barriers can be mitigated through further refinement of the construction processes. Overall, IC offers significant potential for advancing circular housing solutions, particularly through improved resource reuse enabled by digitalisation and precise manufacturing techniques. Both the physical and intangible aspects of IC contribute to enhanced preassembly testing and an increase in the overall future reuse potential of components. Key findings include the following:

- **Barriers and Enablers Across Building Processes:** Numerous enablers and barriers to circular housing were identified across all four building processes, with most challenges and opportunities concentrated in the (re)designing and (dis)assembly stages. Barriers primarily related to Cultural factors, particularly 'Skills and Experience' and 'Cultural Norms', were concentrated within the (re)designing process. Site And Logistics factors were most associated with the (dis)assembly process, with interviewees mostly citing weather issues and transport constraints. In contrast, enablers were mainly associated with Construction System factors, such as 'Theoretical design' and 'Industrialised Approach', alongside Cultural factors, particularly 'Skills and Experience' during the (re)designing process. Most notably, Cultural factors presented critical barriers and enablers, appearing with a frequency nearly equal to Construction System factors, in contrast to the previous literature review.
- **Empirical Data on Disassembly and Reassembly:** The study gathered empirical data on the disassembly, assembly, and reassembly of circular industrialised housing. These data not only deepen our understanding of site, logistics, and transport issues but also informs other thematic areas within the framework. A rich body of evidence has been presented in this paper, highlighting the complex connections that influence the disassembly and reassembly processes in circular housing systems.
- **Emerging Themes and Sub-Themes:** Several new sub-themes emerged from the interview content analysis. In total, 14 common themes and 39 sub-themes were identified across the 6 predefined factors (Cultural, Governance, Financial, Site And Logistics, Construction System, and Building Information). These insights add depth to our understanding of the multifaceted challenges and opportunities within circular industrialised housing.
- **Cultural Norms and Industry Shifts:** While IC is gaining acceptance within both academia and industry, the concepts of Design for Disassembly (DfD) and circular economy (CE), and material reuse, in particular, remain underapplied and lack integration within IC. Based on the SDE study, Cultural factors are key to the success of circular housing, and initiatives such as the Solar Decathlon are essential for shifting the mindset of young professionals and industry collaborators. To address housing affordability and sustainability issues, it is crucial to fully integrate IC, DfD, and CE into both education and industry practices.

5.2. Key Recommendations

To advance the adoption of circular industrialised construction, university education must incorporate Learning-by-Doing, where students engage directly with real-world applications of circular principles. The SDE-2022 competition highlighted a gap in students' theoretical understanding of IC, DfD, and CE prior to their practical involvement. A more integrated approach that embeds these theories—grounded in a whole-lifecycle approach—earlier in academic curricula will better equip students for effective implementation. Moreover, competitions such as Solar Decathlon should more robustly embed the lifecycle concept, requiring student teams to plan for disassembly and reuse after the competition has concluded. While challenges such as transport costs and loss of student participation complicate this, planning for post-competition disassembly is essential for achieving true circularity. Expanding Solar Decathlon-type competitions and fostering stronger industry-academia partnerships will facilitate joint preassembly testing and refinement of circular industrialised housing systems, ensuring students are prepared to drive innovation and sustainability in construction practices.

The findings from SDE-2022 lay the foundation for future research, policy development, and practical applications in circular industrialised housing. Scaling up circular construction will require collaboration between education, industry, and policymakers to create an ecosystem where sustainable, adaptable housing is the norm.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17020638/s1, Spreadsheet S1: Insights from SDE_Bar chart data_Atlas.ti analysis.

Author Contributions: Conceptualization, A.D. and N.M.A.; methodology, A.D., N.M.A. and G.v.B.; software, A.D.; validation, A.D. and N.M.A.; formal analysis, A.D.; investigation, A.D.; resources, A.D.; data curation, A.D.; writing—original draft preparation, A.D.; writing—review and editing, A.D. and G.v.B.; visualisation, A.D.; supervision, N.M.A. and G.v.B.; project administration, A.D.; funding acquisition, A.D. All authors have read and agreed to the published version of the manuscript.

Funding: The work presented in this publication has been carried out within the RE-DWELL Innovative Training Network, funded by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement no. 956082.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Research Ethics Committee of the La Salle Campus Barcelona, Ramon Llull University.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: This study was supported by Ignacio Guillén Guillamón and team Azalea's coordinator José Luis Alapont during the primary author's research stay with Polytechnic University of Valencia in 2022.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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