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Optimizing the Reverse Supply Chain for Deconstructed Steel Building Components

Hosna Ghorab[1], Amin Hammad[1]

[1] Concordia Institute for Information Systems Engineering, Concordia University, Montreal, QC, Canada

ABSTRACT: The construction industry has long adhered to a linear economic model, following the "take, make, dispose" paradigm. However, growing environmental concerns are driving a shift towards a circular economy, where the focus is on extending the lifespan of materials and components through disassembly or deconstruction. Central to this transition is the reuse of building components, which is made possible through efficient deconstruction practices. However, the underdeveloped market for supply and demand of the reclaimed building components continues to impede the full adoption of circular construction practices. One promising approach to address this issue is the development of a reverse supply chain (RSC) model, an area that remains underexplored in current research. This study focuses on optimizing the RSC for the components of deconstructed steel buildings by finding the optimal locations of the reuse hubs based on minimizing the transportation costs throughout the proposed RSC model. The optimal location of hubs aims to efficiently connect the main nodes (i.e. deconstruction sites, hubs, recycling centers, factories, and end users) by integrating a Genetic Algorithm and a Geographic Information System. The study also examines the amount of steel components from deconstructed buildings and facility capacities to create a more practical model for future real-world applications. Simulation results based on the estimated geographic building locations and the potential hub locations demonstrate the effectiveness of the proposed method in identifying optimal hub placements. This research provides valuable insights for firms seeking to implement sustainable, profit-driven strategies and contribute to the advancement of circular economy practices in the construction industry.

1. INTRODUCTION

Resource depletion and climate change have presented significant global challenges, prompting a growing demand for profound shifts in the way industries engage with the environment (Ginga et al., 2020). The construction industry, in particular, is a major contributor to environmental degradation, accounting for approximately 40% of global energy consumption, 30% of greenhouse gas emissions, 17% of freshwater usage, and 25% of global wood consumption (Badi & Murtagh, 2019; Chileshe et al., 2018; Eberhardt et al., 2022). Also, the generated waste is more discarded rather than reused or recycled. This issue is exacerbated by the lack of consideration for waste management during the planning and design stages (Esa et al., 2017).

To address the environmental impact of construction and demolition waste, the adoption of circular economy principles is emerging as a viable and necessary solution (Ostapska et al., 2024). A circular economy model in construction prioritizes the longevity, reuse, and adaptability of materials and components (Mahpour, 2018). This is achieved through design for disassembly/adaptation (DfD/A), recycling, and repurposing (Ostapska et al., 2024). By focusing on deconstruction rather than demolition, the industry can shift from treating components as single-use resources to maximizing their lifespan.

At the core of this shift is the reverse supply chain (RSC), which plays a crucial role in managing the flow of deconstructed materials. Unlike the forward supply chain, which focuses on the procurement and delivery of new materials (Benachio et al., 2020), the RSC manages the collection, refurbishment, and redistribution of reclaimed components (Ding et al., 2023). Despite its importance, the RSC remains underdeveloped, with minimal focus on practical implementation models that integrate modular construction with deconstruction practices. A well-designed RSC is essential for managing the entire lifecycle of construction components (Rios et al., 2015), from disassembly to re-entry into the construction process, reducing waste and minimizing environmental impact.

While some companies have adopted prefabrication techniques, the potential for giving buildings a second life through the reuse of components in RSC has been largely overlooked. The lack of a practical RSC model prevents widespread adoption of circular construction practices, limiting the full potential of modular construction. A functioning RSC would optimize the collection, refurbishment, and redistribution of components, ensuring efficient resource utilization and minimizing waste generation.

This research aims to bridge the existing gaps by developing a RSC for deconstructed building components within the framework of a circular economy. Focusing on hubs as places to repair and bring back the components for a second life cycle, the objective of the paper is to find the optimal locations for hubs to minimize the cost. The goal is to enable a more sustainable RSC for components and supports the transition to a circular economy in the construction industry.

2. LITERATURE REVIEW

2.1 Deconstruction and Disassembly

The adoption of circular economy principles in construction emphasizes the importance of deconstruction and disassembly as alternatives to traditional demolition methods (Akanbi et al., 2019). Deconstruction involves systematically dismantling buildings to salvage valuable materials and components for reuse, recycling, or repurposing (Brandão et al., 2021). While demolition results in a high volume of waste, deconstruction maximizes the recovery of building components, contributing to more sustainable resource management. The deconstruction process is becoming more feasible with the advent of modular construction and prefabrication, which make the disassembly of building components more efficient (Eberhardt et al., 2022). Although modular construction is not new, it has gained renewed interest due to its technological advancements and economic factors. Modular construction enables the production of standardized building components that can be easily disassembled and reused in future projects (Rios et al., 2015). This disassembly approach is more efficient than traditional deconstruction, reducing waste and making the recovery process less labor-intensive and costly. Disassembly also allows for the reuse of components without the need for extensive modifications. This adaptability makes it possible to repurpose building components for new projects or reuse within the same structure’s life cycle (e.g. reconfiguration or renovation projects).

2.2 Forward and Reverse Supply Chains for Circular Construction

The circular economy model requires an integrated approach to the construction supply chain, involving both forward and reverse supply chains. A well-structured forward supply chain ensures the efficient flow of materials and components during construction, while a RSC enables the recovery and reuse of materials from deconstructed buildings (Masood et al., 2022).

RSC allows for deconstructed materials to be reintegrated into the value chain through processes like recovery, refurbishment, and reuse (Minunno et al., 2018). Establishing a RSC is essential for maximizing the benefits of deconstruction and promoting the circular economy in the construction industry (Brandão et al., 2021). The RSC facilitates the efficient movement of components from end-of-life buildings back into the production cycle. This involves collecting, sorting, and reintegrating reusable or recyclable components salvaged through deconstruction.

One innovative approach to smoothening this RSC is the concept of buildings as material banks (BAMB), which gives materials a second life with recycling and reusing them again (Adisorn et al., 2021). Providing material passports (MPs) to track materials throughout the entire lifecycle of a building (Honic et al., 2021) will promote the concept of BAMB. MPs ensure that materials are earmarked for reuse, making them valuable for future building projects (Pan & Zhang, 2023). MPs can operate at both the material and component levels, enhancing the supply chain by facilitating closed-loop processes.

A well-established RSC is crucial for overcoming resistance to off-site construction methods and maximizing component recovery (Lim et al., 2021) by the help of MPs and digital product passports (DPP) (Walden et al., 2021) which facilitate this process by providing the data needed for the specific components in the reuse and repurposing process.

2.3 Genetic Algorithms and Geographic Information System

Genetic Algorithms (GAs) were first introduced by John Holland in his seminal work Adaptation in Natural and Artificial Systems published in 1975 (Holland, 1992), which laid the foundation for the field of Evolutionary Algorithms (EA). Evolutionary algorithms are now widely recognized as a powerful tool for solving complex optimization problems (Gen & Cheng, 1999), such as those encountered in logistics and supply chain management (Reeves & Rowe, 2002).

In the context of circular deconstruction, logistics management plays a pivotal role. The adoption of GA has gained significant traction in the construction industry, particularly for optimizing logistics in circular economy models (Gen & Lin, 2023). As traditional construction methods are being replaced by more advanced, sustainable approaches, the integration of GA has proven instrumental in addressing real-life challenges. Furthermore, hybrid methods that combine GA with other technologies, such as Geographic Information System (GIS), have been increasingly proposed to enhance decision-making processes (Jauhar et al., 2021). The integration of GA with GIS is particularly useful in tracking the flow of reclaimed materials and components throughout the RSC, offering enhanced visibility and control over deconstruction processes to have a more efficient circular construction (Irizarry et al., 2013; Song et al., 2017).

3. METHODOLOGY

Developing a RSC model is crucial for optimizing the collection, refurbishment, and redistribution of reusable building components. A well-structured RSC supports the circular economy by reintegrating deconstructed components into new building projects (Brandão et al., 2021). Focusing on industrial steel structures, this paper aims to optimize the placement of hubs to streamline the flow of components in the RSC from the deconstruction sites to hubs and then to factories, recycling centers, and end users. At the deconstruction sites, components undergo initial quality testing to determine their suitability for reuse. If repairable, components are transported to hubs for refurbishment. Components deemed unsuitable for reuse are sent to recycling centers, minimizing waste, or to remanufacturing facilities. This paper has the following tasks: (1) Identifying the locations of the existing main nodes of the RSC that will be served by the hubs for a predefined period (e.g., in the next 20 years), including the recycling facilities, steel factories, the locations of the buildings that are expected to be deconstructed in the selected jurisdiction area (i.e. the Provence of Quebec), and the locations of the new buildings that could reuse the components from the old buildings. In addition, the capacities of the existing recycling centers and steel factories will be identified in this task. GIS will be used to identify these locations and to calculate the distances between all nodes; (2) Identifying the potential locations of the hubs and their corresponding capacities; (3) Estimating the amount of steel reused components that will be originating from the deconstructed buildings (i.e. the supply side) and will be needed in the new buildings (i.e. the demand side) during the same period assumed in the first task. Statistical forecasting methods (e.g. trend projection) will be used in this task; and (4) Using GA (Reeves & Rowe, 2002) to select the optimal hub locations based on the estimated quantities of supply and demand, the capacities of the hubs and other facilities in the RSC, and the distances. This optimization will aim to minimize transportation distances and costs, and consequently, environmental impacts. Although this hybrid method of combining GIS and GA has been suggested in other studies(Gen & Lin, 2023), it has not yet been applied to the RSC in the construction industry.

Figure 1 shows the five main nodes in RSC model: (1) deconstruction sites (DS_j, where J is total number of deconstruction sites), (2) factories (F_l, where L is total number of factories), (3) recycling centers (RC_m, where M is total number of recycling centers), (4) hubs (H_k, where K is total number of hubs), and (5) end users (U_n, where N is total number of end users). Hubs play a central role among the other four nodes and provide them services and supplies of reusable deconstructed building components.

Different types of data are required to optimize the RSC. GIS plays a critical role in this process by enabling the identification of spatial locations and estimation of distances between nodes through network analysis, which is used to determine the shortest transportation routes. In addition, the capacity of each potential hub (CA_{H_k}) can be assessed by calculating the area of available vacant lands suitable for hub construction. The selection of these vacant lands within industrial zones was facilitated using GIS-based spatial analysis, with a particular emphasis on proximity to existing transportation infrastructure to enhance logistical efficiency. The identified deconstruction sites primarily consist of steel-framed structures and warehouses, which are expected to be dismantled within the next two decades, given that the average lifespan of such warehouses ranges between 50 and 60 years (Andersen & Negendahl, 2023).

To estimate the quantity of steel that can be reused and transported within the RSC framework, a GIS map layer of Land Assessment Units, provided by the City of Montreal, was utilized. This dataset includes information such as the year of construction and the gross floor area, which represents the total area across all floors of each building. Following the methodology proposed by (Eckelman et al., 2018), the potential volume of reusable steel was calculated based on the total floor area of each structure.

GIS was also applied to perform shortest path analysis within the RSC model. The proximity of potential hub locations to major transportation infrastructure significantly enhances the effectiveness of this network optimization process.

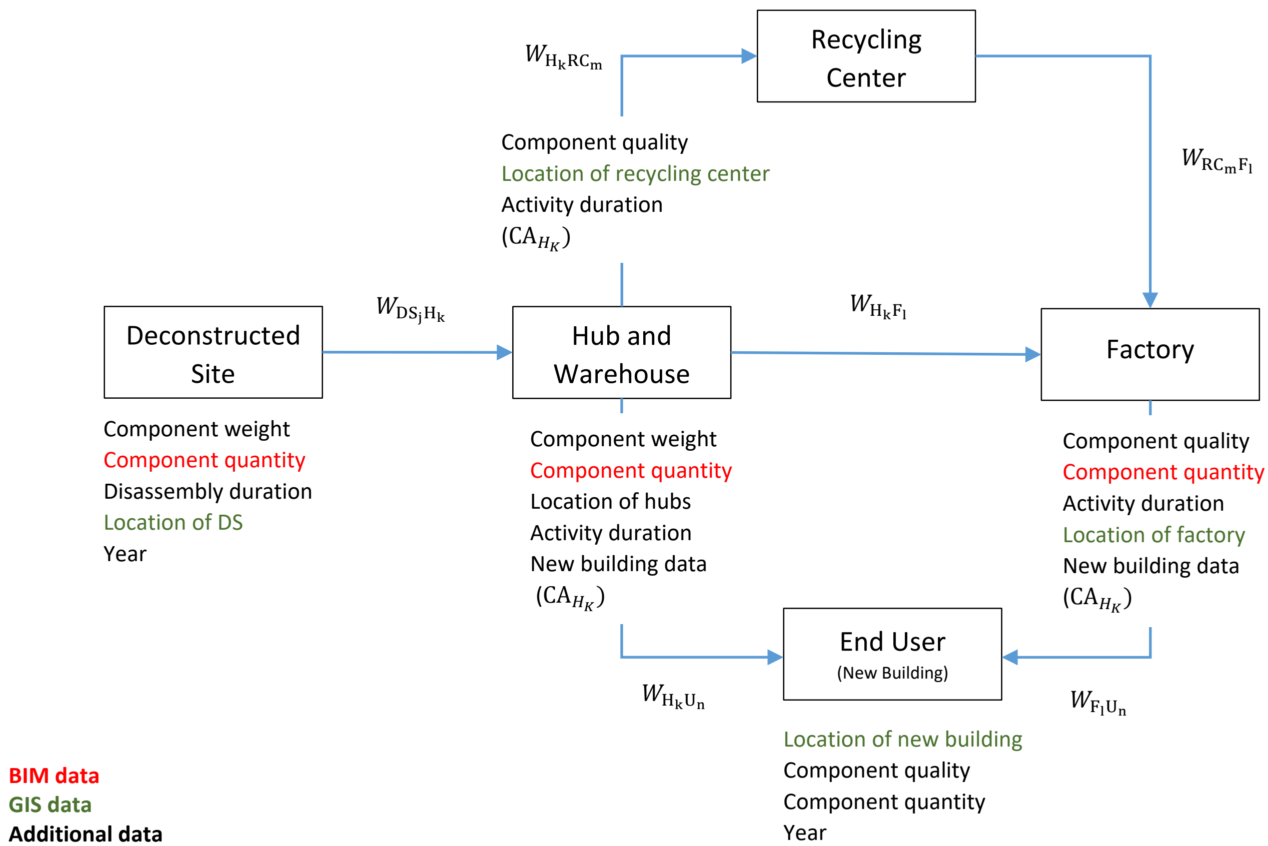


Figure 1: Main Nodes in the RSC

Furthermore, BIM data, when available, can complement GIS data by offering detailed insights into the conditions and spatial arrangement of structural components in deconstructed buildings, thus supporting more accurate component recovery estimations and improving overall RSC planning.

Two critical factors determine the effectiveness of hubs within the RSC: their locations and their capacities. Properly locating hubs is essential for minimizing transportation, operational, and logistical costs, which are significant contributors to the overall system efficiency.

3.1 Location Optimization

The potential locations of hubs and other node locations are provided using GIS. To identify optimal hub locations, GA is employed to evaluate all potential paths connections between hub locations and other nodes. Considering the load transported, their distances from the hubs, hub capacities and the limit of number of hubs that can be built (H_{max}), our model represented the transportation cost as $T_{DS_jH_k}$, $T_{H_kF_l}$, $T_{H_kRC_m}$, $T_{H_kU_n}$, , and the load of components transported as $W_{DS_jH_k}$, $W_{H_kF_l}$, $W_{H_kRC_m}$, $W_{H_kU_n}$.
The decision-making process prioritizes the nodes based on their significance, determined by the load of components they generate or receive. The greater the load of transported components is, the higher priority the node has. Consequently, hub locations are adjusted to minimize transportation costs by positioning them closer to high-priority nodes. This approach ensures that the hub placement aligns with the most critical needs of the RSC, optimizing efficiency and resource allocation. Other loads transported in the RSC, including the loads transported between recycling centers and factories $W_{RC_mF_l}$ and between factories and the end users $W_{F_lU_n}$do not affect the optimization problem, since they do not affect the hub locations.
GA optimization is selected to optimize the locations of the hubs because of its proven effectiveness in solving multi-objective problems, such as facility location optimization, where the solution space is very large, and traditional optimization methods often face significant limitations (Celik Turkoglu & Erol Genevois, 2020). The robustness of the GA in exploring the search space enables it to identify near-optimal solutions efficiently, making it an ideal choice for this problem.

3.2 Decision Variables, Chromosome Representation and Search Space

The primary decision variables in this RSC model are the hub assignments for each node. These variables are directly encoded in the chromosome structure, based on loads, hub capacities, distances and H_{max}.
For each node, there are *K* possible hubs they can be assigned to, as shown in Figure 2. Each chromosome in the GA represents a potential solution to the hub location problem. The chromosome is encoded as a vector of length *A*, which is the sum of the number of *DS, F, RC* and *U* nodes (i.e. *A*= *J*+ *L*+*M*+*N*). Each element of the chromosome corresponds to the nodes and contains an integer value representing the index of the hub to which each node is assigned. This encoding ensures that the assignments of nodes to hubs are explicitly represented, allowing the GA to explore various configurations of hub assignments. Additionally, binary decision variables are implicitly represented because if no nodes are assigned to a potential hub location, it is not considered as a proper place to build a hub. Since there are *A* nodes, and each one can be assigned independently to any of the *K* hubs, the total number of possible combinations (i.e., the size of the search space) is: K^A

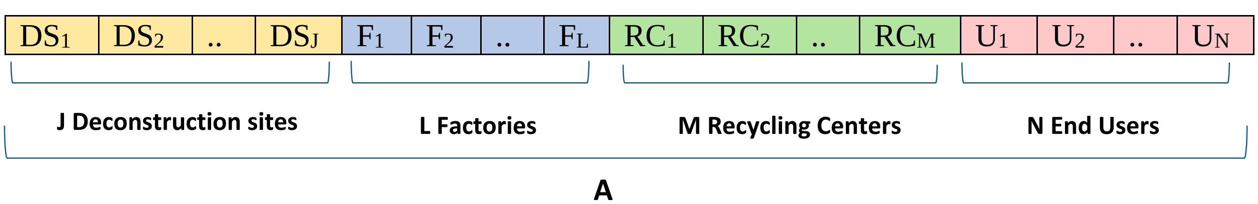


Figure 2: Structure of a chromosome

The decision-making process will be conducted by analyzing the frequency of each selected hub. The frequency is determined by the number of nodes assigned to a hub. The H_{max} hubs with the highest frequency will be selected.

3.3 Objective Function and constrains

The objective function is designed to minimize the total cost, which is calculated as the sum of transportation costs between all nodes. The transportation cost is computed as the product of the distance between a node and the assigned hub and the weight of the transported components (Eq. 1). The goal of the GA is to minimize this cost function by evolving the population of chromosomes over successive generations. Table

1 shows the variables used in the Eq. 1 along with the description. Loads and costs are given in ton and CA$, respectively.

[1] $\min Z = \left(\sum_1^J \sum_1^K T_{DS_j H_k} \times W_{DS_j H_k} \times \propto_{jk}\right) + \left(\sum_1^K \sum_1^M T_{H_k RC_m} \times W_{H_k RC_m} \times \propto_{km}\right) + \left(\sum_1^K \sum_1^L T_{H_k F_l} \times W_{H_k F_l} \times \propto_{kl}\right) + \left(\sum_1^K \sum_1^N T_{H_k U_n} \times W_{H_k U_n} \times \propto_{kn}\right)$

where $\propto_{ak}$ is a binary variable and $\propto_{ak} = 1$ if node *a* is assigned to hub *k*, and 0 otherwise. It is assumed that each node is assigned to only one hub, which is represented by:
$\sum_k \propto_{ak} = 1$

Table 1 Variables and their descriptions used in the Eq.1

Variable	Description
$W_{DS_j H_k}$	Loads from Deconstruction Site *j* to Hub *k*
$W_{H_k U_n}$	load from Hub *k* to End user *n*.
$W_{H_k F_l}$	load from Hub *k* to Factory *l*.
$W_{F_l U_n}$	load from Factory *l* to End user *n*.
$W_{H_k RC_m}$	load from Hub *k* to Recycling center *m*.
$W_{RC_m F_l}$	load from Recycling center *m* to Factory *l*.
$T_{DS_j H_k}$	Cost from Deconstruction Site *j* to Hub *k*.
$T_{H_k F_l}$	Cost from Hub *k* to Factory *l*.
$T_{H_k RC_m}$	Cost from Hub *k* to Recycling center *m*.
$T_{H_k U_n}$	Cost from Hub *k* to End user *n*.

Eq. 2 shows the constraint that the total load received by an end user must equal the sum of loads from hubs and factories. Where W_{U_N} is the total loads to end users.

[2] $\sum_1^N W_{U_n} = \sum_1^K W_{H_k U_n} + \sum_1^L W_{F_l U_n}$

Eq. 3 shows that a node *a* can only be assigned to hub *k* if hub *k* is established. β_k is a binary variable, where $\beta_k = 1$ if a hub is built at potential location *k*, and 0 otherwise.

[3] $\propto_{ak} \leq \beta_k \quad \forall a,k$

Eq. 4 shows that the total loads from DS_j assigned to one hub cannot exceed its capacity. CA_{H_k} is the capacity of the hub.

[4] $CA_{H_k} \times \beta_k \geq \sum_1^J W_{DS_j H_k} \times \propto_{jk}$

Eq. 5 shows the limitation on the number of hubs that can be built the potential locations.

[5] $\sum_k \beta_k \leq H_{max}$

Eq. 6 shows that the loads from deconstruction sites must equal the sum of loads sent to end users, factories, and recycling centers.

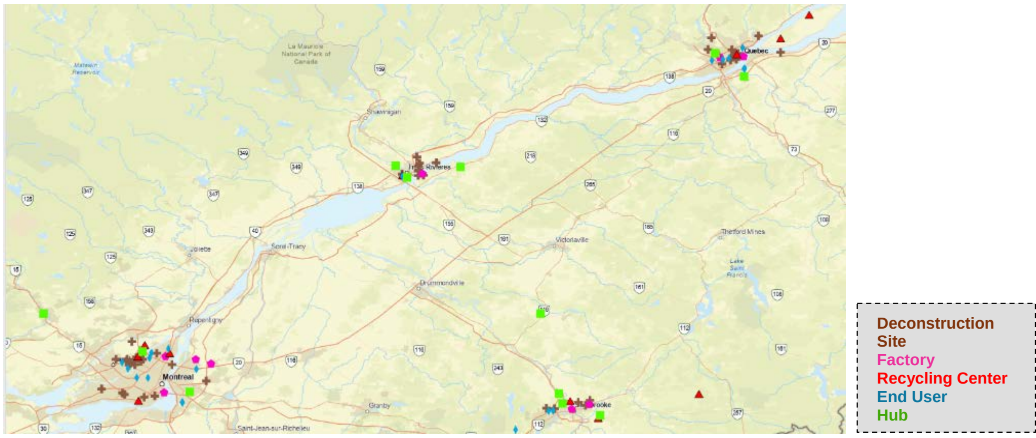
[6] $\sum_1^J W_{DS_jH_k} = \sum_1^N W_{H_kU_n} + \sum_1^M W_{H_kRC_m} + \sum_1^L W_{H_kF_l}$

4. IMPLEMENTATION AND CASE STUDY

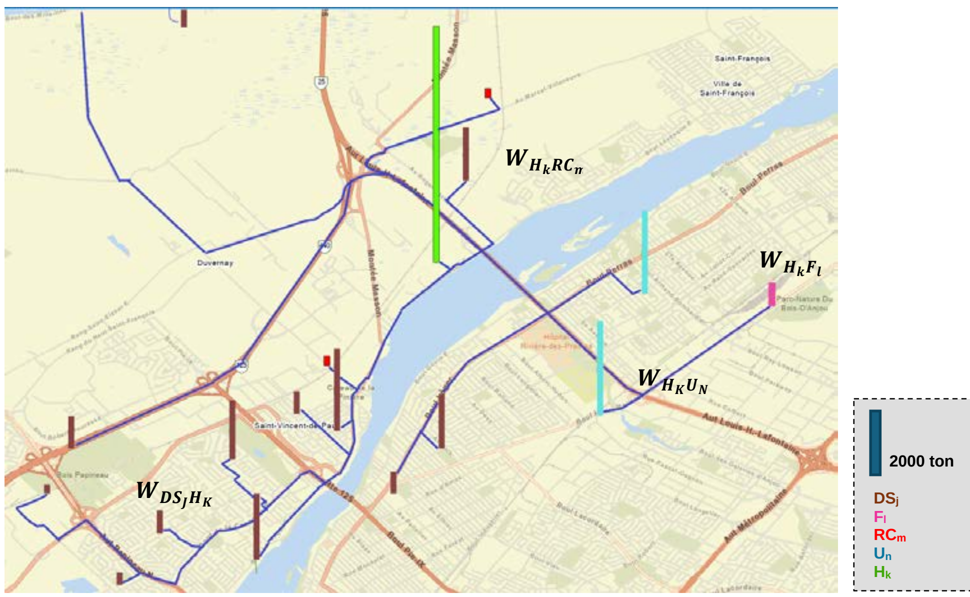
To evaluate the performance of the proposed GA hub location optimization model, it was implemented in MATLAB using data from a simulated case study. The case study targets four major urban centers in the province of Quebec, Canada: Montreal, Quebec City, Sherbrook, and Trois-Rivières. These cities were selected due to their high levels of demand due to high population, making them ideal locations for evaluating the effectiveness of the proposed model. The location data, along with assumptions of potential hub locations and their capacities, were incorporated into a case study. Initially, twelve potential hub locations were identified based on their proximity to industrial zones and transportation networks.

In this study, 91 nodes were selected, including 51 deconstruction sites, 9 factories, 11 recycling centers, and 20 end users. As mentioned in Section 3, the deconstruction sites are primarily old steel structures, such as large warehouses, that are expected to be dismantled within the next 20 years. These sites, shown in Figure3(a), were identified as they represent a significant source of reusable steel components. The factories were chosen focusing on major steel construction manufacturers in the province. The recycling centers were selected among existing metal recycling facilities, ensuring a seamless integration with the RCS. Finally, the end users were selected randomly among the existing warehouses shops assuming that they will reach their end of life in 20 years.

Location data were provided by ArcGIS. All the steel loads from DS_j and the capacity estimations for potential location of hubs were done by this platform. The steel loads from DS_j were estimated based on the area of the structure and the weight of steel per square meter (a ratio of 0.05 to 0.08 ton per square meter of deconstructed building is used).



(a) ArcGIS map with the locations of the main nodes in the four cities.



(b) The routes in the supply chain in a part of Montreal.

Figure 3: Examples of GIS data

The selection of potential hub locations is guided by their proximity to industrial zones and their strategic positioning between the four selected cities. The study also explored the feasibility of placing hubs in intermediate locations between urban centers to determine whether centralized or decentralized placement would be more efficient. The capacity of each hub was estimated based on the available land area and infrastructure as shown in Table 1, ensuring that the facility could handle the expected loads of components.

Figure 3(b) shows example of the he routes in the supply chain in a part of Montreal. The bars at each location represent the loads of components at each node or the capacity of the hub. All the routes are connected to H_K which act as service nodes. Refurbished components from H_K can be reused at U_n. However, based on the state of components, they might be moved to RC_m or F_l.

4.1 Optimization Results

MATLAB was executed for 1000 iterations, 2000 population size, and crossover and mutation rates of 95% and 1%, respectively. A high crossover rate is considered advantageous, as it facilitates a more effective exploration of the solution space through the combination of diverse parent solutions. On the other hand, a

low mutation rate makes minor stochastic variations that reduce the risk of premature convergence to suboptimal local optima (Hassanat et al., 2019). After 120,100 function evaluations (NFE), the optimal result was determined as shown in Figure 4. NFE represents the total count of fitness function evaluations used to assess the quality of individuals in the population throughout the optimization process. This NFE include the evaluations performed during crossover, mutation, and the assessment of the overall population. After executing the optimization process, six hubs were initially selected from the twelve potential locations as shown in Table 2. Also, the frequency in the table shows the number of assigned nodes to the hub, as mentioned in Section 3. Hence, it can be deducting that two hubs were assigned to Montreal and Quebec City due to their significantly higher demand levels based on demand frequency and logistical feasibility. For Sherbrook and Trois-Rivières, one hub was selected for each city.
The results confirm that out of the twelve potential hubs, only six were ultimately selected by the algorithm. Table 1 also shows the allocated nodes for each selected hub.   al to consider optimizing hub development by constructing only the necessary infrastructure, thereby minimizing unnecessary costs associated with establishing new hubs in selected areas. These findings further validate the efficiency of the optimization process in identifying the most suitable hub locations to enhance RSC sustainability.

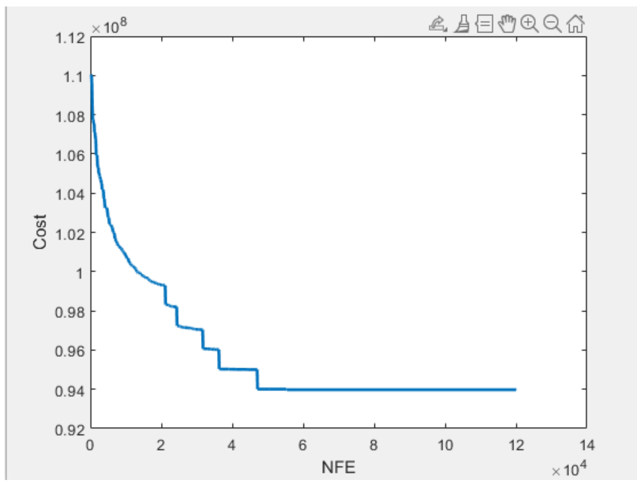


Figure 4: Diagram of cost (CA$) based on NFE count

Table 2 Hub capacities and ranks

Hub Number	Expected Capacity (1000 ton)	Rank	Frequency	Allocated Nodes	Required Capacity (1000 ton)
1	20	0	0		0
2	30	0	0		0
3	40	0	0		0
4	20	5	12	$DS_{2,3,4,5,6,7,8,9,10}$, F_{58}, RC_{71}, $U_{82,}$	2.5
5	30	0	0		0
6	25	0	0		0
7	10	0	0		0
8	35	1	22	$DS_{16,17,18,19,20,21,22,23,24,26,27,28,29,30,31}$, F_{59}, $RC_{62,70}$, $U_{76,79,81,84}$	13.3
9	30	6	5	DS_{25}, F_{56}, RC_{61}, $U_{78,88}$	2.7
10	40	4	12	$DS_{11,12,13,14,15}$, $F_{55,57}$, $RC_{63,64}$, $U_{72,80,83}$	3.2
11	32	3	20	$DS_{1,33,34,35,36 ,47,48,49,50,51}$, $F_{52,54,60}$, $RC_{65,69}$, $U_{85,87,89,90,91}$	18.3
12	22	2	20	$DS_{32,37,38,39,40,41,42,43,44,45,46}$, F_{53}, $RC_{66,67,68}$, $U_{73,74,75,77, 86}$	20.7

5. CONCLUSION AND FUTURE WORK

This study lays a strong foundation for a more sustainable construction industry and underscores the need for continued efforts to advance the principles of the circular construction and RSC management. The paper outlines how the RSC, applied in deconstruction processes, offers an efficient solution to reuse of steel construction components. This study presents a new approach to optimizing the RSC for deconstructed building components, emphasizing the integration of GIS and GA technologies. The findings of this study confirm that strategic hub placement can significantly improve the efficiency of steel reuse and recycling in the deconstruction industry. The optimized hub locations reduced transportation costs, minimized environmental impact, and facilitated a more sustainable supply chain model. These results provide valuable insights for policymakers and industry stakeholders looking to enhance circular economy practices within the construction sector. This focus on sustainability not only facilitates market development for component reuse but also advances deconstruction methodologies such as disassembly, enhancing the effectiveness of the circular economy within construction.

For establishing the RSC, it is essential to have more collaboration among industry stakeholders, which includes clear material flows, the utilization of digital technologies like GIS and BIM, and the development of standardized guidelines. These elements are crucial for integrating modular components into both construction and deconstruction, thus maximizing the benefits of off-site construction while minimizing waste and environmental impact. Furthermore, by designing an effective RSC model specifically for modular construction, the industry stands to benefit from enhanced resource recovery, reduced waste, and greater alignment with the principles of the circular economy. Technologies such as MPs facilitate the tracking of modular components within the RSC, enhancing the efficiency and transparency of their flow. Additionally, BIM can provide detailed data on components during the disassembly process, enabling the development of advanced disassembly methods that minimize damage and preserve component integrity. Looking forward, future research can target developing specialized hubs that handle different component types based on their material composition, such as concrete-specific and steel-specific hubs. Also, shifting focus from traditional deconstruction toward the disassembly of modular constructions can improve ease of process and efficiency, thereby supporting a more sustainable approach to component reuse within the construction industry.

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