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Review

Resource efficiency in industrialized housing construction – A systematic review of current performance and future opportunities

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ABSTRACT

Improved resource efficiency in the construction industry is needed to balance sustainability requirements with growing demand for new infrastructure. Resource efficiency includes the reduction of primary and non-renewable materials, the creation of high-quality products with minimal waste, and the retention of long-term product value. One potential source of resource efficiency is the increased adoption of industrialized housing construction which includes novel construction methods and products. Current literature identifies numerous opportunities for resource efficiency in industrialized housing construction. However, this literature is scattered across several sources and units of analysis. Using a Systematic Literature Review, this paper identifies eight recurrent product and process-related themes and fifteen specific subthemes of resource efficiency in industrialized housing construction across building lifecycle phases. These themes can be based on product such as the use of innovative and industrial materials or on process such as the use of inventory monitoring and tracking. Additional industry and regulatory themes are also identified. Furthermore using frequency analysis of literature, the paper finds while themes of resource efficiency exist across all building lifecycle phases, the most recurring themes occur in design, manufacturing and logistics phases. There is less literature dedicated to resource efficiency during occupancy and end-of-life phases. The paper further discusses how early design decisions such as material design have a systems-level impact that propagates throughout the building lifecycle, and how a beyond-systems approach is needed between stakeholders and processes to integrate current resource efficiency potentials into industrialized housing construction practice. Finally, the paper identifies future research directions for resource-efficient industrialized housing construction including concepts of circular economy, value chain coordination, and socio-economic impacts.

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1. Introduction

Over the past several decades, increased demand for global housing has led to claims of a global housing crisis (Aalbers, 2015). The housing market is characterized by too little supply and too high of demand (Aalbers 2015; Potts, 2020). There is a need to build about two billion homes before the end of the 21st century (Smith, 2018). The issues of access to land and construction costs have been unabating drivers of housing unaffordability (McKinsey Global Institute, 2014). Furthermore, housing plays an important role in global sustainability (Winston and Pareja Eastaway, 2008), including a holistic view that balances societal justice, economic development, and environmental services (Goodland, 1995). These challenges require improved planning and construction of housing.

To balance sustainability requirements and the demand for affordable housing, one potential strategy is *resource efficiency*. Resource efficiency has been studied in housing in several contexts. The work of Wilson and Boehland (2008) shows resource efficiency can be achieved through downsizing housing design. Similarly, the research of Kumar Dhar et al. (2013) points out the importance of having flexibility in housing design to accommodate changing layout demands (during occupancy and end of life phases) for occupants.

However, there has been less discussion of how resource efficiency can be achieved through the industrialization of housing production. Industrialized Housing Construction (IHC) is a holistic term that includes approaches such as prefabrication, modularization, off-site fabrication, or modern methods of construction (MMC). IHC has been a strategy to deploy emerging innovations for resource-efficient housing construction (Rohn et al., 2014). Examples include product innovations such as cross-laminated timber (CLT) and process innovations such as lean manufacturing.

Although resource efficiency should be an integral part of comparing IHC with conventional housing construction, there is limited guidance surrounding the topic (Pan et al., 2012). To address this gap, this paper summarizes current performance and future opportunities for research efficiency in IHC through a systematic literature review (SLR). The paper provides a short departure summarizing existing literature for housing, conventional construction methods, and IHC through the lens of resource efficiency. Next, the SLR research design is introduced, followed by a presentation of fifteen subthemes for resource-efficient IHC across eight recurring themes in five building lifecycle phases. Finally, the paper concludes with a discussion of the key findings, future research directions, limitations, and a conclusion.

2. Point of departure

2.1. Demand for global construction of housing

The global population is estimated to reach 9.7 billion in 2050 (United Nations, 2019). The urbanization of the population has its own positive impact on economic growth (United Nations, 2019). Nevertheless, it also demands careful thought about the provision of adequate housing and urban planning strategies. The global residential buildings in particular account for 38% of the global construction volume (WEF, 2016). Residential buildings also occupy much more floor space compared to non-residential buildings (PE International 2013; Huang et al., 2018). Such demand has so far been supplied by the construction industry that consumes an estimated 3 billion tones of raw materials and other resources (WEF, 2016). Still, this supply of housing has also not been able to meet the demand resulting in more substandard housing (United Nations, 2019). Hence studying this particular segment of the infrastructure demand and supply is vital.

2.2. Current construction methods and resource efficiency

The building construction industry alone is estimated to consume 25% of virgin wood and 40% of raw stone, gravel, and sand globally each year. It also accounts for 40–50% of the global output of greenhouse gas (GHG) emissions (Khasreen et al., 2009). These trends endanger the planetary boundaries that are defined to be a safe operating space for humanity (Rockström et al., 2009; Steffen et al., 2015). Reasons for inefficient construction resource utilization include the fragmented, project-based approach (Hall et al., 2019) and the “linear” economy approach in which construction materials are sourced, used, and disposed of with little re-use or recycling (Zimmann et al., 2016).

Resource efficiency in housing construction is proposed to address the gap between housing demand and current construction methods. Housing resources include materials, water, energy, and land (UNEP, 2011). The definition of resource-efficient housing can include the reduction of materials used, the reduction of waste during production, the replacement of non-renewable materials with recycled or renewable materials, and/or the extension of product lifetime (BRE, 2017). These can be achieved during the creation of the value (extraction, manufacturing, assembly, and retailing) or during use and post-use of the value (maintenance, reuse, and recycling) (Achterberg et al., 2016; Ellen MacArthur Foundation 2013). To measure resource efficiency in construction, scholars often perform a life-cycle impact assessment of flows of materials, energy, and water (Priemus 2005).

2.3. Industrialized housing construction (IHC)

The need for productivity increase in the construction industry has led to the traction in IHC (McKinsey Global Institute, 2017). IHC extends beyond prefabrication of elements. IHC refers to a holistic strategy that includes well-defined technical systems, use of information communication technology (ICT), planning and control of processes, and a stronger relationship with stakeholders (Lessing et al., 2005). The MMC working group (2019) defines IHC using a seven-category framework. The term pre-manufacturing is defined as all activities that occur away from the final site where buildings are permanently placed. These processes are executed in a controlled environment using manufacturing principles. Structures can be pre-manufactured as a volumetric element (3D) or as a panelized system (2D). Additionally, IHC can include on-site improvements such as integrating lean processes, and/or using building information modeling (BIM). These are the sub-systems of IHC that can create a platform to achieve resource efficiency. More recent work has begun to integrate circular economy principles and internet of things (IoT) with IHC to expand the intrinsic benefits of products for resource efficiency (Construction Products Association 2016; Zhong et al., 2017).

Consequently, the application of IHC has been growing in several countries. For example, in Hong Kong, the government has introduced prefabrication strategies for the construction of public housing since the mid-80s. As of 2002, the share of prefabricated components in Hong Kong is estimated to be 17% (Luo et al., 2015). Additional studies show the rise of IHC in North America (Pullen et al., 2019; Hall et al., 2019), Japan (Yashiro, 2014; Steinhardt and Manley 2016), and many regions of Europe (Berger, 2018). As the application of IHC is on the rise, current performances of processes and products need to be analyzed and understood to plan and construct resource-efficient housing.

However, studies on resource efficiency and new forms of construction that can bring about systems-level innovation are scattered across many different individual studies. A few review papers do address IHC and resource efficiency. For example, Jin et al. (2020) used a bibliometric analysis to summarize research methodologies used to study environmental performance of IHC buildings. However, this work has a focus on operational efficiency and the post-construction stage. Other reviews study specific environmental IHC building systems such as modular construction (Sonego et al., 2018; De Carvalho et al., 2017). Still, a comprehensive literature review at the intersection of IHC and resource efficiency does not yet exist.

3. Research design

The research design follows a SLR approach. SLR allows the collection of relevant knowledge created in a specific research domain. The synthesis of this research can lead to an extension of knowledge (Webster and Watson, 2002). To conduct a rigorous review, the approach presented in the research of Wolfswinkel et al. (2013) is implemented. In this approach, key concepts emerge chiefly through the analytical process instead of a deductive method. Five main stages that are done iteratively provide a means to execute a rigorous review of literature. These stages are also followed in this paper, discussed below and summarized in Fig. 1.

Define: In this stage, the specific field of research is identified. Furthermore, as a means to gather the best possible pool of knowledge, confinement strategies are followed. The scope of the SLR is limited to three main thematic areas; industrialized construction, sustainability, and housing. In addition, synonyms, wildcard tokens, and other keywords that can be associated with the three main thematic areas are added. Because this literature search targets research at the intersection of the themes, the Boolean operator “AND” is used between the three thematic areas while the Boolean operator “OR” is used to include all associated keywords. Table 1 shows the main thematic areas and the associated keywords used in the search. To gather quality literature, two acclaimed data sources are used, namely Scopus and Web of Science. Lastly, a confinement strategy is used to limit the number of papers. In this research, only journal articles are studied.

Search: Using the definition in the first stage and the data sources, the search was run. In this stage, 431 journal articles are identified.

Select: In the selection processes, articles that appear multiple times (duplicates) are removed. Following that, the remaining list of articles is refined by the first author by reading the abstract of each article. Papers with abstracts that clearly fall outside of the target scope were removed. After this step, 181 papers remained on the list. Lastly, the final list is obtained after articles were read in their entirety. In the end, 86 papers are selected as the final sample of this SLR.

Analyze: Next, the authors analyzed the 86 articles using a three-step coding procedure (Wolfswinkel et al., 2013). First, in a process of ‘open coding’, the articles were read in their entirety. Specific excerpts were extracted, then re-read and coded by the first author into a set of tentative sub-categories (subthemes). Next, using ‘axial coding’, the first and second author reviewed the subthemes and excerpts in detail to identify interrelationship and abstract the recurring primary themes. Finally, using ‘selective coding,’ the recurring themes were associated with broader categories (building lifecycle phases) to understand the phenomena of resource efficiency in IHC as it sits within a broader context of the built environment. Once new categories and subcategories stopped emerging, i.e. theoretical saturation has been reached, the description of building lifecycle phases, recurring themes, and subthemes was finalized. In addition, some of the identified recurring themes emerged did not fit within a building lifecycle phase. These were coded as additional recurring themes that could act as barriers or enablers for the application of a resource-efficient IHC.

Present: In the final stage, the findings of the SLR are presented through content analysis of literature and two frequency analyses. The content analysis presents a qualitative and comprehensive overview of the content. The first frequency analysis categorized articles according to their mentions of specific building lifecycle phases and recurring themes. The second frequency analysis counted the number of recurring themes mentioned in each of the articles.

4. Findings

From the SLR, eight product and process-related recurring themes emerged for resource efficiency in IHC across five building lifecycle phases (see Table 2). The design lifecycle (A) phase

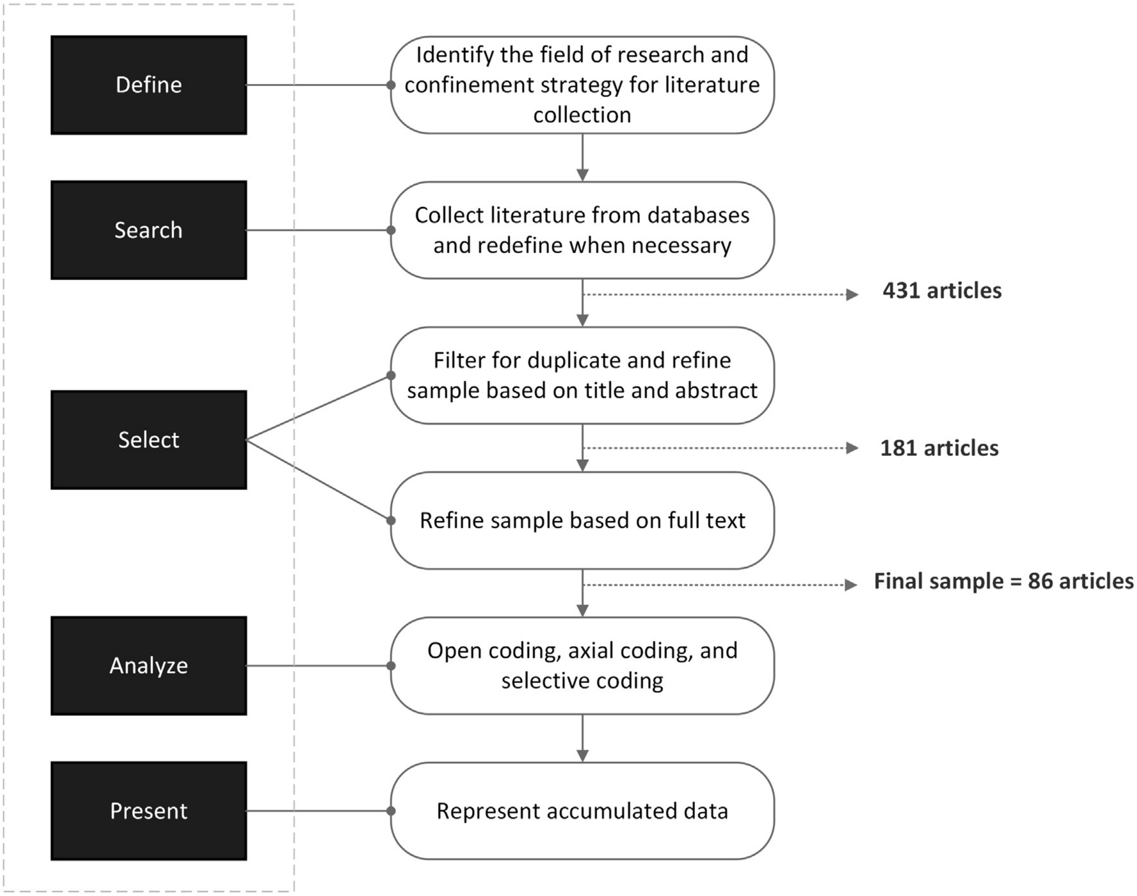

Fig. 1. Research strategy followed across the systematic literature review stages.

Table 1
Keywords used to collect relevant literature.

Industrialized Construction **(OR)**	**(AND)** Sustainability **(OR)**	**(AND)** Housing **(OR)**
Prefabrication, Modular Construction, Pre-built, Digital fabrication, Dfab, Mass-produced, Off-site construction, Prefab*, Factory-built, Additive manufacturing, Mass customization, Industrialized Building system	Green building, Low carbon, Climate change, Environment, Zero carbon, Sustainable*, Environmental-Assessment, Life cycle, LCA, Net zero, Circular economy	Residential Building Apartment House

discusses activities that occur before construction products are realized through manufacturing processes. The manufacturing and logistics phases (B) describe the product manufacturing stage and the outbound logistics until it arrives at the construction site. The assembly phase (C) represents any production activities that occur at the construction site until the project is completed and handed over to the occupant. The occupancy phase (D) includes activities such as use and maintenance. The End of Life phase (E) represents activities such as de-construction. Furthermore, each recurring theme within the building lifecycle phases constitutes specific subthemes related to resource efficiency in IHC. In total fifteen subthemes were identified across eight recurring themes (see Table 2).

4.1. *Content analysis*

In the following section, detailed and comprehensive review of the current scientific knowledge on each of the building lifecycle, recurring themes, and subthemes are presented.

4.1.1. *A — Design*

IHC involves a thorough planning strategy to manage the technical and process performances (Lessing et al., 2005). IHC often uses a product-based approach contrary to the project-based approach found in the construction industry. This product-based approach allows stakeholders to create a common understanding of the product at the very early stages of the construction process (Tykkä et al., 2010). This phase constitutes of two recurring themes and three subthemes that show the performance and potential of IHC in the design phase for resource efficiency.

4.1.2. *A1. Dematerialization*

Dematerialization by design refers to the reduction of material quantities required and specified in the design of housing. The dematerialization can happen throughout a building's lifecycle phases and using different strategies including improved consumer behavior during occupancy phase (Świątek, 2013). In this recurring theme, dematerialization is discussed at both the product and systems levels of optimization.

Table 2
Summary of building lifecycle phases, recurring themes, and subthemes for resource efficiency.

Building Lifecycle Phases	*Recurring themes*	*Subthemes*	Description
A Design	***A1. Dematerialization***	*Product optimization*	Design for reduced primary material usage at the component level, often by using digital design tools for structural optimization.
		System optimization	Design for structures that are resource-efficient at the overall level and not just optimized at a component level.
	A2. Material design	*Innovative and industrial materials*	Design for non-traditional primary and secondary materials that can be fabricated and assembled through new industrialized processes.
B Manufacturing and logistics	***B1. Waste and quality management***	*Precision in manufacturing*	Reliable manufacturing techniques and controlled environment precisely manufacture elements and control excess material waste.
		Perpetuity in manufacturing	Repeated processes and repetitive use of manufacturing tools reduce ad hoc and short-term solutions.
		Synergy in manufacturing	Taking advantage of synergistic manufacturing processes to create integrated products that can reduce unnecessary material use.
	B2. Production system	*Lean production*	Process innovations to drive waste out of the manufacturing system and avoid overproduction.
		Inventory monitoring and tracking	Tracking, tracing, and visualization tools for an efficient material control system shared among multiple stakeholders in the supply chain.
	B3. Transportation system	*Transportation efficiency*	Efficient delivery, batching, and temporary blocking of finished products to reduce material and energy usage during transportation.
		On-site and near-site manufacturing	Manufacturing on-site or near-site to reduce resource consumption during transportation.
C Assembly	***C1. Assembly system***	*Site and equipment efficiency*	Highly specific and efficient equipment use during assembly.
D Occupancy	***D1. Operational performance***	*Operational energy efficiency*	High operational performance that should consider local climatic conditions, air leakage, and heat loss.
		Non-intrusive refurbishment	Building maintenance and retrofit using new products and systems that do not require extensive demolition or on-site waste generation.
E End of Life	***E1. Reusability and recyclability***	*Product flexibility*	Design for systems that can be disassembled and deconstructed, often through use of standard components and product platforms.
		Product-as-a-service	Provides an opportunity to ensure ownership and management of products throughout their lifecycle including after their intended lifespan has ended.

The first subtheme of dematerialization is *product optimization*. This is often achieved through design awareness of advanced manufacturing and/or digital tools for design optimization (Iuorio et al., 2019). Advanced manufacturing and digital fabrication enable new geometrical forms that can be visually appealing, structurally efficient, and rapidly produced. Such examples include CNC machines that can produce homes from CAD files (Knight and Sass, 2010). Designers can experiment with dematerialization design strategies such as introducing hollow sections and reducing the thickness of elements (Ahmed and Tsavdaridis, 2018). Additionally, designers can rely on the manufacturing process and eliminate unnecessary over-design used to account for poor on-site quality control (e.g. poor concrete mix) (Banks et al., 2018). In a case study in China, design for an IHC system reduced concrete and steel materials by 17.5% in comparison to traditional production methods (Shen et al., 2019).

The subtheme *system optimization* includes holistic system design for structures that are resource-efficient at the overall level and not just optimized on a component-by-component basis. System optimization can be obtained in IHC through standardized products and systems using design concepts such as product modularity. With product modularity, individual components can be designed and developed while ensuring integration with the product as a whole (Da Rocha et al., 2015; Hung et al., 2018). This process simplifies the possibility to achieve diversity in design (with optimal response to variances of local conditions or preferences) and resource efficiency in production (Frutos and Borenstein 2003; Sivo et al., 2012; Eid Mohamed et al., 2017). System optimization can also be obtained by coordinating super and substructure designs. For example, the design of lightweight materials in the superstructure system (e.g. wood and aluminum) results in a subsequent reduction in materials usage for substructures such as foundations (Cherian et al., 2017; Brehar and Kopenetz 2011; Mrkonjic 2007). Alternatively, the selection of certain systems can result in resource inefficiency. For example, the design of modular systems often requires extra or redundant structural elements in comparison to traditional systems (Smith et al., 2018). Prefabricated concrete systems can also require supplementary steel materials that are not required by in-situ concrete designs (Wang et al., 2018).

4.1.3. A2. Material design

Resource efficiency in material design means shifting to low carbon materials and moving away from energy-intensive and non-renewable resources (Achenbach et al., 2018; Iuorio et al., 2019; Ahmed and Tsavdaridis 2018; Padilla-Rivera et al., 2018). Research finds that construction materials can account for up to 90% of the environmental impacts for both conventional and prefabricated housing with dominant contributors being concrete, steel, and aluminum (Abey and Anand 2019; Teng and Pan 2019; Mrkonjic 2007). The following section explains the subthemes of resource efficiency through material design in IHC.

The subtheme discusses the opportunity for IHC to embrace products and systems that are made from *innovative and industrial materials* (Puri et al., 2017; Milutienė et al., 2012). A major movement identified in recent literature is the shift to industrialized timber products and systems – often referred to as mass timber – instead of steel and concrete. In general, scholars point to an increased use of wood in the construction sector and associated reduction in global greenhouse gas emissions (Johnston et al., 2014; Frenette et al., 2010; Balasbaneh and Bin Marsono 2017; Kuzman and Sandberg 2017; Bukoski et al., 2017; Tettey et al., 2019; Dodoo and Gustavsson 2016; Lehmann 2013). Examples of industrialized wood include Medium-density fibreboard (MDF), Oriented Strand Board (OSB), Glued laminated Timber (Glulams), or Cross-laminated Timber (CLT). Authors specifically mention increased adoption of CLT systems for IHC (Lehmann 2012; Maoduš et al., 2016). Compared with other materials, CLT has an easier production and assembly process (Araujo et al., 2016). The research of Dodoo et al. (2014) has found that the conventional building required 36% more concrete and 62% more steel than the CLT system. In countries such as Sweden where wood construction has been in practice, such use of industrialized wood is easier. On the other hand, countries such as Malaysia use concrete as the main construction material for IHC (Balasbaneh and Bin Marsono, 2018). This increases the use of non-renewable and environmentally unsustainable materials such as cement and reinforcement steel (Jia Wen et al., 2015; Aye et al., 2012).

On the other side of using innovative and industrial materials is composite systems for IHC (Samani et al., 2015). IHC material design has used slab systems with glass fiber reinforced gypsum to reduce carbon-intensive materials such as cement (Cherian et al., 2017). IHC has also effectively used secondary materials such as prefabricated mortar panels made from polyurethane foam and Electric Arc Furnace Slags (EAFS). The use of secondary materials in IHC can lead to a more circular economy (Briones-Llorente et al., 2019). Nevertheless, scholars find low adoption rates of renewable, environmentally certified, and/or recycled materials for IHC (Kamali et al., 2018; Santin 2009).

4.1.4. B – Manufacturing and logistics

IHC typically moves production activities from the construction site to off-site factories where building elements are manufactured. While manufacturing systems in IHC provide enormous potential for resource efficiency, caution is needed in consideration of related transportation emissions (Du et al., 2019; Quale et al., 2012). Three recurring themes in this phase are waste and quality management, production systems, and transportation systems.

4.1.5. B1. Waste and quality management

One of the recurring themes in the manufacturing and logistics phase in IHC is waste and quality management. When scholars claim potential benefits of IHC, one recurrent claim is the potential to reduce high-levels of construction waste and to limit consumption of primary materials (Khahro et al., 2019; Bakri et al., 2011; Boyd et al., 2013; Wang et al., 2018; Kamali et al., 2018; Du et al., 2019). Shen et al. (2019) find that prefabricated public housing in Beijing reduces construction waste by 12.22%. Additionally, Jaillon and Poon (2008) find a 60–70% reduction of waste with IHC strategies compared with traditional construction. From review of the literature, there are three subthemes to reduce generation of waste and increase quality in IHC.

When IHC embraces reliable manufacturing techniques and a controlled production environment, material waste can be reduced through *precision in manufacturing.* Industrialization and advanced manufacturing enables production of higher quality products (Mohamad et al., 2012). This reduces or eliminates on-site plastering and painting trades (Mao et al., 2013; Brehar and Kopenetz 2011; Jaillon and Poon 2008; Cherian et al., 2017). Additionally, higher-quality products with longer lifespans require less maintenance and replacement during occupancy and EoL phases (Jaillon and Poon 2010; Schuler et al., 2001). On the other hand, conventional construction involves wet trades such as on-site concrete work that produce a large amount of waste on-site. For example, Begum et al. (2010) find that conventional construction sites can record up to 54.6 tones/100 m^2 of on-site waste. When industrialized methods are used, this number dramatically decreases to 1.5 tones/100 m^2. Furthermore, much of the waste generated in an industrial setting is fed back into the system (Begum et al., 2010). This performance can be attributed to the precision of manufacturing equipment like CNC machines and a controlled environment in IHC (Mao et al., 2013; Lehmann 2013). The research of D'Oca et al. (2018) identifies that prefabrication strategies achieved up to 1 mm precision in an innovation project. Additionally, the precision in manufacturing enables trust for designers to avoid overdesign and for contractors to avoid placing surplus orders. Material orders for delivery to the construction site often use a 5–15% contingency anticipating waste during production (Quale et al., 2012). The controlled environment also allows unconventional material saving of water. For example, a steaming method for concrete curing can be applied instead of traditional on-site water application (Cao et al., 2015).

IHC can be more resource-efficient because of *perpetuity in* *manufacturing*. Because IHC uses repeated manufacturing tools and processes, it can reduce reliance on ad hoc and short-term solutions. The reuse of temporary structures such as formwork and props can be much more systematic in a manufacturing environment (Jiang et al., 2018; Mohamad et al., 2012; Teng and Pan 2019; Cao et al., 2015; Banks et al., 2018). The research of Dong et al. (2015) finds a 10% reduction in carbon emissions for precast concrete compared to cast-in-situ concrete structures. The majority of the reduction is associated with the reuse of steel formwork compared to conventional timber formwork used on the construction site. The same research finds that carbon emissions from single-use timber formwork is ten times greater than a steel formwork that can be repeatedly used up to 100 times in a manufacturing environment. Similarly, Jaillon and Poon (2008) find IHC reduces reliance on timber formworks, reducing timber use by 6.16 kg/m^2 of the construction floor area (CFA).

IHC benefits from *synergy in manufacturing*, where manufacturing capacity also allows for more sustainable and integrated product designs. For example, Cao et al. (2015) demonstrate how heat insulation boards can be manufactured in concert with the main exterior wall system. This reduces the amount of mortar required as a bonding agent by 83.6%. Bock (2019) studies a façade system that is cast simultaneously with a steel skin that can harvest solar energy. Höfler et al. (2015) note the possibility of including service systems such as ductwork during the manufacturing process of the building elements.

4.1.6. B2. Production and inventory systems

Production systems for IHC refer to the processes used for the manufacturing of building elements. IHC production systems can improve resource efficiency through improved material process flow planning and the integration and smooth information flow amongst stakeholders (Barriga et al., 2005). Two subthemes related to production and inventory systems are lean production and inventory tracking and monitoring.

The first subtheme is the use of *lean production*. Lean production principles found in the manufacturing industry can be adapted to IHC for process innovation. Lean production seeks to design waste out of the production system (Heravi and Firoozi, 2017). A pull production system can avoid overproduction and excess inventory by using “backward scheduling” that relies on real-time demand instead of historical data and forecasts (Barriga et al., 2005). Several IHC companies have integrated lean production as a means to increase resource efficiency in their production system (Tykkä et al., 2010).

Another subtheme is *inventory tracking and monitoring***.** Materials and products can be tracked, traced, and visualized through the integration of tracking technologies such as RFID and BIM. These benefits are often touted for schedule improvement. However, they can also be extended to improve materials management (Li et al., 2017). The use of digital tracking identifies the precise number of inventories at any given time (Heravi and Firoozi, 2017). In a production system, lean processes should match with an automated material control system. Barriga et al. (2005) find the current control systems used for IHC have much room for improvement. When processes are not successfully automated, there is greater risk for redundancy of information that can lead to excess resource usage. Hence inventory control systems can create shared and automated platforms in which all parties involved have access to visualize and monitor the supply chain (Alwisy et al., 2019; Barriga et al., 2005).

4.1.7. B3. Transportation systems

Transportation systems refer to the system in which IHC products are transferred from the place of manufacturing to the place of final assembly site. The transportation system in IHC is an important theme to compare resource efficiency in IHC with conventional construction (Mao et al., 2013; Abey and Anand 2019; Quale et al., 2012; Wang et al., 2018; Kamali et al., 2018). In the German timber prefabrication industry, building elements are transported on average 350 km. This contributes to one-tenth of the total global warming potential (GWP) of the studied elements (Achenbach et al., 2018). To reduce transportation distance, the selected manufacturing sites should be close to the final assembly location. However, other scholars argue that performance of IHC during the transportation phase is comparable to conventional construction due to fewer, more efficient deliveries of finished products to the construction site (Du et al., 2019; Adalberth 1997).

Resource efficiency in IHC is impacted by *transportation efficiency* for building elements. One issue is the volume of IHC products. Delivery of finished products to construction sites can require more rounds of delivery (Kim and Bae, 2010). In the transportation of volumetric elements, additional materials are required for stability (Tavares et al., 2019; Boyd et al., 2013; Ahmed and Tsavdaridis 2018). The findings of Smith et al. (2018) show that compared to conventional timber construction, panelized timber construction systems use 6.7% more timber material while volumetric/modular systems use 69.4% more timber material. The significant increase in the case of volumetric/modular system is because of the added wood requirement for transportation rigidity. Overall, conventional construction performs better in resource consumption associated with the transportation phase (Kamali et al., 2019). Within different IHC production systems, transportation efficiency can differ depending on the design of the supply chain. A lean supply chain that requires frequent just-in-time (JIT) delivery of materials to reduce batch size will also require more energy and emits more pollutants (Kim and Bae, 2010). The type of materials being transported also plays a role. Lightweight building systems such as aluminum can reduce the environmental impacts associated with transportation (Mrkonjic, 2007).

Another subtheme is *on-site and near-site manufacturing.* On-site or near-site production systems can reduce the impacts associated with transportation. The distance between where elements are manufactured and are assembled plays a big role.Li et al. (2018b) find that the further manufacturing of a product occurs from the construction site, the worse the environmental performance of that product compared to other alternatives. In Hong Kong, precast elements are manufactured offshore which leads to a much higher environmental impact (Teng and Pan, 2019). Iuorio et al. (2019) show case studies that use “flying factories” as a resolution. Some IHC production systems are designed for portable machines such as CNC routers or 3D printers that can be set up close to the assembly site. This significantly reduces transportation distance of finished products.

4.1.8. C — Assembly

IHC typically conducts fewer production activities at the construction site. However, some activities need to also take place in the construction site. The assembly system employed in this phase is a recurring theme for resource efficiency in IHC.

4.1.9. C1. Assembly system

The assembly system refers to on-site processes required to form the entire building system such as erection and joinery works. Conventional construction activities require operational energy to power various tools and equipment. By contrast, IHC uses a more efficient assembly process (Wang et al., 2018; Jiang et al., 2018; Kim and Bae 2010; Shen et al., 2019; Quale et al., 2012; Zhu et al., 2018; Adalberth 1997). The assembly process is simplified and condensed. However, IHC can require additional materials such as connecting pieces and steel bars for assembly (Zhu et al., 2018).

Site and equipment efficiency is a subtheme under the assembly system of IHC. The opportunity to increase site and equipment efficiency stems from higher levels of standardization in products and processes of IHC. Moreover increased use of digital tools such as BIM facilitate resource efficiency in assembly through clash detections (D'Oca et al., 2018; Alwisy et al., 2019). Mao et al. (2013) find a 10% reduction in impacts associated with equipment use compared to conventional construction. Hoisting of large IHC products such as volumetric module systems can be more efficient than the hoisting of smaller, more frequent material deliveries (e.g. batch of rebars, batch of electrical conduit). The overall number of crane "picks" for a conventional site will be higher, requiring more electricity demand. Additionally, concrete trades in traditional construction sites often use concrete pump trucks whereas, in IHC, projects have already prefabricated the elements (Du et al., 2019; Cao et al., 2015). Cao et al. (2015) find the absence of pump trucks for concrete trade in IHC reduces diesel usage by 51.4% per unit area compared to conventional construction. Similar to the transportation phase, material selection also has an impact. Bukoski et al. (2017) find the assembly of steel IHC systems consumes 590 more liters of diesel for crane and other lifting equipment compared to the assembly of timber IHC systems.

4.1.10. D — Occupancy

Occupancy refers to the use phase of IC buildings. The following section describes the recurring theme and two subthemes identified in this stage.

4.1.11. D1. Operational performance

Operational performance refers to the consumption of resources during the occupancy phase of housing. Resource efficiency in this phase can be used in the form of construction materials or energy. Operational performance for IHC depends on many site and design conditions such as buildings' quality, orientation and site location, ventilation, and energy sources. These decisions should be well integrated with the design of IHC to make sure site-specific resource-efficient buildings are built (Johnston et al., 2014; Frenette et al., 2010; Dong et al., 2018; Dodoo and Gustavsson 2016; Bukoski et al., 2017).

The first subtheme under the operational performance of IHC is *operational energy efficiency*. Researchers have found differing operational energy efficiency for IHC. Some literature suggests energy efficiency for IHC is similar to conventional construction (Zhu et al., 2018; Briones-Llorente et al., 2019; Aye et al., 2012; Korjenic and Klarić 2011; Brehar and Kopenetz 2011). In other researches, IHC products seem to outperform traditionally constructed buildings. For example, Samani et al. (2015) find the extruded polystyrene (XPS) wall system performs 1.8 times better in thermal resistance than a brick wall. Some IHC products such as CLT claim high acoustic and thermal performance that do not require additional insulation materials (Lehmann, 2012). Nevertheless, there are opportunities to have better-performing structures in IHC. Although IHC systems can use lightweight materials such as timber and aluminum that benefit prefabrication and assembly processes, these materials have lower thermal inertia that leads to decreased stability in indoor temperature (Mrkonjic 2007; Rodrigues et al., 2016). Also, volumetric and dry-construction systems in IHC can suffer from higher heat loss and air leakage at the intersection of modules and elements (Maoduš et al., 2016). Hence more attention should be given to interfaces between products to ensure a balanced system in which indoor conditions are comfortable (D'Orazio and Maracchini, 2019).

An additional subtheme is *non-intrusive refurbishment*. IHC can be used to refurbish older buildings and improve operational energy performance. The application of prefabricated insulation panels or façade systems to existing buildings reduces the operational energy resource demand (Pihelo and Kalamees 2019; Passer et al., 2016). This opportunity for non-intrusive refurbishment is large. For example, Paiho et al. (2015) note that close to 60% of Russia's multi-family housing stock needs renovation. Various façade solutions have been developed for this application. In the research of Paiho et al. (2015), a standardized multifunctional energy-efficient façade (MEEF) system is introduced as a non-intrusive refurbishment solution. Such solutions promote an opportunity to renovate buildings with minimum resources and less distraction of existing structures (D'Oca et al., 2018).

4.1.12. E - End of life

End of Life (EoL) refers to post-occupancy once a building structure has served its initial design lifetime or purpose. The recurring theme of reusability and recyclability discusses resource efficiency in this phase.

4.1.13. E1. Reusability and recyclability

Reusability and recyclability potential for IHC refers to reintegration of IHC products and systems into the supply chain. Such lifecycle benefits have been given low importance in the past (Jaillon and Poon, 2010), but recent scholarship points to the increasing need for such approaches (Borsos et al., 2019). Two subthemes during the EoL phase include product flexibility and product-as-a-service.

The first subtheme is the *product flexibility* of IHC. Product flexibility is a design solution such as design for disassembly (DfD) that ensures design solutions are dynamic to operations, maintenance, and EoL requirements. IHC structures can be designed for more efficient dismantling or deconstruction (Brehar and Kopenetz 2011; Borsos et al., 2019). Designing products for flexibility contributes to easier repair or replacement processes (Jaillon and Poon 2010; Mrkonjic 2007; Khahro et al., 2019; Wang et al., 2018; Tettey et al., 2019). Design strategies such as separating building components based on expected lifespan eases the disassembly during maintenance and EoL (Nijs et al., 2011). Technical systems fastened together using nails can cause more structural damage during EoL when compared to modular systems fastened with bolted connections. Bespoke connections should be avoided (Phillips et al., 2016). Apart from the technical systems employed in IHC, the type of material used for construction increases or decreases the reusability and recyclability opportunities. Reusability potentials of timber and steel composite are found to be high (Loss and Davison 2017; Balasbaneh and Bin Marsono 2018). The research of Aye et al. (2012) shows the reusability potential of prefabricated steel to be 81.3%, timber buildings 69.1%, and concrete buildings 32.3%. Ultimately, the disassembly process is much easier and there is more opportunity for reuse or recycling of the elements, especially compared to conventional demolition which typically leads to landfill disposal.

The second subtheme is *product-as-a-service*. Product-as-a-service is a new business model where manufacturers shift from selling products to providing services. This builds a long-term relationship between the customer (or the product) and the manufacturer. The reusability and recyclability potential of IHC elements is not insured until there is a specific stakeholder designated to handle the end of life of a building. Mrkonjic (2007) describes an "overall management system" in which a building can be rented (leased) out to individuals while manufacturers retain permanent responsibility for the EoL. Information on customers' preference, lifecycle product performance, and frequent fault patterns can be collected and shared using extended function quality deployment and data mining technologies (Ni et al., 2007).

4.2. Frequency analysis

From the 86 papers studied, 80 discuss the eight recurring primary themes and those are analyzed in this section.

From the 80 papers, 48 articles study resource efficiency during the design phase, and 47 articles study resource efficiency during the manufacturing and logistics phase. The number of articles studying resource efficiency in downstream building lifecycle phases is much lower than in the early phases. When analyzing the frequency of recurring themes, material design (A2) is the most discussed theme followed by waste and quality management (B1). Recurring themes belonging to downstream building lifecycle phases such as reusability and recyclability (E1) and assembly system (D1) are mentioned infrequently. The least frequent recurring theme is the topic of production system (B2). The results from the first frequency analysis are illustrated in Fig. 2 and elaborated in Appendix A and B.

The second frequency analysis shows that all 80 articles mention at least one recurring theme. However, only 24 articles mention more than one recurring theme and only 10 articles discuss 3 recurring themes. Lastly, only 2 articles cover 5 of the recurring themes. The analysis also shows that no articles cover the entire eight recurring themes that were identified in the SLR. The second frequency analysis in this paper is demonstrated in Fig. 3 and Appendix C.

4.3. Additional recurring themes

There are several recurring themes and subthemes associated with resource-efficient IHC but that do not fit within a single building phase. These themes can be categorized as industry factors (Table 3) and regulatory factors (Table 4). The list of articles and additional recurring themes can also be found in Appendix D.

4.3.1. Industry factors

First, because there can be general skepticism around IHC, *user integration* is a crucial step (Zhai et al., 2014a) (Table 3). Customers' willingness to pay (WTP) differs based on what they are paying for. For green building features such as LED lighting and water-saving showerheads, the WTP is high. However, the WTP for prefabricated elements is low. Customers tend not to value resource efficiency in processes such as industrialized production methods as highly as they might value resource efficiency seen in more visible end-products (Yau et al., 2014). Providing a user-friendly interface for users is a good step to take to integrate users (Iuorio et al., 2019). Additionally, showcasing benefits through demonstrative projects helps to reduce uncertainties surrounding innovations in the face of stakeholders and add to the learning process for product development (Koch and Bertelsen, 2014).

Second, because construction firms operate within a networked industry structure, there is a network effect that challenges *firm-level commitment* to adopt more sustainable IHC (Table 3). For example, six of the IHC companies studied by Tykkä et al. (2010) mention the lack of competencies in timber engineering as an impediment. Lack of knowledge surrounding technology and equipment in IHC lifecycle phases can compromise the benefits of IHC such as quality assurance (Luo et al., 2015; Wu et al., 2019). Moreover, IHC requires earlier involvement of stakeholders but this can be difficult in a conventional project and organizational structures (Jaillon and Poon, 2008). In that sense the role IHC firms to implement resource-efficient construction systems is pivotal (Warren-Myers and Heywood, 2018).

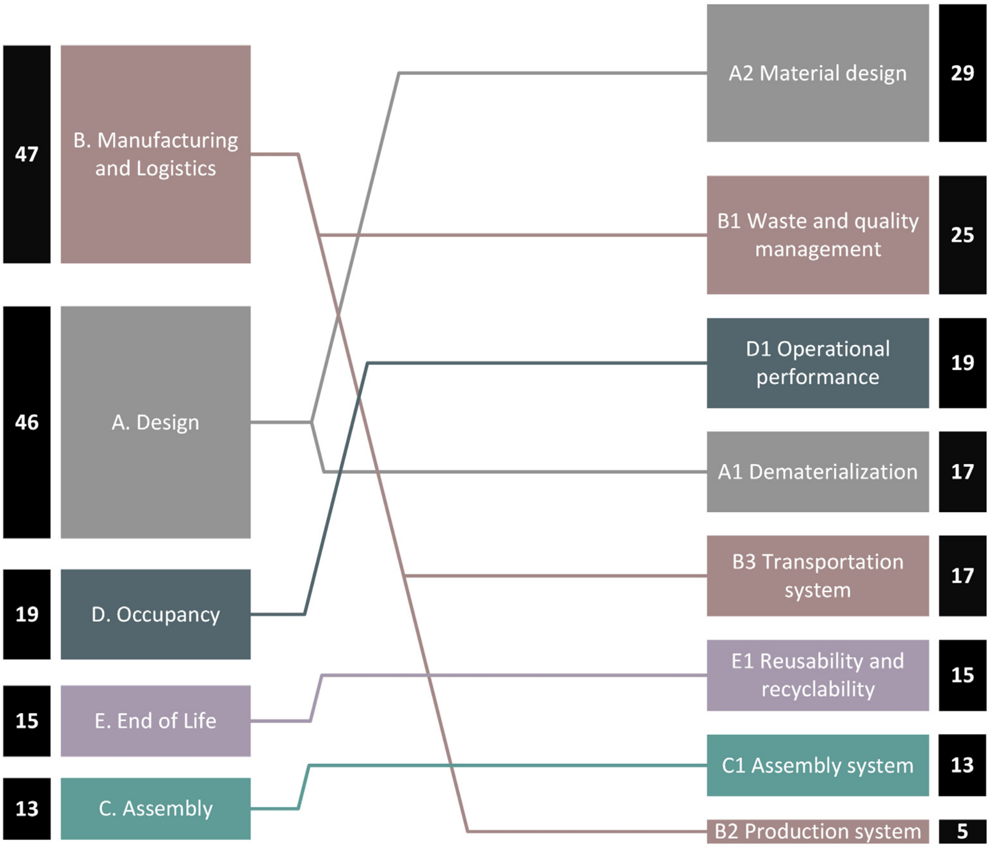

Fig. 2. Frequency of mentions of building lifecycle phases and recurring themes in studied literature.

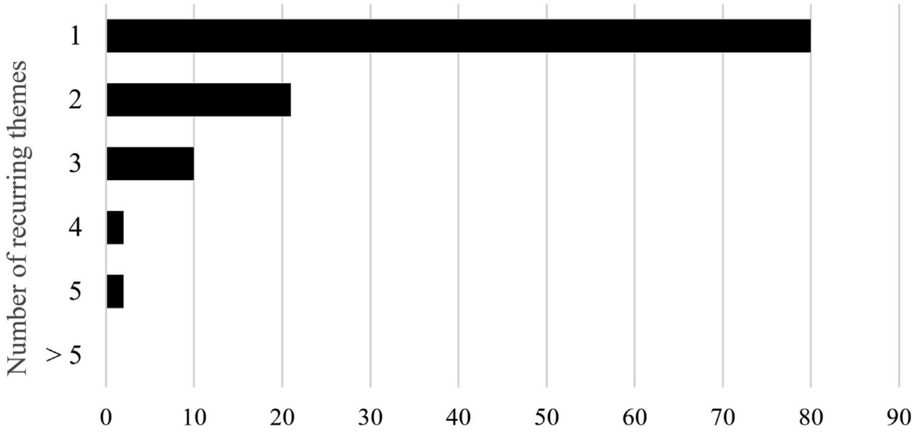

Fig. 3. Number of recurring themes mentioned by articles.

Table 3
Additional recurring theme (industry factors) and subthemes.

Industry factors	
User integration	The integration of end customer for better development of resource-efficient IHC.
Firm-level commitment	The advancement of firms towards resource-efficient IHC.

Table 4
Additional recurring theme (regulatory factors) and subthemes.

Regulatory factors	
Building codes	Introduction of building codes that permit and promote innovative and industrial materials and products with resource efficiency potentials.
Incentives and policies	The need for regulatory bodies to facilitate the adoption of resource efficiency in IHC.

4.3.2. Regulatory factors

Regulatory factors are related to the codes, policies, and incentives that locally impact IHC (Table 4). The shift towards performance-based *building codes* has led to an increase in innovative ways of building houses. Contrary to the compliance code, these codes only specify the intended performance of materials and products and do not mention specific materials or products (Schuler et al., 2001). The lack of building codes that fit innovative materials and products also hinders resource efficiency in IHC (Zhai et al., 2014b; Luo et al., 2015; Khahro et al., 2019; Lehmann 2012).

Regulatory bodies also use differing *incentives and policies* to promote innovation for IHC (Tykkä et al., 2010; Li et al., 2018a; Wu et al., 2019; Zhai et al., 2014b; Jaillon and Poon 2008). Builders request incentives to help with high capital investment costs in IHC (Luo et al., 2015; Shen et al., 2019). Policies implemented in different countries can promote IHC for its resource efficiency potentials (Tykkä et al., 2010). For example, Hong Kong provides government incentives for IHC specifically to address waste reduction and quality improvements (Jaillon and Poon, 2008).

5. Discussion, limitations, and future research directions

This SLR identifies eight recurring themes and fifteen subthemes for resource efficiency across the building lifecyle phases of IHC. The diversity of the contribution from the studied literature revealed the importance of aggregating the recognized performance and potential of IHC into a holistic overview. In particular, the following two observations emerge as points of further discussion.

The first discussion point is **the impact of early systems decisions** on resource efficiency that perpetuate across the building lifecycle phases. Early system decisions should aim to create high-value products during the value creation processes and plan to maintain value in the value retention phases (Achterberg et al., 2016). Although different resource efficiency subthemes popped up in the design, manufacturing and logistic, occupancy, and EoL phases of IHC, many of them are planned and implemented in the early stages of the building lifecycle phases. These subthemes are enormous and can be placed in the *value creation* process of IHC (Fig. 4). During the value creation process of IHC, the product and manufacturing-led approach taken by IHC shows the strength of IHC to design and manufacture *high-value* products. Once the value is created, the product should be at its highest value and delivered for use. During the use phase, the potential of IHC to increase resource efficiency is mainly seen by its *value retention* potentials through products that can sustain their quality and design solutions that allow flexibility in occupancy and after EoL. The research has found a significant relationship between early design decisions and subsequent resource efficiency potentials of IHC across lifecycle phases. For example, the types of materials specified in the design phase show a propelling effect in energy requirements during transportation and assembly phases. In the same way, the forethought given to the assembly platform was found to be crucial for the occupancy and EoL resource efficiency of IHC. To that end, all of the subthemes in IHC for resource efficiency should be evaluated at a systems-level and integrated into the early design phases. Nevertheless, researches (Jaillon and Poon, 2010) point to the limited considerations given to both value creation and retention performances of IHC for resource efficiency.

Viewed more broadly, this relates to the second discussion point, the **opportunity for *beyond*-systems** optimization. These opportunities complement the individual performances of the

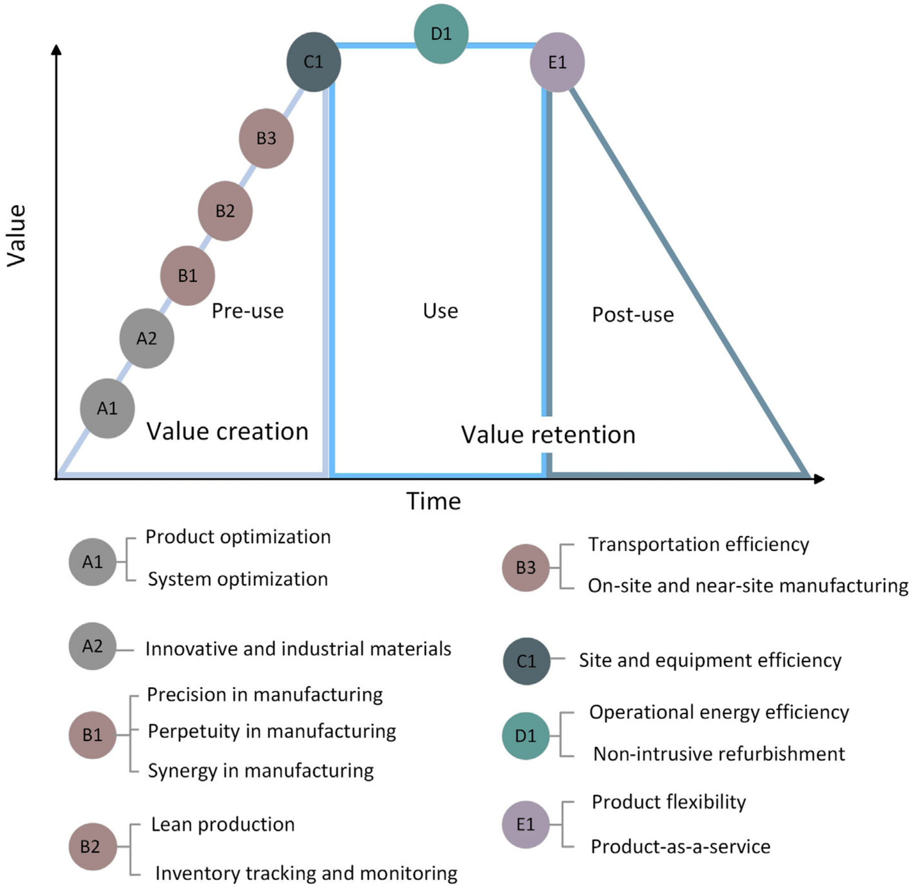

Fig. 4. Subthemes for resource efficiency in IHC across the value hill, adapted from Achterberg et al. (2016).

products and stakeholders along the construction value chain. Through IHC, a much better adoption of supply chain integration is studied (Lessing and Brege, 2015). This research also shows opportunities such as digital platforms that can increase monitoring of resources and business models that promote resource efficiency. This can amount to a much greater cross-systems resource efficiency accounting. Furthermore, the additional recurring themes reveal that resource efficiency in IC cannot be achieved with only technical innovation but rather through integrating people and policies.

Although the SLR identifies many examples of successful resource-efficient IHC systems, there are also many opportunities for improvement. Future IHC systems can be organized through digital manufacturing-led supply chains that enable better control of the entire lifecycle and value chain of products. Forward-looking frameworks give explicit attention to resource efficiency for the future of the built environment (Fig. 5) (Construction Products Association, 2016). This may include consideration of 1) *intelligent built assets* that give feedback on their actual performance in real-time, 2) resource-efficient economic models such as *circular economy* that enable the re-use, re-distribution, remanufacturing, and recycling of materials and products, and 3) a manufacturing-led industry through the *4th industrial revolution* encompassing several strategies that enable a digital and automated production and value chain (Oesterreich and Teuteberg, 2016). The combination of these three elements can lead toward IHC products and systems that are smart, optimized, and resource-efficient.

5.1. *Future research directions*

From consideration of the findings and the above future trends for the built environment, we suggest three future research directions. First, IHC scholars could investigate *resource-efficient economic models* such as the circular economy. In theory, there could be strong symbiosis between circular economy and IHC supply chains. IHC scholarship to date has looked at linear production models, but emerging scholarship on design for disassembly (Mrkonjic 2007; Rausch et al., 2019) and renewable or bio-based materials (Briones-Llorente et al., 2019) can create circular, technical, and biological feedback loops.

Second, IHC scholars could study the intricate ecosystem of the construction value chain. Capturing, storing, and distributing manufacturing data is an advantage for strategic manufacturer-supplier-client relationships. Studies increasingly show the collaboration and coordination of the value chain provide stakeholders with the incentives for more resource-efficient design and manufacturing of IHC that capture this value (Dallasega et al., 2018). This research direction can create awareness and commitment to resource efficiency in IHC firms that are studied to be insufficient (Chang et al., 2016).

Third, attention must be paid across technological, institutional, and relational aspects (Scrase et al., 2009). For example, the impact of customers' perspectives and WTP for IHC housing construction will impact how effectively the resources have been deployed. Some early research has identified this but much more research is needed (Kedir et al., 2020). Other research suggests

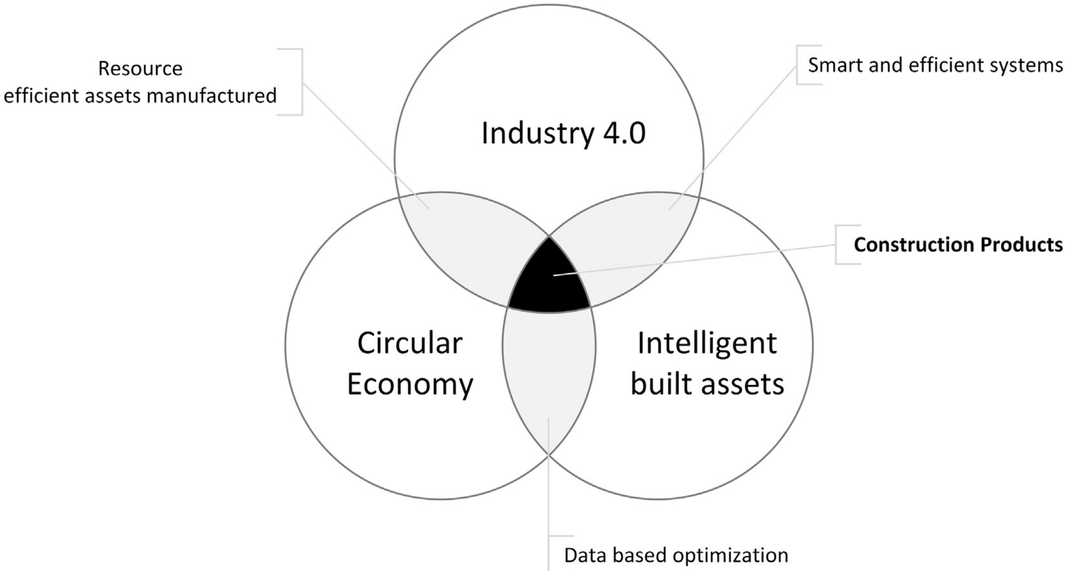

Fig. 5. Construction products framework, adapted from Construction Products Association (2016).

the role of IHC firms in driving resource efficiency could be similar to the power of the consumer (Warren-Myers and Heywood, 2018). Nevertheless, It is still unclear how IHC will shape the societal and economical aspects of resource efficiency (Memari et al., 2014).

5.2. Limitations

Some limitations to the SLR must be recognized. The findings and discussion are based on available literature gathered through a limited number of keywords and databases. While the search was designed for broad initial gathering of papers that were filtered through a structured process, there is still potential that some literature has been overlooked. Next, the reviewed papers are diverse with respect to the types of project, scope, context, and assumptions employed in different impact assessment methods. Many authors themselves point out the difficulty of comparing resource efficiency potentials across studies due to this uniqueness. Therefore, this paper should be understood as an attempt to identify themes and trends in the literature and not as a source of specific data or form of meta-analysis. Finally, the paper studied only a particular application of Industrialized Construction, i.e. housing, in order to limit the overall scope. However, we expect the findings presented here can be applied or adapted for other infrastructure and facilities in the built environment.

6. Conclusion

Given the enormous global housing demand coupled with unsustainable approaches to housing construction, there has been increased research attention to alternative housing construction methods such as IHC. This paper provides a comprehensive overview of resource efficiency in IHC. Through a systematic review of a broad range of literature, the paper provides a foundational list of resource efficiency themes in IHC. A structured categorization unpacks resource efficiency in IHC through eight recurring themes and fifteen specific subthemes across building lifecycle phases. As presented in this paper, IHC does not inherently deliver complete resource-efficient solutions. However, IHC can facilitate resource-efficiency through a combination of approaches such as digitalization, standardization, production, and advanced logistics. Findings show the interrelationship between the different themes and the need to make early systems decisions to achieve all-out resource efficiency. Furthermore, beyond-system optimization strategies of socio-technical factors can foster the adoption of resource efficiency in IHC. The paper also implies the key opportunities for future iterations of IHC to improve upon its current performance. Resource efficiency is dependent upon multiple stakeholders and various building lifecycle phases. It is paramount to study these holistically and implement resource efficiency at a scale. Therefore, future implementation of IHC should in addition to the recurring themes exploit resource-efficient economical models, value chain collaboration, and socio-technical perspectives.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.125443.

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