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KNOWLEDGE GRAPH-BASED CUSTOMER-CENTRIC DECONSTRUCTION ASSESSMENT MODEL

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Abstract

Demolition remains the dominant practice at the end-of-life stage, primarily due to its immediate economic advantages. Transitioning from demolition to deconstruction requires a shift in focus toward meeting customers' needs in the second-hand market. Therefore, the present study proposes a customer-centric deconstruction assessment model to enhance deconstruction planning. The research followed a three-stage methodology: (i) analyzing the attributes of existing deconstruction models; (ii) identifying the requirements of potential customers; and (iii) developing a knowledge graph model. The proposed model, which focused specifically on wood-based products, demonstrated its practical applicability by effectively matching products with suitable customers across five test scenarios.

Introduction

The construction industry is a major consumer of virgin materials and a significant contributor to landfills through Construction, Renovation, and Demolition (CRD) waste. Tackling the high consumption of materials and the large volumes of waste being dumped is a priority on the United Nations agenda through Sustainable Development Goal (SDG) 12, 'Responsible Consumption and Production' (*SDG12*, 2023). This focus has led the research community in the construction industry to concentrate on the design stage (to create facilities with lower consumption of virgin materials and being able to be deconstructed in the future) and the End-of-Life (EoL) stage (to increase the utility of existing products in the built environment) (Guerra & Leite, 2021). The key to success in both stages is 'deconstruction', which refers to systematically dismantling a built facility.

Adopting deconstruction is still in its infancy. In practice, demolition, which involves less manpower and takes less time, is generally cheaper than deconstruction, which is labor-intensive and more time-consuming (Aidonis, 2019; Mollaei et al., 2023). However, the statement that demolition is more economically viable than deconstruction is questionable, as there is a lack of models that account for the potential benefits of adopting deconstruction over demolition (Tatiya et al., 2018). These benefits include obtaining high-quality products that can be reused elsewhere, which, in turn, can offset deconstruction costs by generating revenue or providing tax deductions. To ensure reaching this goal, post-deconstruction (i.e., the destiny of the extracted products) needs to be investigated (Allam & Nik-Bakht, 2024b). This necessitates integrating various information about the facility in question and its surrounding environment (Hübner et al., 2017).

Demolition contractors can assess the economic demand for deconstructed products by reaching out to potential buyers or customers of second-hand products (van den Berg et al., 2020b). As the market for second-hand products is still limited (Allam et al., 2023), there is a dire need to involve potential customers early in the decision-making process to ensure the deconstruction of products that have market demand (Arora et al., 2021; Elmaraghy et al., 2018). On the other hand, demolition contractors are also concerned about the deconstructability (i.e., ease of deconstruction) of the subject facility (van den Berg et al., 2020a). In other words, for deconstruction to be viable, the project must be assessed as both 'feasible' to deconstruct and 'profitable', i.e., disassembled products or materials are likely to have potential customers.

Ineffective coordination among stakeholders and the information gap at the EoL stage are two critical barriers to adopting deconstruction (Allam & Nik-Bakht, 2023a). Therefore, it is essential to provide interoperable solutions that are easily integrated with various data sources and conducive to stakeholder collaboration. This is where semantic web technologies can play a pivotal role. Recently, studies have utilized Knowledge Graphs (KGs) to identify the sequence of deconstruction activities (Allam & Nik-Bakht, 2024a, 2025). KGs can model, consolidate, and deduce insights from complex and diverse data originating from various sources, offering scalability, expressiveness, and extensibility (Kebede et al., 2023).

Deconstruction assessment is crucial for making informed decisions during the deconstruction planning phase. To the best of the authors' knowledge, the existing deconstruction assessment models that consider second-hand customers' requirements and products' deconstructability are scarce, if any. Therefore, the present study aims to develop a customer-centric deconstruction assessment model to support decision-making in the deconstruction planning process.

Research Methodology

A three-stage research methodology was adopted to develop a customer-centric deconstruction assessment model. In the first stage, the attributes of existing deconstruction assessment models were systematically identified and analyzed. The second stage focused on examining the requirements of potential customers for accepting second-hand products extracted from the built environment. In the third stage, these deconstruction attributes were integrated with the acceptance criteria of potential customers to construct a comprehensive knowledge graph model, ensuring alignment with market demands. Finally, the developed model was validated through application to a hypothetical case study, demonstrating its practical feasibility. Details of each step are explained in the following paragraphs.

The existing deconstruction assessment models were sourced from a previously published review article on the deconstruction of the built environment (Allam & Nik-Bakht, 2023b). Yet, to ensure the inclusion of the most up-to-date models, an additional search was conducted in the Scopus database using the query "deconstruct* assessment". This search targeted articles by examining their titles, abstracts, and keywords. Quotation marks were applied for searching n-grams (i.e. sequence of n terms) to retrieve exact phrases. Also, an asterisk has been used to implement a level of 'stemming' and find the words that have the same or similar roots as the keyword of interest. For example, deconstruct* returns both 'deconstruction'; and 'deconstructability'. The collected existing models were analyzed, and their attributes were organized into a reference matrix (**R**), with the identified attributes represented as columns and the reviewed models as rows.

In the second stage, two types of customers in the second-hand market were examined: (i) retailers and (ii) material suppliers/ manufacturers. Second-hand retailers typically operate through collaborative agreements with entities that provide deconstruction and salvaging services, sourcing products for resale to other customers. Material suppliers, on the other hand, receive extracted products and process them into new products. This study focuses on wood, the predominant construction material in North American residential buildings (*US New-Home Completions - Forest Economic Advisors*, n.d.). A Google search was conducted to identify companies and organizations that accept reused wood products, such as doors and windows, as well as wood components like dimensional lumber. It is important to note that companies involved in downcycling activities (e.g., shredding wood for biomass solid fuel or pulp production) were excluded from the identified list.

In the last stage, the attributes required for deconstruction assessment and the unstructured data gathered from the potential customers were represented by the Resource Description Framework (RDF) to form the KG. RDF serves as a versatile and universal data model employed for the representation and amalgamation of data through directed labeled graphs (Kebede et al., 2022). Each triple consists of two nodes (i.e., subject and object) connected with an edge (i.e., predicate) that defines the relationship between them. In this research, the Blazegraph database was utilized to construct the knowledge graph of the case study (*Blazegraph Database*, n.d.). RDF triples were encoded using Terse RDF Triple Language (Turtle) format.

Results and Discussion

The first stage of this research resulted in 14 deconstruction assessment models, as listed in Table 1. Generally, all models revolved around two main concepts: the first was the ease of deconstruction of the product, and the second was the destiny of the product after deconstruction. It was observed that there was one main model that influenced most of the others, which is the Deconstructability Assessment Score (DAS) proposed by Akinade et al. (2015). DAS is calculated using the following formula:

$$Original\ DAS = 0.5\frac{t_n + d_c + R_p}{3} + 0.5\frac{R_1 + R_2 + R_s + R_x}{4} \qquad (1)$$

where t_n is the material type-number ratio for a subsystem, d_c is the ratio of demountable connections, R_p is the ratio of prefabricated elements, R_1, R_2, R_s, and R_x are the ratios of reusable elements, recyclable elements, elements without secondary finishing, and non-toxic elements, respectively.

Table 1: Comparison of various deconstruction assessment models and common attributes used in their calculations

Model	Attributes											
	Reusability	Recyclability	Toxicity	Finishes	Material Type	Connections	Accessibility	Prefabrication	Resources	Handling	Age	Life Expectancy
(Akinade et al., 2015)	✓	✓	✓	✓	✓	✓		✓				
(Mayer & Bechthold, 2017)	✓	✓	✓	✓	✓	✓	✓	✓	✓			
(Akanbi et al., 2018)	✓	✓	✓	✓	✓	✓		✓			✓	✓
(Akanbi et al., 2019)	✓	✓	✓	✓	✓	✓		✓			✓	✓
(Basta et al., 2020)	✓		✓	✓	✓	✓		✓				
(Atta et al., 2021)	✓	✓	✓	✓		✓		✓				
(O'Grady et al., 2021)	✓	✓							✓	✓		
(Zoghi et al., 2021)	✓			✓	✓	✓			✓	✓		
(Mattaraia et al., 2021)	✓	✓		✓	✓	✓		✓	✓	✓		
(Cottafava & Ritzen, 2021)					✓	✓	✓					
(Janani et al., 2022)	✓	✓	✓	✓	✓	✓		✓				
(Mahmoudi Motahar et al., 2023)	✓	✓	✓	✓	✓	✓	✓		✓			
(Kim & Kim, 2023)	✓	✓	✓	✓	✓	✓		✓				
(Mohammed et al., 2024)	✓	✓	✓	✓	✓	✓		✓				

Given the widespread use of the DAS in the field, it was adopted as the foundation for developing our customer-centric deconstruction assessment model. However, we introduced modifications to address three key limitations. First, we resolved the redundancy between 'recycling' and 'reusable' attributes. In practice, once a product is extracted from the built environment, it is either recycled or reused. These two attributes were therefore consolidated into a single indicator: market demand (MD). This new attribute reflects the proportion of products for which there is customer interest post-deconstruction.

The second adjustment to the DAS involved distinguishing between attributes related to the ease of deconstruction (i.e., deconstructability) and those concerning the destiny of products (i.e., recoverability). Originally, DAS addressed this by incorporating a deconstructability score consisting of t_n, d_c, and R_p alongside a recoverability score consisting of R_1, R_2, R_s, and R_x. However, this classification overlooked the role of certain attributes, particularly R_s, and R_x, which contribute to the ease of deconstruction through the decontamination process (European Commission, 2016).

The final adjustment was to highlight the importance of both market demand and deconstructability by changing the operator from addition to multiplication in the DAS score. This ensures that both factors are essential; if either market demand or deconstructability is missing, deconstruction would not be viable. The following equation presents the proposed customer-centric deconstruction assessment model:

$$Customer-centric\ DAS = MD \times \frac{t_n + d_c + R_p + R_s + R_x}{5} \qquad (2)$$

All attributes of the customer-centric DAS are based on the inventory of the subject facility, except for MD, which is determined by the presence of interested customers. Each product can have an MD value of 0 when there are no customers for it, and 1 when one or more customers are seeking the product. To assess the overall facility, the MD values of all products are summed and then divided by the total number of products, yielding a market demand ratio that reflects the facility's alignment with current market interest.

In this context, it is essential to consider the perspective of second-hand customers during the deconstruction assessment stage. To support this, a Google search was conducted to identify retailers and manufacturers of second-hand wood products across North America. A total of 40 retailers and 9 manufacturers were identified. We reviewed their websites to better understand how these customers operate and to determine what information needs to be incorporated into the knowledge graph to effectively match reclaimed wood products with potential customers' needs.

The retailers identified are primarily various branches of non-profit organizations, including 'Habitat for Humanity' and 'The Reuse People'. Figure 1 illustrates the types of products these retailers trade, the economic benefits homeowners can gain from doing business with them, the service fees involved, and their acceptance criteria. Most of these retailers accept products like doors and windows. Meanwhile, the identified manufacturers, seven based in the United States and two in Canada, mainly focus on producing flooring from salvaged wood, as illustrated in Figure 2. Retailers typically offer deconstruction services free of charge, or in some cases, for a nominal fee. These services are generally considered highly affordable compared to standard market rates (Haywood Habitat for Humanity, n.d.). Once the salvaged products are sold, a tax receipt is sent to the original owners. However, retailers do not accept all products indiscriminately; many set specific acceptance criteria based on factors such as age, type, and condition. For example, one retailer only accepts windows that are 10 years old or newer (Habitat for Humanity of Greater Sioux Falls, Inc., n.d.), while others require items to be in excellent condition (Habitat for Humanity of East and Central Pasco County, n.d.). Out of the 40 retailers analyzed, 11 explicitly stated their acceptance criteria. This information helps reduce uncertainty during the deconstruction assessment, as it enables stakeholders to identify early on which products align with which retailer's requirements.

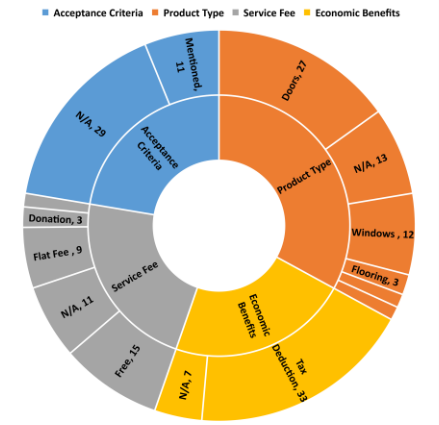

Figure 1: A sunburst chart of active retailers in the construction second-hand market of North America

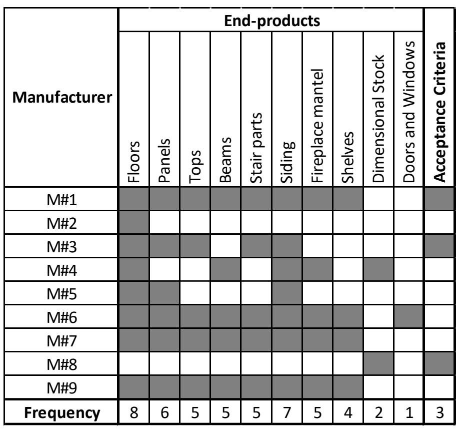

Figure 2: End-products and acceptance criteria of second-hand wood manufacturers

Similar to the retailers, manufacturers also sometimes establish acceptance criteria for input materials to ensure compatibility with their production processes and value proposition. For example, manufacturers that produce decorative beams often require salvaged lumber to be 'hand-hewn' as a condition for acceptance (*Armster Reclaimed Wood, CT*, n.d.). Another common criterion is the length of dimensional lumber; for instance, one manufacturer specifies a minimum length of 30 cm for reclaimed lumber to be eligible for use in their production process (*Urbanjacks*, n.d.).

The diversity of acceptance criteria established by retailers and manufacturers underscores the importance of incorporating these requirements into a knowledge graph to effectively match products with potential customers. To achieve this, ten predicates were defined to describe the relationships of the KG, as listed in Table 2. Four predicates represent the acceptance criteria set by the potential customers, while five describe the attributes of a product in the subject facility. The remaining predicate, ':accept', is inferred when there is a match between a product's attributes (i.e., type, condition, length, and age) and the customer's specified criteria (i.e., accepted types, minimum condition, minimum length, maximum age).

Table 2: The predicates used to define relationships.

Predicate	Description
:accept	Describes products that will be sent to the customer
:may_accept	Describes products eligible to be sent to the customer (pending acceptance criteria approval)
:min_condition	Describes the minimum condition required for the customer to accept the product
:min_length	Describes the minimum length required for the customer to accept the product
:max_age	Describes the maximum age required for the customer to accept the product
:has_type	Describes the product type
:has_condition	Describes the condition of the product
:has_length	Describes the length of the product
:has_age	Describes the age of the product
:has_count	Describes how many similar products, both in type and dimensions, are in the facility

To test the usability of the proposed KG-based customer-centric deconstruction assessment model, a hypothetical case study was utilized. The case study presents conventional wall construction framing in North America, as shown in Figure 3. Typically, the key components are vertical members (i.e., studs), horizontal members (i.e., plates, sill, and header), and sheathing. These components may vary in size and cut length depending on their intended structural function. Consequently, this variation can influence their EoL pathways based on the acceptance criteria set by potential customers. Although this case study does not reflect a real-world scenario, the concept of matching products' attributes with the acceptance criteria of potential customers is scalable, especially when utilizing KGs.

Products (p) and customers (c), including manufacturers and retailers, serve as the primary nodes in the KG, represented as Internationalized Resource Identifier (IRI) nodes, as shown in Figure 4. In contrast, product attributes and customer acceptance criteria were modeled as literal nodes. Product attributes were extracted from a model developed in Autodesk Revit, as shown in Figure 3. For the purpose of this study, all products were assigned to a condition of 'good', and an age of seven years. Customer acceptance criteria were defined based on five hypothetical scenarios, detailed in Table 3. These scenarios were designed to explore the impact of customers in the second-hand market on the original DAS and the customer-centric DAS.

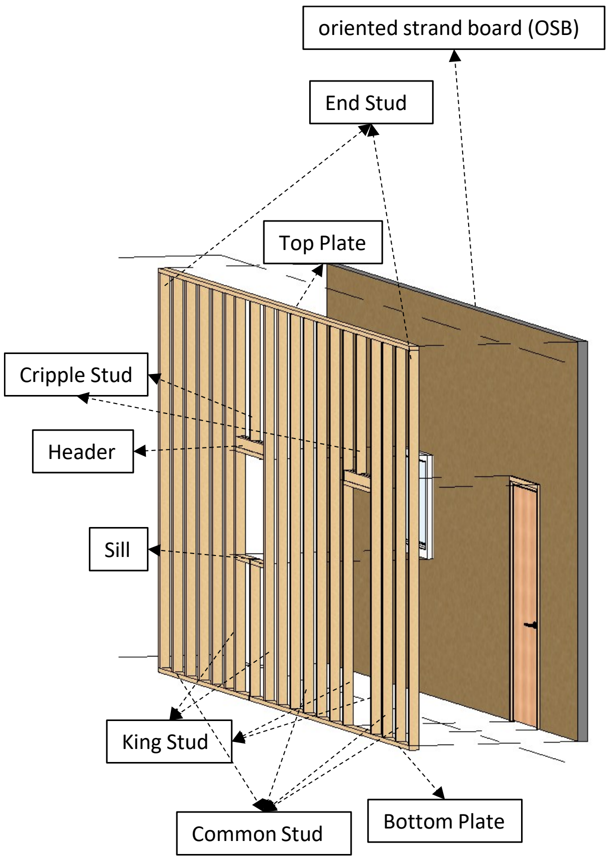

Figure 3: Conventional wall framing assembly in North America

The hypothetical case study includes 34 elements categorized into four types: Oriented Strand Board (OSB), dimensional lumber, doors, and windows. All elements are connected using nails and have the potential for both recycling and reuse, except for the OSB, which is limited to recycling. Additionally, the dimensional lumber does not contain secondary finishes or toxic materials, whereas the other elements do. The resulting scores of the original DAS remained unchanged across all scenarios, as it does not account for market dynamics in its calculations. In contrast, the customer-centric DAS demonstrated sensitivity to the availability and preferences of potential customers, as shown in Figure 5. For instance, in scenario B, where the only potential customer was a retailer interested solely in doors and windows, the MD was at its lowest level. However, after adding a manufacturer to the pool, who accepts all types of dimensional lumber, the primary material in the wall framing, the MD score rose accordingly. Scenarios D and E further highlight how customer acceptance criteria influence the customer-centric DAS score. In scenario D, the manufacturer specified a minimum lumber length of 100 cm, reducing the number of qualifying lumber pieces. In scenario E, the retailer raised the condition requirement for accepting doors and windows from ‘good’ to ‘excellent’, resulting in the exclusion of the existing doors and windows. Figure 6-a shows that SPARQL update to infer the ‘:accept’ predicate and Figure 6-b shows the inferred ‘:accept’ predicates in scenarios D and E.

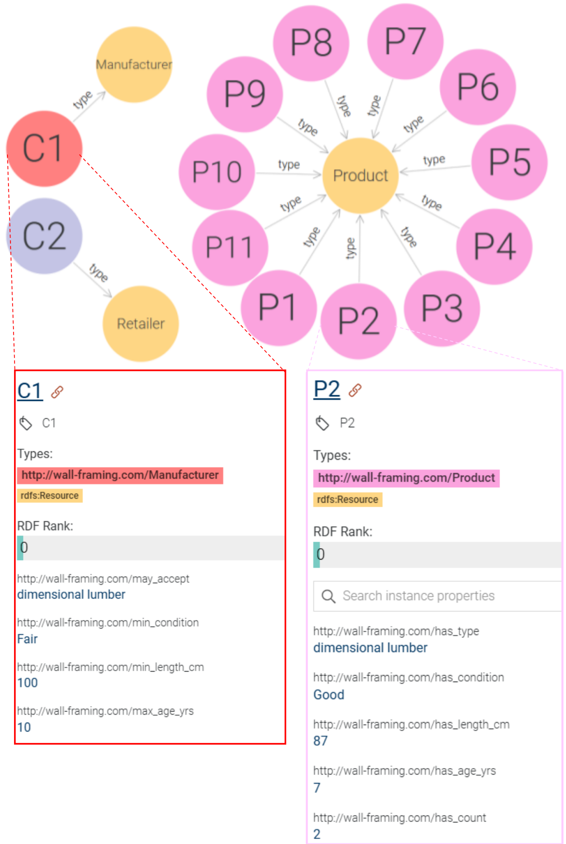

Figure 4: The generated knowledge graph of the wall framing (processed by GraphDB)

The proposed KG-based customer-centric deconstruction assessment model effectively integrates the perspective of the second-hand market into the deconstruction assessment process. As a result, the assessment becomes more reliable, as it considers not only the contractor’s ability to carry out deconstruction but also the specific needs of potential customers. To scale up the proposed model, active engagement from a wide range of stakeholders is essential. Establishing an open platform for collaboration can significantly enhance the model’s capabilities. For example, potential customers could disclose and update their acceptance criteria as needed, pre-deconstruction auditors could assess the deconstructability of products within the subject facility, and contractors could provide information about their available resources. Such a platform would foster transparency, coordination, and more effective decision-making across the deconstruction value chain.

This study is part of an ongoing project focused on deconstruction planning, and the proposed model serves as proof of concept. In the next stages, the model will be integrated with other frameworks to create a comprehensive decision support system for deconstruction planning.

Table 3: The tested scenarios on the original DAS and the customer-centric DAS

Scenario	Description
A	Unknown market demand
B	Retailers in the second-hand market
C	Retailers and manufacturers in the second-hand market.
D	Retailers and manufacturers in the second-hand market. Manufacturers only accept lumber of 100 cm length or more
E	Retailers and manufacturers in the second-hand market. Manufacturers only accept lumber of 100 cm length or more and retailers only accept doors and windows of excellent condition

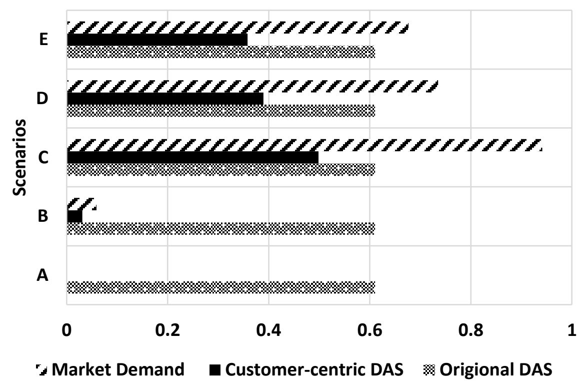

Figure 5: DAS scores based on different scenarios

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX : <http://wall-framing.com/>

INSERT {
  ?entity :accept ?product .
}
WHERE {
  # Product properties
  ?product a :Product .
  ?product :has_type ?typeP .
  OPTIONAL { ?product :has_condition ?conditionP . }
  OPTIONAL { ?product :has_length_cm ?lengthP . }
  OPTIONAL { ?product :has_age_yrs ?ageP . }

  # Manufacturer or Retailer
  {
    ?entity a :Manufacturer .
  }
  UNION
  {
    ?entity a :Retailer .
  }
  ?entity :may_accept ?typeM .
```

(a)

```
PREFIX : <http://wall-framing.com/>

SELECT ?Customer ?Product
WHERE {?Customer :accept ?Product}
```

Scenario D

Customer	Product
<http://wall-framing.com/C2>	<http://wall-framing.com/P10>
<http://wall-framing.com/C2>	<http://wall-framing.com/P11>
<http://wall-framing.com/C1>	<http://wall-framing.com/P3>
<http://wall-framing.com/C1>	<http://wall-framing.com/P6>
<http://wall-framing.com/C1>	<http://wall-framing.com/P7>
<http://wall-framing.com/C1>	<http://wall-framing.com/P8>

Scenario E

Customer	Product
<http://wall-framing.com/C1>	<http://wall-framing.com/P3>
<http://wall-framing.com/C1>	<http://wall-framing.com/P6>
<http://wall-framing.com/C1>	<http://wall-framing.com/P7>
<http://wall-framing.com/C1>	<http://wall-framing.com/P8>

(b)

Figure 6: A snapshot of the applied SPARQL update to match products with potential customers

Conclusions

Adopting deconstruction instead of demolition requires detailed planning. To achieve this, the destiny of the extracted products from the built environment should be determined during the early stages of the deconstruction project. In this context, involving potential customers for second-hand products in the deconstruction assessment process is crucial for producing a realistic deconstruction plan. Therefore, the present study proposed a KG-based customer-centric deconstruction assessment model. The proposed model adds and updates potential customers and their acceptance criteria in a KG that is linked to the inventory list of the subject facility. When a match occurs between a product and potential customer(s), the customer(s) is/are assigned to the subject product to indicate market demand for the product after deconstruction.

The main contribution of this work is incorporating the market perspective into the deconstruction assessment process through the use of KG, providing greater flexibility and dynamic adaptability. However, this dynamic capability comes with certain limitations, as it requires the active participation of various stakeholders to achieve a realistic solution. Additionally, the flow of information may be constrained by the need for more standardized data to ensure interoperability. Future research should focus on exploring the integration of standardized data schemas, such as IFC, with knowledge graphs to achieve a reliable deconstruction assessment model. Furthermore, expert-based surveys should be conducted to identify the essential information required for effective deconstruction planning. As a result, more predicates can be defined to represent the relationships between nodes in the KG.

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