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Integrating Sustainability Criteria into a Decision Model for Reverse Logistics in Industrialized Housebuilding: A Field Study Approach

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Abstract

Question: How can sustainability criteria be integrated into a decision model to enhance the application of reverse logistics in construction?

Purpose: The study explored how economic, social, and environmental sustainability criteria could be integrated into a decision model for reverse logistics design.

Research Method: A field study tested a decision model based on multiple-criteria decision analysis at an industrialized housebuilding firm in Sweden. Through theory, observations, interviews, and expert validation, a practical decision model was developed and tested to enhance transport and weatherproofing of modules.

Findings: The theoretical framework primarily developed for the engineering and automotive industries can be adapted for reverse logistics in industrialized housebuilding by using a decision model based on multiple-criteria decision analysis.

Limitations: Further research is needed to validate and refine the model, and to extend its application to other construction products and processes. The findings may be more specific to the process examined in the field study rather than across the industry.

Implications: The criteria of the decision model support decision-making in the weather and transportation protection process, though they can be further refined to provide a more precise basis for decisions.

Value for practitioners: Understanding the importance of systematic decision-making in reverse logistics design can improve sustainability and ensure compliance.

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Introduction

Challenges in reverse logistics are particularly relevant to the Architecture, Engineering, and Construction (AEC) industry (Pushpamali et al.2019), as the sector significantly contributes to climate impact (Guggemos and Horvath 2006; Pachauri et al.2014; United Nations 2021). The urgent need for shifting to better sustainability is driven by the necessity to minimize waste, optimize resource use, and reduce environmental impact. The circular economy (Joensuu et al.2020) offers a way of achieving this shift by emphasizing reuse (Ericsson et al.2024), demolition waste management (Iodice et al.2021; Assaf et al.2024), and reverse logistics (Chinda and Ammarapala 2016; Marzouk et al.2019; Ding et al.2023), ensuring materials remain in circulation for as long as possible. However, for these strategies to be effective, they should align with Lean Construction principles.

The concept of reverse logistics is not new, yet it remains underutilized in construction, and is sometimes confused with reuse or waste management. Reuse extends the lifespan of materials (O'Grady et al.2021), reducing the demand for virgin resources, while waste management focuses on minimizing, sorting, and reintegrating construction and demolition waste into supply chains (Rosli et al. 2023). Reverse logistics, however, facilitates the efficient redistribution of materials, optimizing material flows (Hosseini et al.2015). When integrated with Lean Construction, as described by Orsi et al. (2021) when applied to green building project management and Alazmi et al. (2024) who incorporated sustainability, reverse logistics could then eliminate inefficiencies (Muda) such as overproduction, excess inventory, and transportation, and thereby emissions and demolition waste.

Emissions from the Swedish construction sector account for 22% of Sweden's total emissions, according to the National Board of Housing (2025a). In 2022, approximately 13.6 million tons of primary construction and demolition waste were generated in Sweden, including nearly 0.6 million tons of hazardous waste. This represented 39% of all waste generated in Sweden and 20% of all hazardous waste, excluding the large volume of mining waste (National Board of Housing 2025b). Waste reduction is, therefore, considered crucial for achieving Sweden's climate goals by 2035. The implementation of European directives on packaging, packaging waste, and landfill disposal in Swedish construction waste legislation has intensified the need for effective decision-making tools in reverse logistics design within AEC companies.

Reverse logistics in construction is an emerging research area that integrates principles from Lean Construction, supply chain management, and sustainability. It involves managing and recovering materials, resources, and waste generated during construction, demolition, or renovation projects (Hammes et al.2020). The process focuses on planning and controlling the flow and storage of materials to facilitate reuse, recycling, or proper disposal (Ding et al.2023). The theoretical field of reverse logistics emphasizes the controlled reuse of materials and includes the relocation and management of products and resources after delivery to the customer (Blumberg 2004; Karabacak and Saygılı 2022). However, its application has primarily been developed for the engineering and automotive industries (Hosseini et al.2015).

For studying reverse logistics in construction, industrialized housebuilding serves as a suitable context. It shares similarities with the engineering and automotive industries, and industrialized housebuilding companies implement a systematic approach to logistics as part of their business model (Brege et al.2014). Therefore, carrying out a a case study within the context of industrialized housebuilding provides a setting where we might expect to find reverse logistics processes to examine.

Industrialized housebuilding, also known as modular construction, shifts the traditional project-based focus in the construction industry to a process-oriented approach (Höök and Stehn 2008). This transition aims to enhance efficiency through platform thinking (Jansson et al.2014) and the prefabrication of building components (Erikshammar et al.2013). For industrialized housebuilding companies utilizing off-site prefabrication, it is crucial to protect modules during transport and on-site storage. This is typically achieved by wrapping or covering them with tarpaulins or plastic. According to the National Board of Housing (Boverket 2024), modules must be safeguarded against moisture damage and physical impacts caused by wind and dirt. This safeguarding often generates plastic waste. Industrialized housebuilding companies aim to standardize covering, uncovering, and waste management processes while leveraging modular construction's potential to reduce waste (Zhang et al.2024).

However, decision-making support for reverse logistics in the AEC industry remains underdeveloped (Chinda and Ammarapala 2016). A literature review by Pushapamali et al. (2019) found that construction industry research does not fully address the impact of reverse logistics on upstream construction activities. The authors argued that reverse logistics decisions should be integrated early in the construction process, considering both upstream and end-of-life activities. Chileshe et al. (2018) highlighted how reverse logistics implementation in the construction industry remains limited. Studies from different regions, including Nunes et al. (2009) in Brazil, Arif et al. (2012) in India, and Chileshe et al. (2015) in Australia, suggest that its application primarily focuses on waste minimization through recycling and reduction. Overall, discussions on reverse logistics in construction are largely centered on waste management. This view is supported by scholars (Sobotka and Czaja 2015; Chinda and Ammarapala 2016; Brandão et al.2021), who have emphasized the need for a foundation to develop a decision-support system for reverse logistics design.

The purpose of this study was to explore how economic, social, and environmental sustainability criteria could be integrated into a decision model for reverse logistics design in construction. The study contributes to a deeper understanding of reverse logistics and its application in sustainable industrialized housebuilding, as well as how decision models for reverse logistics design can be applied in construction more broadly.

The paper is structured as follows: it begins with a literature review of reverse logistics, followed by a methodology section detailing the field study and the development of the decision model. The next section presents the field study results, including a description of the transport and waterproofing process and the decision model tested at the case company. Finally, there is an analysis of both the decision model and the study, conclusions that outline key findings, and suggestions of directions for future research.

Reverse Logistics

Carter and Ellram (1998) noted the early lack of a theoretical foundation in reverse logistics, with most studies focusing on practice rather than theory-building. Blumberg (2004) emphasized that growing sustainability requirements, digitization, shorter product lifespans, and increasing demand for customer-friendly returns have intensified the focus on product handling, repair, and recycling. Blumberg (2004) also highlighted its emergence in the 1990s as a business strategy to explore new markets and improve financial performance, considering a product's entire life cycle. Regulatory frameworks, including 'green legislation,' have further shaped reverse logistics by enforcing requirements for product returns, recycling, and reuse (Tseng et al.2019).

Murphy (1986) introduced the concept of reverse distribution, emphasizing the movement of products from consumers back to producers or suppliers within a distribution network, with a focus on transport and inventory management. Carter and Ellram (1998) later defined reverse logistics as a strategy to enhance efficiency and sustainability through recycling, reuse, and material reduction. Rogers and Tibben-Lembke (1999) expanded on this by describing it as the management of cost-efficient material and information flow from consumers back to the source, aiming to create value through reuse and recycling. Dekker et al. (2013) further refined the concept, emphasizing its role in optimizing how society uses and reuses products efficiently.

Carter and Ellram (1998) stressed that understanding the supply chain for reuse and recycling provides competitive advantages. While Rogers and Tibben-Lembke (1999) cited economic benefits as the main driver of reverse logistics, Carter and Ellram (1999) highlighted its growing role in sustainability. Reverse logistics can also boost profits (Srivastava 2005) by optimizing cost structures (Carter and Ellram 1999) and reducing resource investment, warehousing, and distribution costs (Genchev 2009). Beyond cost savings, it minimizes environmental impact.

High costs and the need for quality checks often deter organizations from implementing reverse logistics (Genchev 2009). Rogers and Tibben-Lembke (1999) suggested earlier that, when focusing on reducing materials in manufacturing, 'green logistics' is a more accurate term than reverse logistics. Dekker et al. (2013) noted that reverse logistics had shifted from an environmental focus to a broader, value-driven approach. It is now widely recognized as part of sustainable development (Pearce and Atkinson 1998; Srivastava 2007; Tseng et al.2019; Amir et al.2023).

Reverse Logistics in Construction

Reverse logistics can be examined from the perspective of either the production phase or the product life cycle. This study focuses on the production process rather than end-of-life demolition. However, the production process can begin with the demolition of a previous building (Chileshe 2016). The literature review revealed a lack of studies of reverse logistics in construction production. According to Hosseini et al. (2015), this is partly because its application in the construction industry has primarily emphasized environmental benefits rather than economic and social advantages, which previously have not been in focus.

Hosseini et al. (2015) stated that much of the existing research on reverse logistics is rooted in the engineering and automotive industries, leaving a gap in deeper studies within the construction sector. In construction literature, the term 'reverse logistics' is often borrowed from studies in these industries and applied to the construction context (Sharma et al.2011). Hosseini et al. (2014) emphasized that reverse logistics is not yet a fully established concept in construction, and many researchers in the field do not consider it integral to the industry. The lack of consensus on its role in construction has led to confusion about its boundaries in relation to similar concepts such as 'forward logistics' and 'green logistics' (Rogers and Tibben-Lembke 2001), as well as demolition (Wijewickrama 2020) and waste management (Hosseini et al.2014).

Lu and Yuan (2011) categorized construction waste management research into waste quantification, reduction measures, and implementation. Poon et al. (2004) assessed waste reduction strategies in Hong Kong, focusing on planning, sorting, and recycling. Hao et al. (2008) used system dynamics modeling to evaluate waste management benefits on Hong Kong construction sites, with minimization and recycling. Tam et al. (2007) highlighted the role of prefabrication's role in reducing waste and improving reverse logistics through modular design.

Hosseini et al. (2014) argued that these concepts have often been misinterpreted, possibly due to increased awareness of environmental issues. They defined green logistics as primarily aligned with 'forward logistics,' focusing on the environmental aspects of logistics activities from production to handover. Despite these differences, Hosseini et al. (2014) acknowledged some overlap. Reverse logistics involves manufacturing and reuse with environmental and ecological benefits, while waste management focuses on efficiently collecting and processing materials for recycling (Hosseini et al.2014; Genchev 2009). Jayasinghe et al. (2014) also identified and analyzed the cause-and-effect relationships of the risks associated with reverse logistics, highlighting the need for a systematic assessment of different designs. Furthermore, Chinda (2017) investigated key factors influencing the successful implementation of reverse logistics in the construction industry. This indicates that a decision model for practitioners could support implementation and enhance understanding of the process. However, this aspect falls outside the scope of this paper.

Criteria and Sub-criteria for Reverse Logistics Application

Applying reverse logistics in the construction industry presents challenges, as the approach used in engineering and automotive sectors does not directly translate (Schultmann and Sunke 2007). The construction sector has a fragmented supply chain, making implementation barriers more complex. Key differences include production strategies, product life cycles, and recycling processes. Additionally, the fragmented supply chain in construction projects complicates coordination, as suppliers, subcontractors, and contractors follow their own recycling processes (ibid.). Reverse logistics is driven by economic, ecological, and social sustainability (Dekker et al.2013; Schamne and Nagalli 2016). Most research discusses these three main criteria, further broken down into sub-criteria used in decision-making. Economic sub-criteria often relate to marketing, competition, or financial sustainability, while environmental sub-criteria include legislation and consumer or governmental incentives. Social sub-criteria typically focus on workplace safety, health, and shared value expectations.

Dekker et al. (2013) noted that defining clear boundaries between these criteria is challenging, as legislation, costs, and consumer attitudes vary across industries and regions. Consequently, no universal decision-making framework applies across sectors, making it impractical to transfer reverse logistics models directly from engineering and automotive industries to construction (Schultmann et al.2007; Hosseini et al.2014; Chileshe et al.2015; Hosseini et al.2015). However, Chinda and Ammarapala (2016) examined factors (economic and site-specific) with their 15 sub-factors affecting the decisions to design reverse logistics and suggested that the transportation cost, the processing cost, the specific sorting technology, and the limited project time must be considered first.

Economic sustainability criteria in the construction industry

Hosseini et al. (2014) stated that the primary economic driver for reverse logistics in the construction industry is cost saving. Companies can reduce overall costs and improve productivity by minimizing energy, material, equipment, maintenance, transportation, and labor expenses. The main drivers of reverse logistics have been explored by several researchers, including Hosseini et al. (2014) and Dekker et al. (2013). Chileshe et al. (2018) highlighted its role in optimizing resource use, improving material quality, and enhancing efficiency. According to Chileshe et al. (2018), key economic drivers include:

- Cost reduction through minimized waste management and recycled materials
- Increased revenue from new value streams
- Legislation or financial incentives for building demolition and the use of recycled materials

Ecologic sustainability criteria in the construction industry

Hosseini et al. (2014) discussed applicable environmental criteria, emphasizing that construction organizations are driven to minimize their environmental impact through legislation, regulations, and consumer demands. Effective reverse logistics in the construction industry can reduce landfill waste and increase product reuse, which is particularly important in this sector (ibid.). Hosseini et al. (2014) and Chileshe et al. (2018) outline key environmental factors in construction, including:

- Legislation and client/consumer requirements
- Use of raw materials in production

- Energy consumption in production and transportation
- Waste reduction
- Policies for disassembly, demolition, and material reuse
- Reputation and green image

Social sustainability criteria in construction industry

In the construction industry, the social aspects of reverse logistics primarily relate to meeting environmental criteria to enhance a company's green image and improve public perception (Rogers and Tibben-Lembke 1999; Chiou et al.2012; Chileshe et al.2018). The key social benefits of reverse logistics include:

- Enhancing the company's reputation and image
- Job creation
- Strengthening brand loyalty, particularly in the labor-intensive and locally focused construction sector

Dependent driving forces

The driving forces behind reverse logistics are interdependent, making it difficult to distinguish sub-criteria or establish clear links between them and specific drivers. As a result, no universal criteria currently exist for applying reverse logistics to achieve sustainability (Akdoğan and Coşkun 2012; Dekker et al.2013; Hosseini et al.2014).

Sub-criteria vary depending on context, goals, and industry-specific challenges, but they generally align with economic, ecological and social sustainability. Akdoğan and Coşkun (2012) highlighted the difficulty of defining universally applicable criteria due to the wide range of factors involved. Companies must assess relevant sub-criteria based on their industry and objectives to effectively implement reverse logistics (Coşkun 2012).

Vaz et al. (2012) and Dekker et al. (2013) emphasized the challenges of designing an efficient reverse logistics system, as economic, environmental, and social factors are complex and vary across different contexts.

Method

The design of reverse logistics remains relatively unexplored in the construction industry (Hosseini et al.2015). To address this, we carried out a field study (Malsch and Salterio 2016) at an industrialized housebuilding company in southern Sweden, serving as an extreme case (Flyvbjerg 2006), to examine reverse logistics and explore how sustainability criteria can be integrated into decision models for reverse logistics in construction.

First, a literature review was carried out to translate theoretical concepts into practical decision-making criteria. The initial literature search used 'reverse logistics' and 'construction,' followed by keyword extraction from top-ranked articles. The review revealed that reverse logistics is underexplored in construction, prompting further searches using related terms such as 'closed-loop supply chain,' 'waste management,' and 'green logistics'. Most studies focused on the engineering and automotive industries, leading to an additional search within the 'construction industry'. To develop the decision model, searches included 'easy decision-making matrix,' 'decision models,' 'weighted sum model,' and an in-depth review of Multiple-Criteria Decision Analysis.

The contextualized decision model and its criteria for Industrialized Housebuilding for weather and transport proofing was then tested in a field study to evaluate a solution for the case company on how to weatherproof and transport modules effectively. The selection of weather and transport proofing was suitable for the field study as it is a limited and controlled process within industrialized housebuilding, making it comparable to waste management and reverse logistics for material reuse. This process involves temporary protective coverings, often discarded after use, creating a clear link to material flows and reuse opportunities. By focusing on this aspect, the study effectively examined how reverse logistics might be applied to reduce waste and extend reuse in a structured setting.

The rationale for conducting the field study was to test the decision model within the company context, allowing us to follow the participants' reasoning and, ultimately, ensure that the analysis is relevant for theoretical development. The study prioritized developing a decision model that was both easy to understand for practitioners and adaptable to various reverse logistics scenarios. However, by narrowing the criteria to those most relevant to the case company's operations, the study ensured a focused and applicable evaluation.

Finally, to ensure the validity of the study, an independent researcher specializing in decision-making evaluated the material. The researcher reviewed the summarized case study data, providing an assessment of the decision model and its applicability. This independent evaluation helped validate the findings and potential areas for refinement.

The field study took place both at the case company's off-site production facility and a construction site. The case company is an industrialized housebuilding firm that designs, produces, and assembles modular multifamily dwellings. It operates as a joint venture between a construction company and a retailer, focusing on providing affordable housing while reducing waste, emissions, and build lead times. Based in southern Sweden, the company has delivered 12,000 homes across Sweden, Finland, and Norway.

Data for this field study were collected through process mapping (Damelio 2011), interviews (Galvin 2015), and observations (Arumugam et al.2012). The process mapping involved observations off- and on-site, photographing, and interviewing workers and supervisors engaged in off-site activities and on the construction site over one week. The process mapping focused on covering procedures in the factory, protection during transport, and uncovering at the construction site. The choice of process mapping over Value Stream Mapping (VSM), as used by Erikshammar et al. (2013), was based on the goal of obtaining a rich dataset with diverse criteria. This approach differs from VSM, which primarily focuses on capturing Muda and single values (leadtime, work hours, inventory). Observations and unstructured interviews were carried out both off-site and on-site to develop a comprehensive understanding of the system and validate the process mapping with practitioners.

Two semi-structured (Galvin 2015) online interviews, each lasting between 45 and 60 minutes, were carried out primarily to validate the theoretical model against industrial requirements and enhance the study's external validity. The formulation of interview questions was guided by criteria from the literature review. The interviews were carried out with on-site staff and involved two individuals: a manager responsible for environmental, quality, and workplace conditions in the factory, and a project manager with technical expertise in construction site production. Supplementary questions were addressed using email.

A Decision Model

Multiple-Criteria Decision Analysis (MCDA) encompasses various methods, as discussed by Angelis and Kanavos (2017). Figueira et al (2005) emphasized that while MCDA is not always necessary for decision-making, a decision matrix can help streamline the process and reduce confusion.

Figueira et al (2005) further explained that decisions are often made by simply listing advantages and disadvantages. However, when multiple input parameters influence a decision, a decision matrix provides a more structured approach by highlighting key factors that impact the final choice (ibid.). A decision matrix simplifies MCDA, making it more accessible. The method used in this study was based on a simplified version of MCDA, ensuring greater ease of understanding and practical application for decision-making

The Decision Model in Industrialized Housebuilding for Weather and transportation proofing

The decision model consists of several analysis steps, criteria and sub-criteria that were evaluated. The selected decision criteria and their data sources are presented in Table 1. The selected decision criteria were chosen specifically to align with the context of industrialized house building. This selection was made through discussions with the case company, leveraging their prior knowledge and practical experience, as well as insights gathered from the literature review.

Decision criteria are a crucial component of the model (Figure 1). They were prioritized on a scale of 1 to 3, with 3 being the most important and 1 the least. For yes-or-no questions, only 3 or 1 was assigned. The grading process used a 1–3 point scale for the products involved. If there was insufficient information for a specific criterion within a product category, a comment was added, and a rating of 0 assigned unless an assumption was made.

The model serves as a decision-making tool to compare products, with comments highlighting key reflections. Since decisions are often based on both factual data and assumptions, it is important to document any underlying considerations. For example, if one solution requires a crane while another can be lifted by a single operator, this distinction should be noted.

Table 1: Decision criteria and data sources

Criteria	Data source
Purchase price per module	Purchasing department, supplier home page
Environmental assessment based on certified environmental data	Swedish databases (SundaHus)
Workload in factory	Time sheets, Production calculation and outcome
The weight of the material	Supplier web page
Potential for reuse	Assessment
Degree of manageability (easy / difficult)	Assessment
Workload on site	Time sheets, Production calculation and outcome
Additional costs, such as expansion of the factory or other investments in the process	Production manager
Number per module	Drawings
Environmentally / health hazardous substances	Swedish Database (Basta), Supplier homepage
Cost of waste management	Invoices from suppliers, Supplier tender

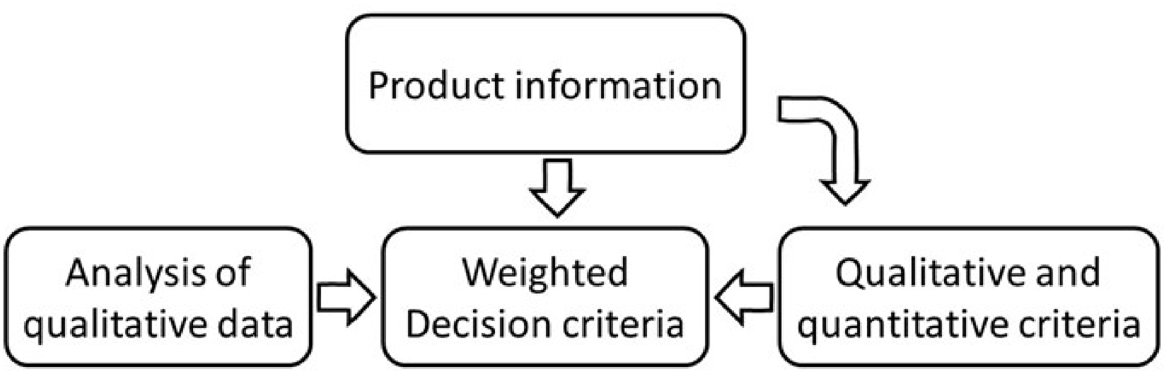

Figure 1: Components in the model for decision-making in reverse logistics

The total score is calculated by multiplying each criterion's priority level by the product's assigned grade, then summing the scores. The outcome depends on both priority levels and product ratings. The alternative with the highest total score is highlighted, but the results should be carefully reviewed, considering the chosen criteria, their assigned priorities, and product ratings. The decision model is intended to facilitate discussion and decision-making rather than automatically selecting the highest-scoring option.

Results of the field study

The results of the field study are presented in three parts: the packaging process and criteria defined by the case company, alternative reverse logistics designs, and the criteria assessment that leads to a proposed reverse logistics solution.

Packaging process

The packaging process (Figure 2) begins with assembling the roof protection. Once the roof element is complete, a layer of cover foil is applied, followed by a lightweight tarpaulin measuring 7.2 × 12 m. Finally, an all-over foil is applied to the entire module. After the packaging process is complete, the module foil is rolled up onto the roof to facilitate the final stage, where it is pulled down to cover the entire module during comprehensive packaging.

The roof element is then transported to the module assembly line, where the module undergoes assembly, including installations, quality controls, and bathroom construction. At the final station, operators apply a protective plastic layer to the module’s bottom. Once the plastic adheres, they pull the tarpaulin halfway down each side. Next, the module foil is pulled down to cover the entire module, with excess plastic trimmed. Using a safety lift, the operator secures the foil around the roof section. The comprehensive module foil protects against moisture and other potential issues during storage or transport. Finally, the foil is folded and secured with a batten screwed around the module to prevent it from coming loose.

Once the module is complete, it is moved into storage using a truck before being loaded onto a trailer for transport to the construction site. Upon arrival, the packaging is removed while the modules are still on the trailer, and they are then lifted directly to the designated mounting location. The discarded packaging is placed in a container for combustible materials. Plastic sorting does not occur on-site; instead, all waste is collected and later sent for energy incineration. In some cases, modules are temporarily stored on-site or nearby due to long transport distances, on-site delays, or changes in the assembly sequence. In such instances, the plastic foil remains in place until installation.

Criteria designed by the case company

During the study, a decision model was developed to guide the case company in determining the best approach for weatherproofing apartment modules from manufacture through storage and transport to the construction site. Observations, surveys, interviews, and discussions with employees informed adaptations to the theoretical model. The key modifications to the model criteria are:

- Purchase price per product was redefined as purchase price packaging module to focus on the total packaging cost per module rather than per product.

- Total purchase price packaging was added as a criterion, as understanding the total estimated cost of current and alternative solutions is essential.
- Environmental assessment of product was initially based solely on Swedish data. It was merged with the Environmentally/Hazardous Substances criterion to streamline the model, as these aspects were closely related.

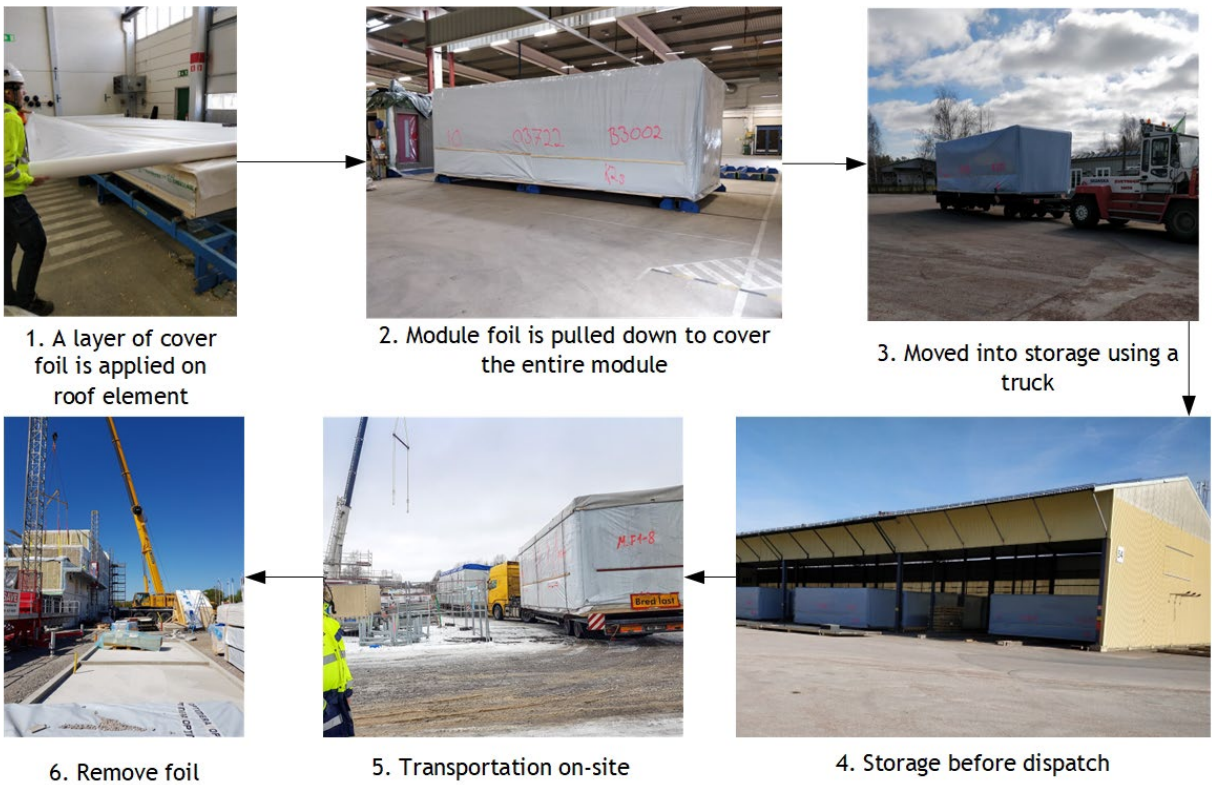

Figure 2: Overview of the weather and transportation protection process.

- Workload at the construction site and workload off-site were combined with Weight of Material and Manageability since they are interrelated. This consolidation removed two separate criteria while maintaining their relevance.
- Waste management was introduced to assess how waste from the solution is handled, including recyclability or disposal using energy recovery.
- Item number per module was removed, as it did not provide sufficient value as a criterion. It is partially covered by the Total Purchase Price Packaging criterion, which considers the number of packaging products from a cost perspective.
- Country of Origin was added after evaluating whether it should be a standalone criterion or integrated with environmental assessment. It classifies the environmental impact of production based on the country of origin.
- Intermediate storage was identified as both a cost and social issue, as module damage can lead to delays, increased costs, and branding concerns.

Alternative reverse logistics design

The field study evaluated alternative products for module weather protection. In addition to a literature review, a broader investigation examined weather protection methods used in other industries. However, many approaches were found unsuitable early on, as they were not optimized for large modules.

Alternative products were analyzed in comparison to the current system, which uses cover foil, module foil, and lightweight tarpaulin (Table 2). The selection of products was primarily based on observations at the construction site and factory, as well as interviews. Key considerations included feasibility, supplier capability to provide products in large quantities, and applicability to module protection.

Table 2: Alternative Solutions

Product	Supplier
Current solution	A
PVC Tarpaulin 10 x 15m	B
PVC Extreme 10 x 15m	C

The study first explored whether environmentally friendly alternatives, such as environmental plastic, could replace the current system. Module foil and cover foil were compared with environmental plastic and other potential substitutes. However, environmental plastics, primarily composed of recycled polyethylene (such as module and cover foil), were not considered viable due to incompatible dimensions. Module foil, specifically designed for comprehensive protection, is tailored to fit the modules. Tarpaulin solutions were selected for their durability. Only heavier, long-lasting tarpaulins were examined, as a short lifespan would make the investment unfeasible for the case company. Of the alternatives studied, two tarpaulin materials emerged as the best options based on supplier availability.

Criteria Assessment

Based on discussions with respondents within the organization, the cost and the environmental effects were interpreted as the points where the greatest focus should be placed. The fact that economic and environmental issues are considered to have high priority compared to social issues in this context means that these are most important when decisions on weather protection are made through the final decision model for the specific case of weather protection of apartment modules (Table 3).

Reverse logistics design

The selected reverse logistics design, based on the tested decision model and both quantitative (numbers in the matrix) and qualitative analyses (reasoning among the company representatives), indicated that the company should continue using its current method (Supplier A) for weather and transport protection. However, the company decided to explore the possibility of adopting tarpaulins from Supplier B further, which yielded the best results in the decision model.

Table 3: Assessment of solutions. Supplier B (PVC Tarpaulin) had thr best rating with 57 points, the current solution scored 56 points and the third option 48 points.

Analysis: Weather and transportation protection of modules				
Decision Criteria (A)	Priority (B)	Products (C, D)		
		A	B	C
Purchase price per module	3	3	2	1
Total purchase price	3	3	2	1
Environmental assessment	3	2	1	1
Workload in factory	1	3	2	2
Possibility of reuse	2	1	3	3
Workload construction site	1	3	2	2
Additional costs	3	3	2	2
Cost of waste management	3	1	3	3
Country of origin	3	2	3	2
Intermediate storage	2	1	3	3
Score (F)		**56**	**57**	**48**

Product (E)	List of products	Supplier
A	Current solution	Supplier A
B	PVC Tarpaulin 10x15m	Supplier B
C	PVC Extreme 10x15m	Supplier C

The field study also revealed that several critical factors currently lack sufficient data, preventing a definitive decision on the optimal method for apartment modules. Supplier C was deemed economically unviable due to its significantly higher cost compared to both the current and alternative solutions, and was therefore rejected by the interviewees. Additionally, potential extra costs associated with each option should be further investigated before finalizing the logistics design, according to the interviewees.

Analysis

The assessment of alternative products was carried out by replicating the existing system and evaluating whether more cost-effective and environmentally friendly options could replace current products. It quickly became clear that the dimensions of the cover foil and module foil were specifically adapted to the company’s needs. Other alternatives were considered but ultimately excluded based on interviews and discussions with knowledgeable personnel during field observations.

The decision model ranked Supplier B's tarpaulin fabric the highest, though the difference in score between this alternative and the current system was minimal. While the decision model proved useful, its foundation was limited and required further refinement to better reflect real-world conditions. For both existing and proposed weather protection methods, key considerations were identified and discussed with the company informants for decision-making (Table 4). Additionally, transport logistics must be optimized to ensure the cost-effective and sustainable reuse of tarpaulins.

Table 4: Impact assessment and comparison between methods

Product	Supplier
• Moisture issues may arise in the existing process due to leaks or damage.	• The materials are strong and durable, providing resistance to cold and moisture.
• The current process generates a large amount of waste, making it unsustainable.	• Reusable solutions produce less waste per module and reduce purchasing costs.
• Workload off-site and on-site is currently considered low.	• Heavier materials increase workload.
• The solution involves three different products from three manufacturing countries, complicating environmental impact assessments.	• The primary environmental impact occurs during manufacturing and waste disposal, as the solutions contain PVC plastic.
	• Additional costs arise both during implementation (process adaptation) and usage (returns).
	• Allows for intermediate storage of apartment modules on-site if needed.

The economic, environmental, and social driving forces described by Dekker et al. (2013) in the context of reverse logistics primarily apply to the engineering industry. However, these forces, particularly economic and environmental factors, are interrelated and reflected in decision-making criteria. For example, Hosseini et al. (2014) emphasized the importance of reducing raw material use in manufacturing, aligning with the core objectives of reverse logistics. This connection reinforces the relevance of the selected criteria in assessing weather protection solutions. However, direct adaptation of criteria from the engineering industry was not feasible due to significant differences between construction and engineering sectors, but a method of combining criteria from literature and industry background guided the selection of criteria.

Hosseini et al. (2014) also highlighted key drivers for reverse logistics in construction, including regulatory compliance, emission reduction, material reuse, and recycling, as factors that contribute to cost savings, increased revenue, and enhanced brand reputation. The final recommendations from the decision model align with most of these theoretical arguments. However, a direct link to industrial housebuilding, particularly weather protection, is lacking. Given the specificity of weather protection, the criteria were tailored to address the research question in the case study but could also be applicable in other decision-making contexts. Social factors were primarily linked to product-specific concerns such as handling, weight, workload, and safety.

Early discussions with the company identified environmental and economic criteria as key priorities. According to theory, prioritizing these aspects and developing a 'green brand' can also yield social benefits, as financial gains often result from environmentally friendly initiatives (Hosseini et al.2014; Dekker et al.2013). Reverse logistics, when effectively implemented, supports sustainability by optimizing material flows and minimizing waste, which can enhance a company's reputation and competitiveness (Carter and Ellram 1998; Rogers and Tibben-Lembke 1999).

While specific branding criteria were not explicitly included in the decision model, ongoing efforts to identify sustainable and cost-effective solutions—such as recycling plastic packaging instead of incineration or selecting durable, reusable materials—can indirectly strengthen the company's brand (Genchev 2009; Chileshe et al.2018). Furthermore, reducing waste and incorporating sustainable materials align with industry efforts to meet long-term climate goals (Hosseini et al.2014; Schamne and Nagalli 2016).

Discussion

This study strived to create a deeper understanding of reverse logistics and how it can be applied in sustainable industrialized housebuilding decision making. It focused on the process from when weather protection is applied to a finished module off-site until it is removed at the construction site. This scope was chosen to align with the purpose of the study. which was to explore how economic, social, and environmental sustainability criteria can be integrated into a decision model for reverse logistics design in industrialized housebuilding.

The theoretical contribution of this paper lies in its adaptation and extension of reverse logistics theory to the context of industrialized housebuilding, an area where its application remains underexplored. While reverse logistics has been extensively studied in the engineering and automotive industries (Hosseini et al.2015), this study contributes by demonstrating how economic, environmental, and social sustainability criteria can be integrated into a decision model tailored to weather protection processes in industrialized housebuilding.

However, this approach also introduces a limitation, as only a subset of the available criteria in the broader market was considered. This means that alternative criteria, which might be relevant in other industrialized construction contexts, were not explored. As a result, the findings may be more tailored to the specific case company rather than being universally applicable across the industry. This limitation should be considered when interpreting the results and assessing their generalizability.

The concept of reverse logistics may be confusing, especially in relation to reuse and waste management. Reuse extends material lifespan, reducing demand for virgin resources. Waste management minimizes and reintegrates construction waste into supply chains (Poon et al.2004; Lu and Yuan 2011. Reverse logistics enhances material recovery, refurbishment, and redistribution, optimizing resource flows (Carter and Ellram 1998; Rogers and Tibben-Lembke 1999). Reverse logistics is more easily understood in the housebuilding context during the construction phase. However, after handover to the client, later maintenance and refurbishment also present reverse logistics challenges, though these are typically categorized as reuse or recycling activities. This represents an inherent tangible problem as the product life cycle in housebuilding differs from other products with shorter lifespans. While reverse logistics in construction has often been associated with waste management and recycling (Poon et al.2004; Lu and Yuan 2011), this study expands its scope to include material flows during off-site production, transport, and storage before waste generation.

The main idea of the process mapping was to better understand the study's context. Instead of using established theoretical methods such as Value Stream Mapping (Erikshammar et al.2013) the process was documented through descriptive text and images. This approach may have influenced the interpretation of criteria and results. Mapping was carried out at a single construction site, meaning the results reflect only the observations made, potentially overlooking other influencing factors.

While the interview questions were systematically developed, only two interviews were carried out, which may have impacted the analysis and interpretation of results. Although the respondents were highly knowledgeable, increasing the number of interviews could have strengthened the study's validity. Additionally, more weather protection suppliers could have been included, but limiting alternatives had practical benefits for testing the decision model.

Certified environmental data were used for assessments. The BASTA database, a joint venture between the Swedish Environmental Research Institute and the Swedish Construction Federation, was considered but lacked necessary information for weather protection alternatives. In cases where data were unavailable, assumptions were made, which affected the study's overall validity. To supplement the data, sources on PVC and polyethylene were used, including reports from the Environmental Management Council (a former government organization) and the Swedish Society for Nature Conservation. While these reports are supported by scientific facts, their unverified origins may impact the study's reliability.

Social factors could have been examined in greater detail. Interviews and discussions with packaging operators revealed no significant safety concerns, and the current system's workload was considered low, with only a slight increase expected if a tarpaulin solution were introduced. While economic and environmental factors are well-documented (Carter and Ellram 1998; Rogers and Tibben-Lembke 1999), this study incorporated social sustainability by assessing workload, safety, and ergonomics. Further research on ergonomic aspects could help mitigate potential workplace risks.

To enhance reliability, assumptions and estimates were clearly documented, mainly within the decision model, ensuring that uncertainties could be tracked and adjusted as needed. However, additional research would be required for a more precise recommendation on how the case company should best protect apartment modules during storage, transport, and on-site handling.

Discussion of the Decision Model

While Multiple-Criteria Decision Analysis (MCDA) is commonly used in decision-making, this study refines the model by adapting criteria from engineering (Dekker et al.2013; Chileshe et al.2018) to construction-specific challenges, particularly weather protection of modules. While the use of MCDA in this project was valuable, some weaknesses and alternative decision models should be considered.

One limitation was the inclusion of monetary values, such as costs. Typically, costs are precisely quantified, allowing for more fine-grained comparisons than a fixed-point decision model (e.g. a three-point scale, as used here). This limitation can lead to borderline cases, vagueness, and ambiguities (Erikshammar et al.2010). Additionally, there is a risk of double-counting costs, first, within multiple criteria in the model, and again when making the final decision, where overall costs may still influence the outcome, potentially leading to suboptimal choices.

An alternative to MCDA is cost-benefit analysis (CBA), also known as risk-benefit analysis, where decisions are made by evaluating the total costs and benefits of each option and selecting the one with the best net value. CBA consolidates multiple dimensions into a single metric, usually monetary value. However, this method has well-documented challenges, including the difficulty of assigning monetary values to social and ecological risks and the time-consuming nature of obtaining reliable cost estimates (Hansson 2007).

Another alternative is expected utility theory, which suggests that when probabilities are known, the decision with the highest expected utility should be chosen. While theoretically sound, its practicality in this context is limited. Like CBA, it requires precise valuations of expected utility, making MCDA a more manageable approach for this study.

Considerations for Decision Model Design

The choice of scale in the decision model is another consideration. This study used a three-point scale, but a wider scale could allow for more precise evaluations. However, increasing the number of possible scores also makes it harder to assign values consistently and non-arbitrarily. Conversely, a lower-scale model risks failing to capture meaningful differences between options, potentially impacting reliability.

A more critical limitation is that the model violates the independence of irrelevant alternatives principle (Arrow 1950), a key criterion in rational choice theory. Suppose there are two options, A and B, and option A initially receives a slightly higher score. If a third alternative, C, is introduced, one that is significantly cheaper but has major drawbacks, the scores for A and B might change even though C is ultimately not chosen. In this case, A’s score might decrease relative to B simply because it is no longer the cheapest option in the comparison. This means that introducing an irrelevant alternative can alter the internal ranking of existing choices, creating a risk of manipulation or unintended distortions in decision-making.

One way to mitigate this issue is to eliminate suboptimal alternatives before making a final decision. However, this approach introduces the possibility of the Condorcet paradox (Herings and Houba 2016), where cyclic preferences emerge depending on how pairwise comparisons are made. In applied decision-making, the challenge is balancing theoretical rigor with practicality. While the current decision model has limitations, it remains a viable approach for this study and warrants further refinement.

Conclusion

The study suggests that a decision model based on criteria from the engineering industry can also be applied to decision-making on weather protection for modules in industrialized housebuilding, though some modifications are necessary. Further research is needed to refine this process for greater effectiveness. The theoretical contribution of this study lies in advancing the understanding of reverse logistics in construction by expanding its application beyond waste management to include material flows before disposal and position itself to reuse practices.

Although the decision model is contextualized to this specific case, both the criteria and priority levels can be adjusted. Relevant criteria for weather protection in industrialized housebuilding (Table 5) align with economic, ecological, and social sustainability.

Table 5: Relevant Criteria

Product	Supplier
Purchase price packaging module	Waste disposal
Total purchase price for packaging	Workload in factory and construction site
Environmental assessment product	Possibility of reuse
Cost of waste management	Intermediate storage
	Country of origin

The contribution of this study to practice lies in providing a structured decision model that helps industrialized housebuilding companies optimize weather protection processes while considering costs, sustainability, and operational feasibility. The recommendation for the case study company is to continue using its current reverse logistics design while further exploring tarpaulin hoods as an alternative. Since product information is currently based on available data, a more in-depth life cycle analysis would be necessary for a more accurate assessment.

Future Research

Further studies are needed to test, refine, and validate the decision model using a broader data collection regime, including more in-depth interviews and observations. Expanding criteria to address plastic packaging reduction and integrating life cycle analysis (LCA) would improve assessment accuracy and model reliability. Exploring circular economy principles could further enhance sustainability and competitiveness.

Research on alternative processes, such as moisture levels with different weather protection methods and mitigation strategies, would expand knowledge in industrialized housebuilding. Additionally, social factors such as safety, workload, and ergonomics should be analyzed to refine criteria and minimize work environment issues.

While field studies offer valuable insights, their limited generalizability, small sample size, and organizational context constraints require careful interpretation. Observer bias and time limitations may also impact findings. To strengthen applicability, future research should include multiple case studies and larger datasets to enhance reliability.

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