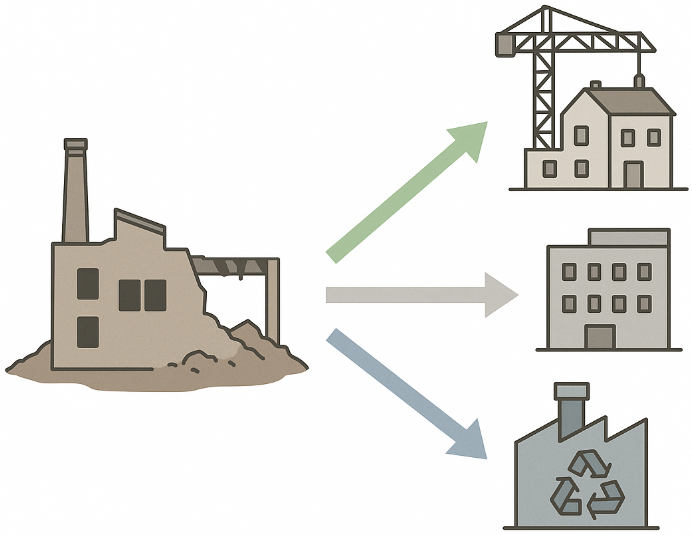

A decision-support system for brownfield rehabilitation: Optimizing material usage and transport for sustainable urban redevelopment

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Abstract

The valorization of brownfields presents a significant challenge in urban redevelopment, as decisions in this domain involve a trade-o; between environmental sustainability and financial feasibility. Our study, focusing on three sites in Switzerland, introduces a comprehensive decision-support system (DSS) that integrates operations research methodologies to optimize the rehabilitation process of such sites. Within this DSS, we identify key cost components related to material transport and rehabilitation expenses, including routing, vehicle usage, tools, materials, storage, transformation/repackaging, and recycling costs. Our DSS finds the most efficient strategy while considering (i) spatial constraints, i.e., the locations of brownfield sites, storage sites, recycling centers, transformation/repackaging facilities, and construction sites; (ii) technical constraints, i.e., facility and vehicle capacities and material-related restrictions; and (iii) financial constraints, i.e., budget limitations. By developing a mixed-integer linear programming model, we aim to provide the optimal assignment of materials between sites and the vehicle routing of material transport. The results of this research are planned to be integrated into a brownfield rehabilitation framework that benefits from circular economy practices in construction, proposing incentives to promote sustainability.

Keywords

Brownfield; Logistics; Sustainability; Urban redevelopment

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1 Introduction

A brownfield is previously developed land that is not currently in use. These sites are often abandoned or underutilized and may be contaminated by hazardous substances, pollutants, or contaminants from past industrial or commercial activities (EPA, United States Environmental Protection Agency, 2024). The presence of such contamination can complicate the expansion, redevelopment, or reuse of these properties. Driven by the scarcity of undeveloped land and the need for sustainable practices, industrial brownfield rehabilitation offers a solution. This process involves cleaning and remediating contaminated sites, transforming them into safe and suitable land for new development. In turn, it promotes urban renewal while reducing environmental hazards. The decision-making process for these sites often involves a complex trade-off between environmental sustainability and financial feasibility.

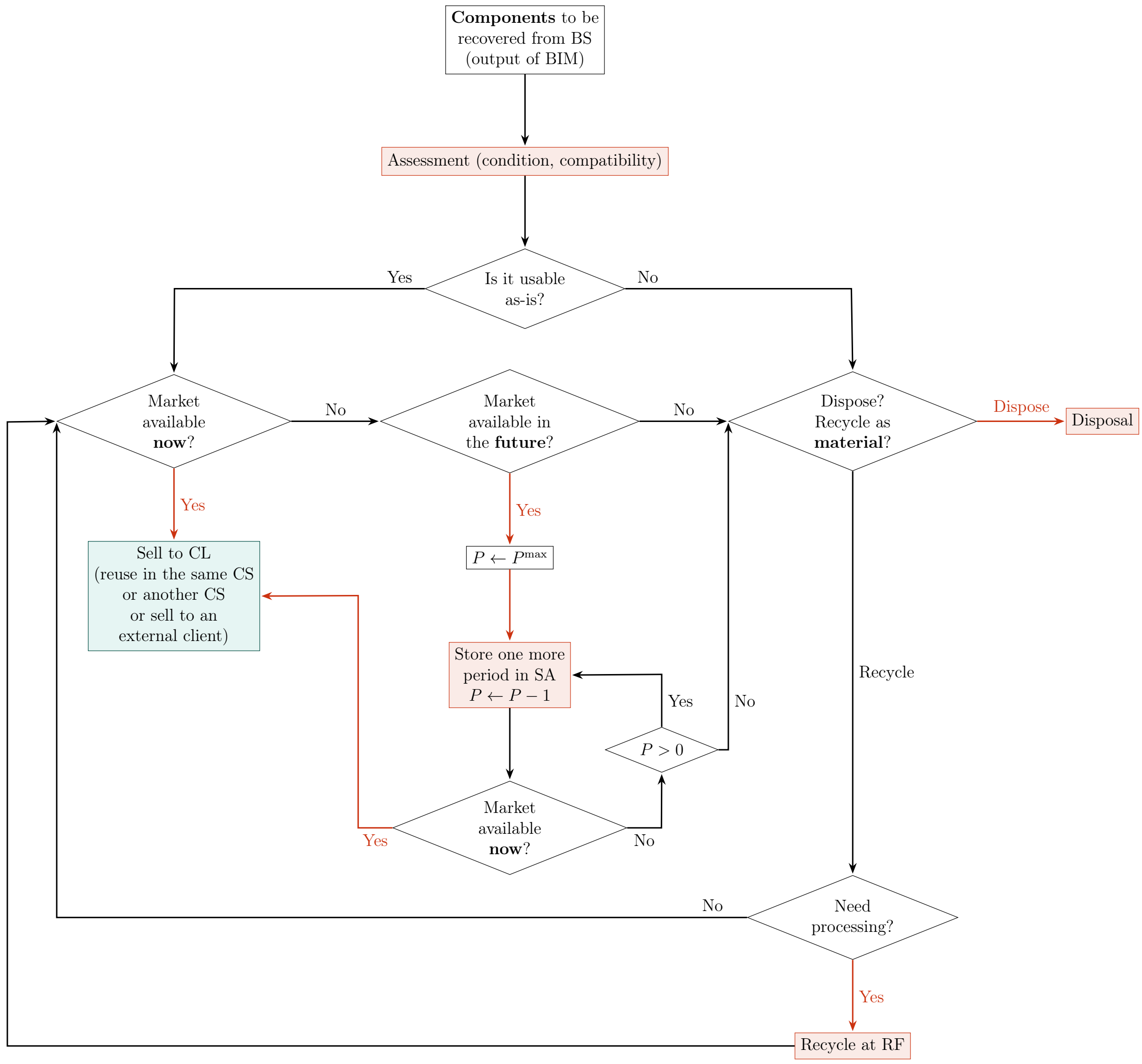
The literature covers several aspects of brownfield remediation such as the future land use activity selection (Ameller, 2020), overall evaluation of rehabilitation (Bardos *et al.*, 2016; Zhu *et al.*, 2015), and stakeholder involvement (Zhu *et al.*, 2015; Morio *et al.*, 2013). Ameller (2020) works on the allocation of future land use activities on the brownfield sites (BSs). They use an activity profile to maximize the sum of individual net revenues, considering expected costs and benefits. Rehabilitation costs include remediation of contaminants, management of excavated soils, deconstruction of existing buildings, and soil reconditioning. However, transportation and use of dismantled materials are not included. Bardos *et al.* (2016) assess the overall valuation of a rehabilitation process by proposing the Brownfield Opportunity Matrix to help identify and value multiple services from these sites suggesting a comprehensive assessment approach that includes both tangible and intangible benefits. Similarly, Zhu *et al.* (2015) establish an evaluation index system that incorporates 27 criteria across societal, economic, financial, and environmental dimensions. This optimized evaluation index system provides a practical tool for stakeholders to derive informative reference values and tailor their own criteria sets. They emphasize the importance of applying and validating the system across various real-world examples to ensure its generalizability and effectiveness. The framework proposed by Morio *et al.* (2013) aids decision-making by determining mixed land-use options that balance economic benefits with sustainable development. They identify near-optimum configurations based on spatial evaluation functions and stakeholder objectives and demonstrate the benefits of separately considering remediation costs and market value, revealing that similar economic outcomes can be achieved with varying land use configurations, and emphasizing the importance of detailed and transparent stakeholder discussions for sustainable brownfield reuse. They suggest that investigating the role of normalization methods and weighting in the optimization process is a promising research direction. A review by Hammond *et al.* (2021) evaluates decision-support systems for brownfield land applications, identifying common applications such as remediation technology selection and land use suitability, and noting several limitations like the lack of socioeconomic criteria and poor user interfaces. They indicate that future research should include improving user interfaces and web functionalities. On the other hand, they do not consider the transportation of materials.

All in all, the literature mainly focuses on land use options and the overall evaluation of the rehabilitation process. However, none of the works is coupled with material transportation operations for reusing and recycling. This paper provides an optimization model that solves material reuse and recycling logistics of brownfield rehabilitation, which will later be made available to its users through a user interface as indicated as a gap by Hammond *et al.* (2021). Our study also allows for analyzing the trade-off between different objectives as mentioned by Morio *et al.* (2013) thanks to the flexibility of the objective function.

2 Problem Statement and Methodology

In the context of brownfield redevelopment, a variety of building components can be recovered during the demolition and deconstruction process. These components present potential value if reused, resold, or recycled. However, due to their varying conditions, market demand, and logistical constraints, a systematic decision-making process is required to determine the most appropriate course of action for each recovered component. Elements, i.e., reusable building components, can typically be used as-is in another location with little to no intervention, such as inspection, cleaning, and minor repairs. Doors, windows, beams, and tiles are common examples of elements. At the start of the rehabilitation process, all recovered components are initially treated as elements. Materials, i.e., recyclable construction components, cannot be reused directly and must be converted into a raw or processed state for possible reuse. Examples include concrete, bricks, asphalt, and steel, which may require crushing, refining, or sorting. These processed materials can then be used as backfill, road base, or incorporated into new construction. Both elements and materials can be reused on the same site, transferred to another site, or sold to third-party clients (e.g., salvage companies and architectural reuse markets). Elements and materials undergo various activities, (i.e., assessment, storage, sale, reuse, recycling, and disposal) in facilities. Figure 1 illustrates the decision-making process for the reuse and recovery planning of such components, integrating both economic considerations (e.g., cost-incurring

Figure 1: Decision flow for reuse, resale, storage, recycling, and disposal of building components recovered from BSs, where costs and revenues are indicated by red and green blocks and arrows, respectively.



activities in red-colored blocks, transportation costs in red-colored arrows, and revenues in green-colored blocks) and logistical constraints (e.g., storage time, processing needs). Decision points are represented as diamonds, while process activities (e.g., assessment, storage) and terminal outcomes (e.g., disposal, sale) are depicted as blocks. P refers to the remaining allowable storage periods, with $P^{\max}$ indicating the maximum number of periods a component can remain in storage awaiting market demand.

A Building Information Model (BIM) developed by specialists identifies the components that are supposed to be available following the demolition of the building. This information is given to our framework as an input to plan their recovery journey. At the beginning, each component undergoes a technical assessment to determine its structural integrity and compatibility for reuse. If considered unusable, it is either disposed of or directed toward material recycling, depending on whether further processing is feasible. If the component is found to be usable as-is, the system evaluates whether immediate market demand exists. If such demand exists, the element can be reused on the same CS, reused on a different site, or sold to an external client. These options enable either internal cost savings or external revenue generation. If no immediate demand is present, the system checks whether future demand is anticipated. In that case, the element is transferred to an SA and held for a limited number of periods. After each period, market demand is re-evaluated. If no demand arises before $P^{\max}$ elapses, the element is routed to disposal or material recycling, depending on its characteristics. The diagram also accounts for the possibility that recyclable elements may require additional processing before entering the market as raw materials. In such cases, they are sent to RFs.

We design a mixed-integer linear program (MILP) to aid decision making in such a framework. The notation used in the model is given in Table 1. We can classify the overall cost evaluation in this system in three categories: activity-based revenues, activity-based costs, and transportation costs. Activity-based revenues include the sale of components and cost savings achieved through reuse. Activity-based costs encompass operations such as assessment, recycling, storage, and disposal. Transportation costs are incurred whenever components are transferred between BSs, CLs, SAs, CSs, or RFs. The objective then becomes minimizing the total cost of managing recovered building components (1).

Developed MILP is given in 2-30. Constraints 2 ensure that there is one and only one outcome for each component. Constraint set 3 makes sure that transportation and activity do not take place at the same time for a component at a specific time. Constraints 4-5 initiate the movement of components from their respective BSs. Release of components from BSs is ensured in a timely manner, i.e., after the assessment is complete, with constraints 6. Constraints 7-10 assure that the demands at CS and CL are not exceeded. We also impose flow conservation of transport and activities. Constraint sets 11 and 12 respectively make sure that a transport operation is always followed by an activity at the arrival facility after the required time for transportation, and an activity is followed by travel after the required time for that activity for BSs and RFs. 13 and 14 ensure that this condition is satisfied for SAs, too. 15-17 prohibit further actions after an outcome has occurred. We also make sure that each activity takes place at its corresponding facility by constraints 18. In order for the components to be sold or reused, 19 and 20 ensure that they are transported to the corresponding facility. Constraints 21-26 link the corresponding decision variables and constraints 27-30 ensure the domains are well-defined.

Table 1: Notation

Set	**Description**
I	set of components
T	set of time periods
A	set of activities
S	set of storage areas
B	set of brownfield sites
R	set of recycling facilities
C	set of construction sites
L	set of clients
F	set of facilities, i.e., $S \cup B \cup R \cup C \cup L$
F^-	set of departure facilities, i.e., $S \cup B \cup R$
F^+	set of destination facilities, i.e., $C \cup L$

Parameter	**Description**
$\mathrm{d}^{\mathrm{trans}}_{f,g}$	time to go from facility $f \in \mathcal{F}$ to $g \in \mathcal{F} \setminus \{f\}$
$\mathrm{d}^{\mathrm{act}}_{a}$	time to complete activity $a \in \mathcal{A}$
$\mathrm{c}^{\mathrm{trans}}_{i,f,g}$	cost of component $i \in \mathcal{I}$ traveling from facility $f \in \mathcal{F}$ to facility $g \in \mathcal{F}$
$\mathrm{c}^{\mathrm{act}}_{i,a}$	cost of component $i \in \mathcal{I}$ undergoing activity $a \in \mathcal{A}$
$\mathrm{r}^{\mathrm{reuse}}_{i,t}$	revenue obtained from reusing component $i \in I$ at time $t \in \mathcal{T}$
$\mathrm{r}^{\mathrm{sale}}_{i,t}$	revenue obtained from selling component $i \in I$ at time $t \in \mathcal{T}$
$\mathrm{h}^{\mathrm{CS}}_{i,f,t}$	demand for component $i \in I$ at construction site $f \in \mathcal{C}$ at time $t \in \mathcal{T}$
$\mathrm{h}^{\mathrm{CL}}_{i,f,t}$	demand for component $i \in I$ at client $f \in \mathcal{L}$ at time $t \in \mathcal{T}$
$\mathrm{s}_{i,f,t}$	supply for assessed component $i \in I$ at BS $f \in \mathcal{B}$ at time $t \in \mathcal{T}$

Decision variable	**Description**
$x^{\mathrm{start}}_{i,f,g,t}$	1 if component $i \in \mathcal{I}$ travels from facility $f \in \mathcal{F}^-$ to facility $g \in \mathcal{F}^+ \setminus f$ starting at time $t \in \mathcal{T}$, 0 otherwise
$y^{\mathrm{start}}_{i,a,f,t}$	1 if component $i \in \mathcal{I}$ undergoes activity $a \in \mathcal{A}$ at facility $f \in \mathcal{F}$ starting at time $t \in \mathcal{T}$, 0 otherwise
$x_{i,f,g,t}$	1 if component $i \in \mathcal{I}$ is traveling from facility $f \in \mathcal{F}^-$ to facility $g \in \mathcal{F}^+ \setminus f$ at time $t \in \mathcal{T}$, 0 otherwise
$y_{i,a,f,t}$	1 if component $i \in \mathcal{I}$ is undergoing activity $a \in \mathcal{A}$ at facility $f \in \mathcal{F}$ at time $t \in \mathcal{T}$, 0 otherwise
$\alpha_{i,t}$	1 if component $i \in \mathcal{I}$ is reused at time $t \in \mathcal{T}$, 0 otherwise
$\beta_{i,t}$	1 if component $i \in \mathcal{I}$ is sold at time $t \in \mathcal{T}$, 0 otherwise
$\gamma_{i,t}$	1 if component $i \in \mathcal{I}$ is disposed at time $t \in \mathcal{T}$, 0 otherwise
$\mathrm{loc}_{i,f,t}$	1 if component $i \in \mathcal{I}$ is at facility $f \in \mathcal{F}$ at time $t \in \mathcal{T}$, 0 otherwise

$$\begin{aligned}
\min \quad & \sum_{i\in\mathcal{I}}\sum_{f\in\mathcal{F}^-}\sum_{g\in\mathcal{F}^+}\sum_{t\in\mathcal{T}} c^{\text{trans}}_{i,f,g}\cdot x^{\text{start}}_{i,f,g,t} + \sum_{i\in\mathcal{I}}\sum_{t\in\mathcal{T}} c^{\text{act}}_{i,\text{dispose}}\cdot\gamma_{i,t} - \sum_{i\in\mathcal{I}}\sum_{t\in\mathcal{T}}\left(r^{\text{reuse}}_{i,t}\cdot\alpha_{i,t} + r^{\text{sale}}_{i,t}\cdot\beta_{i,t}\right)\\
& + \sum_{i\in\mathcal{I}}\sum_{f\in\mathcal{F}}\sum_{t\in\mathcal{T}}\left(c^{\text{act}}_{i,\text{assessment}}\cdot y^{\text{start}}_{i,\text{assessment},f,t} + c^{\text{act}}_{i,\text{recycle}}\cdot y^{\text{start}}_{i,\text{recycle},f,t} + c^{\text{act}}_{i,\text{storage}}\cdot y_{i,\text{storage},f,t}\right) \qquad (1)
\end{aligned}$$

$$\begin{aligned}
\text{s.t.}\quad & \sum_{f\in\mathcal{F}}\sum_{\substack{a\in\{\text{sell},\\ \text{reuse},\text{dispose}\}}}\sum_{t\in\mathcal{T}} y^{\text{start}}_{i,a,f,t} = 1 && i\in\mathcal{I} && (2)\\
& \sum_{a\in A}\sum_{f\in F} y_{i,a,f,t} + \sum_{\substack{f\in F^-\\ g\in F^+\\ f\neq g}} x_{i,f,g,t} \le 1 && i\in\mathcal{I}, t\in\mathcal{T} && (3)\\
& \text{loc}_{i,f,t} = 1 && i\in\mathcal{I}, f\in\mathcal{F}, t\in\mathcal{T}: s_{i,f,t}>0 && (4)\\
& \sum_{\substack{g\in\mathcal{F}^+\\ g\neq f}} x^{\text{start}}_{i,f,g,t} = 1 && i\in\mathcal{I}, f\in\mathcal{B}, t\text{: } \text{s}_{i,f,t}=1 && (5)\\
& y_{i,\text{assessment},f,t+\delta} = 1 && i\in\mathcal{I}, f\in\mathcal{F}, t\in\mathcal{T}: s_{i,f,t}>0,\ \delta<\text{d}^{\text{act}}_{\text{assessment}} && (6)\\
& \alpha_{i,t} \le \text{h}^{\text{CS}}_{i,g,t} && i\in\mathcal{I}, g\in\mathcal{C}, t\in\mathcal{T} && (7)\\
& \beta_{i,t} \le \text{h}^{\text{CL}}_{i,g,t} && i\in\mathcal{I}, g\in\mathcal{L}, t\in\mathcal{T} && (8)\\
& \sum_{i\in I}\alpha_{i,t} \le \sum_{i\in I}\text{h}^{\text{CS}}_{i,g,t} && g\in\mathcal{C}, t\in\mathcal{T} && (9)\\
& \sum_{i\in I}\beta_{i,t} \le \sum_{i\in I}\text{h}^{\text{CL}}_{i,g,t} && g\in\mathcal{L}, t\in\mathcal{T} && (10)\\
& \sum_{a\in\mathcal{A}} y^{\text{start}}_{i,a,g,t+\text{d}^{\text{trans}}_{fg}} \ge x^{\text{start}}_{i,f,g,t} && i\in\mathcal{I}, f\in\mathcal{F}^-, g\in\mathcal{F}^+, f\neq g, t\in\mathcal{T}: t+\text{d}^{\text{trans}}_{fg} && (11)\\
& \sum_{\substack{f\in\mathcal{F}^+\\ f\neq g}} x^{\text{start}}_{i,g,f,t+\text{d}^{\text{act}}_a} \ge y^{\text{start}}_{i,a,g,t} && i\in\mathcal{I}, a\in\mathcal{A}, g\in\mathcal{B}\cup\mathcal{R}, t: t+\text{d}^{\text{act}}_a\in\mathcal{T} && (12)\\
& \sum_{\substack{g\in\mathcal{F}^+\\ g\neq f}} x^{\text{start}}_{i,f,g,t+1} \ge y_{i,a,f,t} - y_{i,a,f,t+1} && i\in\mathcal{I}, a\in\{\text{storage}\}, f\in\mathcal{S},\ t<T_{\max} && (13)\\
& y_{i,a,f,t} \le y_{i,a,f,t-1} + y^{\text{start}}_{i,a,f,t} && i\in\mathcal{I}, a\in\{\text{storage}\}, f\in\mathcal{S},\ t>1 && (14)\\
& x_{i,f,g,t'} \le 1-(\alpha_{i,t}+\beta_{i,t}+\gamma_{i,t}) && i\in\mathcal{I}, f\in\mathcal{F}^-, g\in\mathcal{F}^+, t\in\mathcal{T}, t'\in\mathcal{T}: t'>t && (15)\\
& \text{loc}_{i,f,t'} \le 1-(\alpha_{i,t}+\beta_{i,t}+\gamma_{i,t}) && i\in\mathcal{I}, f\in\mathcal{F}^-, t\in\mathcal{T}, t'\in\mathcal{T}: t'>t && (16)\\
& y_{i,a,f,t'} \le 1-(\alpha_{i,t}+\beta_{i,t}+\gamma_{i,t}) && i\in\mathcal{I}, a\in\mathcal{A}, f\in\mathcal{F}, t\in\mathcal{T}, t'\in\mathcal{T}: t'>t && (17)\\
& y^{\text{start}}_{i,a,f,t} = 0,\quad y_{i,a,f,t} = 0 && i\in\mathcal{I},\ a\in\mathcal{A},\ f\notin\mathcal{F}_a,\ t\in\mathcal{T} && (18)\\
& \alpha_{i,t} \le \sum_{\substack{g\neq f\\ (g,f)\in D}} x^{\text{start}}_{i,g,f,t-d_{g,f}} && i\in\mathcal{I}, f\in\mathcal{C},\ t\in\mathcal{T} && (19)\\
& \beta_{i,t} \le \sum_{\substack{g\neq f\\ (g,f)\in D}} x^{\text{start}}_{i,g,f,t-d_{g,f}} && i\in\mathcal{I}, f\in\mathcal{L},\ t\in\mathcal{T} && (20)\\
& x_{i,f,g,t+\tau} \ge x^{\text{start}}_{i,f,g,t} && i\in\mathcal{I}, f\in\mathcal{F}^-, g\in\mathcal{F}^+, t\in\mathcal{T}, \tau\text{: } \tau<\text{d}^{\text{trans}}_{fg},\ t+\tau\in\mathcal{T} && (21)\\
& y_{i,a,f,t+\tau} \ge y^{\text{start}}_{i,a,f,t} && i\in\mathcal{I}, a\in\mathcal{A}, f\in\mathcal{F}, t\in\mathcal{T}, \tau\text{: } \tau<\text{d}^{\text{act}}_a,\ t+\tau\in\mathcal{T} && (22)\\
& \text{loc}_{i,f,t} = \sum_{a\in\mathcal{A}} y_{i,a,f,t} && i\in\mathcal{I}, f\in\mathcal{F}, t\in\mathcal{T} && (23)\\
& y^{\text{start}}_{i,\text{sell},f,t} \le \beta_{i,t} && i\in\mathcal{I}, f\in\mathcal{F}, t\in\mathcal{T} && (24)\\
& y^{\text{start}}_{i,\text{reuse},f,t} \le \alpha_{i,t} && i\in\mathcal{I}, f\in\mathcal{F}, t\in\mathcal{T} && (25)\\
& y^{\text{start}}_{i,\text{dispose},f,t} \le \gamma_{i,t} && i\in\mathcal{I}, f\in\mathcal{F}, t\in\mathcal{T} && (26)\\
& x^{\text{start}}_{i,f,g,t}, x_{i,f,g,t} \in\{0,1\} && i\in\mathcal{I}, f\in\mathcal{F}^-, g\in\mathcal{F}^+: g\neq f, t\in\mathcal{T} && (27)\\
& y^{\text{start}}_{i,a,f,t}, y_{i,a,f,t} \in\{0,1\} && i\in\mathcal{I}, a\in\mathcal{A}, f\in\mathcal{F}, t\in\mathcal{T} && (28)\\
& \alpha_{i,t}, \beta_{i,t}, \gamma_{i,t} \in\{0,1\} && i\in\mathcal{I}, t\in\mathcal{T} && (29)\\
& \text{loc}_{i,f,t} \in\{0,1\} && i\in\mathcal{I}, f\in\mathcal{F}, t\in\mathcal{T} && (30)
\end{aligned}$$

where $\mathcal{F}_a$ is the subset of facilities where activity a is allowed and D is the set of facility pairs with defined travel durations.

3 Results and Discussion

In this project, we are concerned with three industrial sites from Switzerland to be rehabilitated: Condor SA, Filature de laine peignée d'Ajoie SA (FLASA), and SAFED located in Courfaivre, Alle, and Delémont, respectively. These sites present various characteristics in terms of material availability and constraints due to their former usage purposes.

To validate our model, we work on sample data. We consider two BSs, i.e., BS1 and BS2, one RF, i.e., RF1, two storage areas, i.e., SA1 and SA2, one CS and one CL, i.e., CS1 and CL1, respectively. There are seven components becoming available at BSs at different times. CS1 and CL1 offer reuse and sale activities for specific components at specific time periods, which are fed into the model as demand from these facilities. In other words, they represent the future market availability. The model ensures that a material cannot be reused or sold at a facility if it does not have demand for that component at that time period. The results obtained on a CPLEX solver are presented in Figures 2 and 3. The x-axis represents the time period, the y-axis on the left shows the facility IDs. Each component is represented with a different color, which can be seen in the legend, and the activity they are undergoing are indicated on the lines.

Here, we present results for two different scenarios where we change the duration of assessment. In Figure 2, we assume that the assessment activity takes one period to complete for all components. In this case, we see that three components are sold at CL1, and four components are reused. Some components (e.g., door_A and beam_B) are directly transported to facilities where they are sold or reused whereas some others (e.g., window_A and door_B) have to be stored before they are sold or reused. We also see that door_C visits two different SAs as this minimizes the cost. We present the results for an increased required time for assessment in Figure 3. In this scenario, we see some recycling and disposal activities. For example, door_B and beam_B are stored before disposal, and door_C is recycled before reuse.

Figure 2: Component movement and activities over time for representative sample data with 1-period long assessment

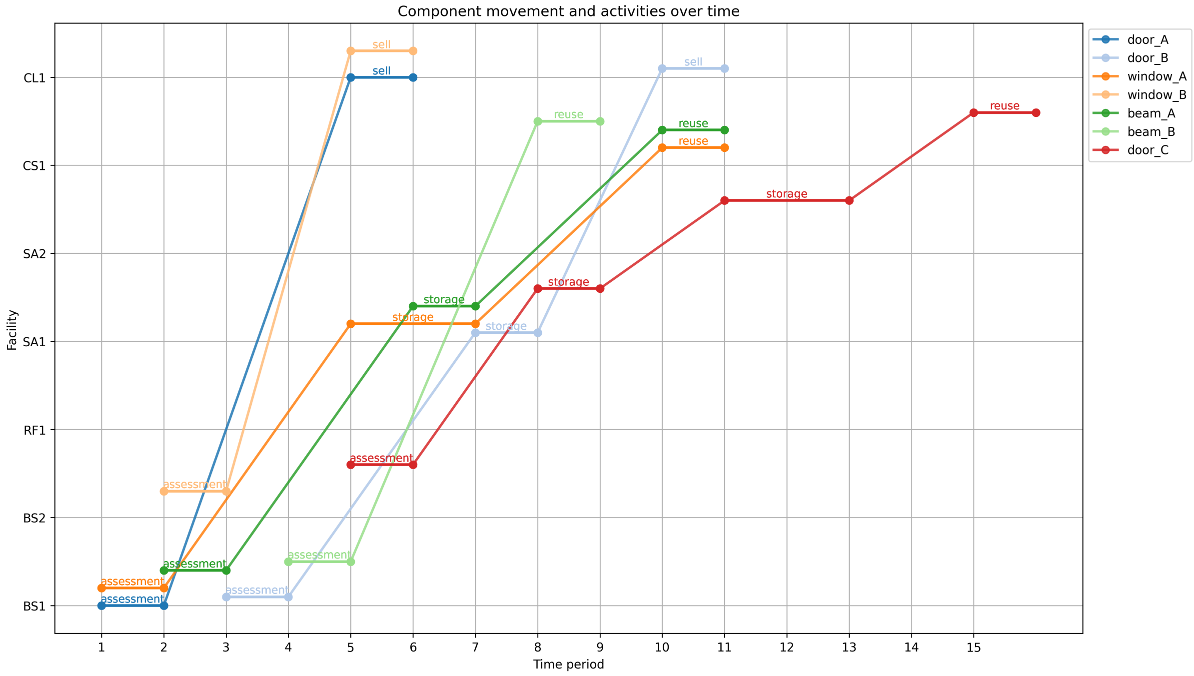
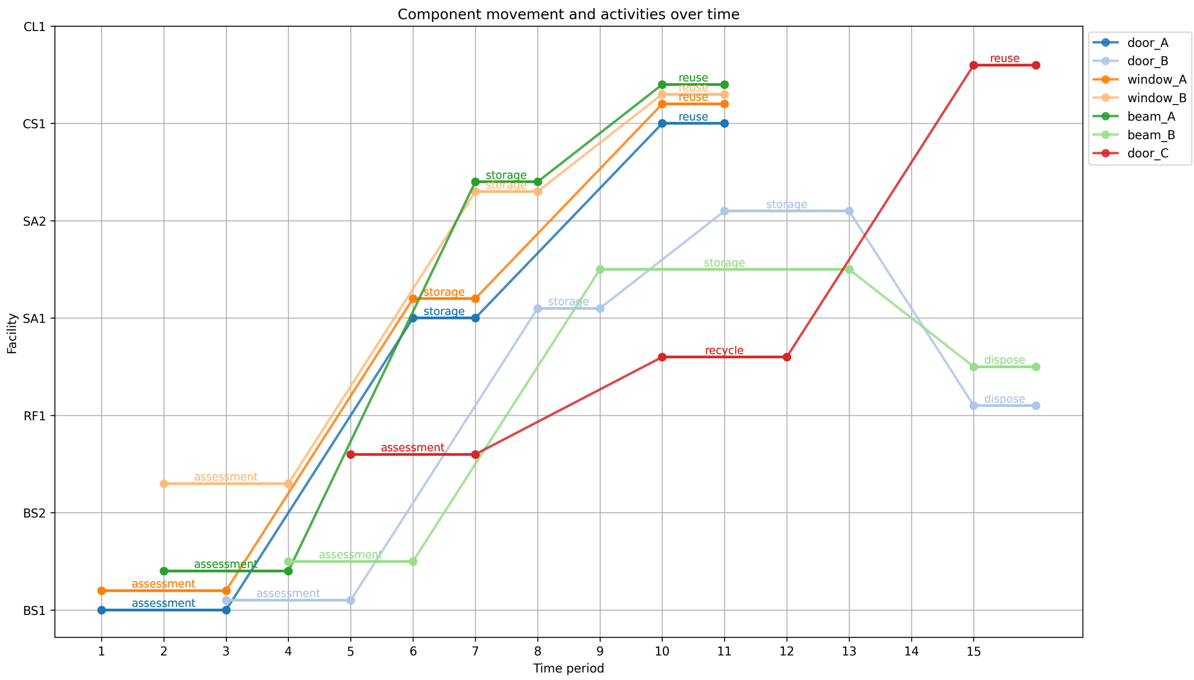


Figure 3: Component movement and activities over time for representative sample data with 2-period long assessment



4 Conclusion and Future Work

The decision-making process outlined in our framework addresses the operational challenges of brownfield redevelopment and highlights the societal, economic, and environmental benefits of circular economy principles in construction. By integrating spatial, technical, and financial analyses, our framework provides a comprehensive approach to optimizing component handling in the context of brownfield rehabilitation.

The results demonstrate that the proposed model effectively represents component handling operations. The objective function can be further detailed to account for additional operational factors. For example, perishable materials can be identified, and penalties can be applied for the time between their pick-up and drop-off. Time windows for each site and facility can be incorporated. Environmental factors, such as CO2 emissions, energy, and water consumption, can be included in the objective function to assess and, if possible, minimize the environmental impact.

Future research can expand our framework by incorporating additional strategic factors such as social impacts (e.g., creating job opportunities) and long-term sustainability metrics. Applying the framework to different geographical regions and varying types of BSs would help generalize its applicability and effectiveness. Collaboration with policymakers and industry stakeholders can facilitate the implementation of the proposed strategies and promote wider adoption of sustainable practices in urban redevelopment. Finally, Life Cycle Assessment (LCA) is a method that quantitatively evaluates the environmental impact of a service or component, showing that recycling and upcycling are efficient strategies, supporting a circular economy.

Methodological enhancements could include the investigation of a stochastic approach, which would consider market uncertainty for materials and elements. This way, decision makers can optimize current decisions according to a set of scenarios that are likely to happen in the future.

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