

TOPIC: OPTIMISATION OF REUSABLE STRUCTURAL ELEMENTS FROM MATERIAL BANKS FOR SUSTAINABLE BUILDING CONSTRUCTION

ABSTRACT: Optimisation, sustainability, and reusability in the construction industry are becoming more important in attaining a circular economy. The construction industry has a high potential to reduce material and energy consumption, accounting for 39% of carbon emissions, with 11% from material production and construction. Reusing structural components from deconstructed buildings preserves embedded energy and is more efficient than recycling, which requires high energy and material investment. However, to realise a circular economy, well-organised material banks are essential. The study aims to create an algorithm using Grasshopper-Rhino to optimise the reuse of structural components from deconstructed buildings. The program takes input from a theoretical material bank that provides parameters such as geometry, cross-section sizes, and material grade to limit waste, minimise cutting, and reduce the use of new materials. Basic structural design calculations that comply with the Eurocode standards will be integrated, and the algorithm's applicability will be demonstrated by the design of a simple frame structure. Another aim of the study is to present a detailed literature overview of the circular economy extended by case studies and the role of material banks in reuse. It highlights how reusing components can reduce consumption while meeting structural criteria such as stiffness and resistance in both the Ultimate Limit State and Serviceability Limit State, using widely accepted construction technologies.

KEYWORDS:

SUSTAINABILITY, CIRCULAR ECONOMY, REUSABILITY, MATERIAL BANK, STRUCTURAL DESIGN, OPTIMISATION

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1. Introduction

1.1 Background

The construction industry significantly contributes to global waste due to its high resource consumption, making integrating sustainability into the construction process a significant challenge. The word "**circular economy**" has become more prevalent and is receiving more attention worldwide to improve the current production and consumption model, which relies on producing, using, and disposing of waste [1]. The circular economy provides a more sustainable method of take-make-consume-reuse and recycle [2].

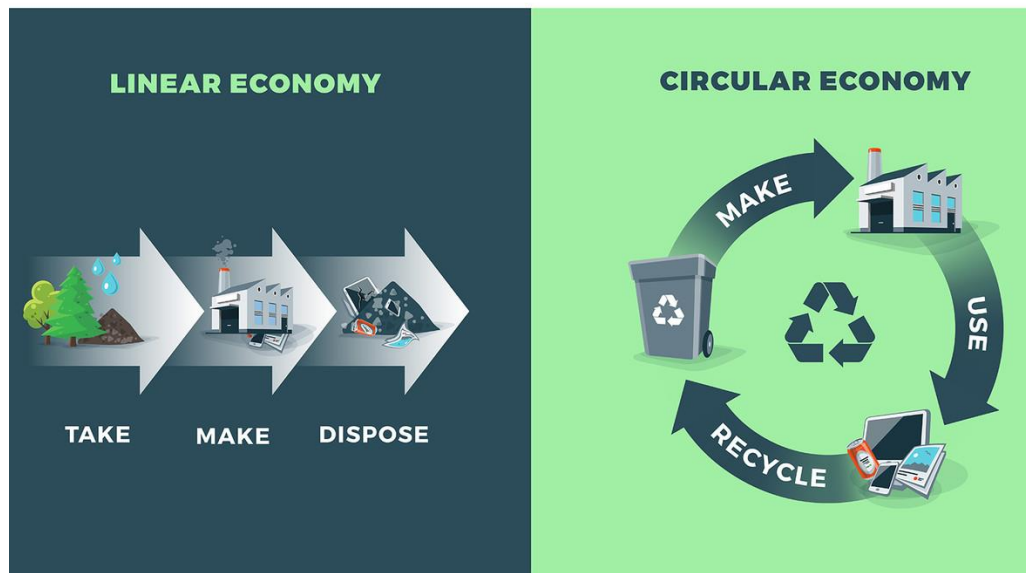


Figure 1:Diagram that compares linear and circular economy [3].

Construction and Demolition contribute to about 40% of the waste generated in the European Union. It is highly attributed to the inability to reuse the materials from the deconstructed buildings, thus causing heavy dependence on raw materials and a **linear economy**. The study further estimates the potential for recycling and preparing for reuse for each material fraction of Construction Demonstration Waste(CDW), indicating that, excluding excavated soils and dredging spoils due to their significant uncertainty, 83% of CDW can potentially be sent for preparing for reuse and recycling (of which potentially 16% for preparing for reuse)[4].

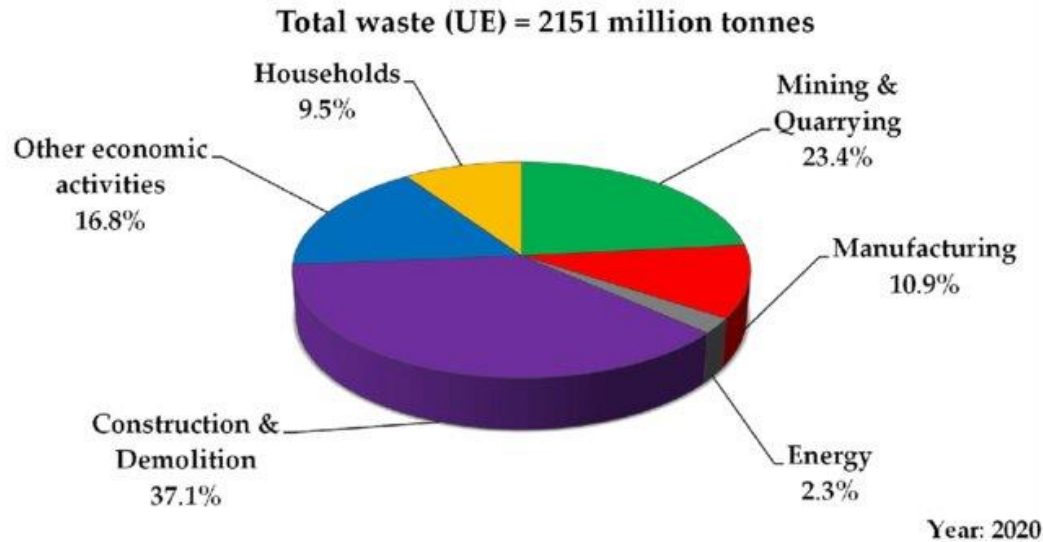


Figure 2: Pie chart that shows the construction waste generated from demolition [5].

Innovative approaches are essential in the construction industry's transition towards a circular economy. Focusing on sustainable construction practices such as reusing material components and optimising reusable structural elements like beams and columns will achieve a circular economy and offset **greenhouse gas emissions** by as much as 88% [6].

1.2 Problem statement

Primary demolition continues to be a significant source of waste in the construction industry despite the varied benefits due to the heavy dependence on raw materials. It leads to a **linear economy** where large volumes of waste are generated, and opportunities for material reuse are a far-away thought [5-6]. To attain the circular economy vision, the reuse of existing materials and components, especially load-bearing elements like beams and columns, must be enacted. Reducing the need for new raw materials and the embodied carbon energy of future construction projects [7].

However, several obstacles prevent this shift toward structural component reuse. Structural elements from deconstructed buildings often have different construction sizes, material grades, and conditions, making reuse difficult. Furthermore, structures must be designed to meet strict **structural integrity standards**, making it more complicated to use reusable elements [8].

However, one potential solution to ensure efficiency is integrating a material bank database containing information on reusable elements, including their geometry, material grade, and

dimensions. This will allow a more efficient selection and use of reusable components for new structures [9].

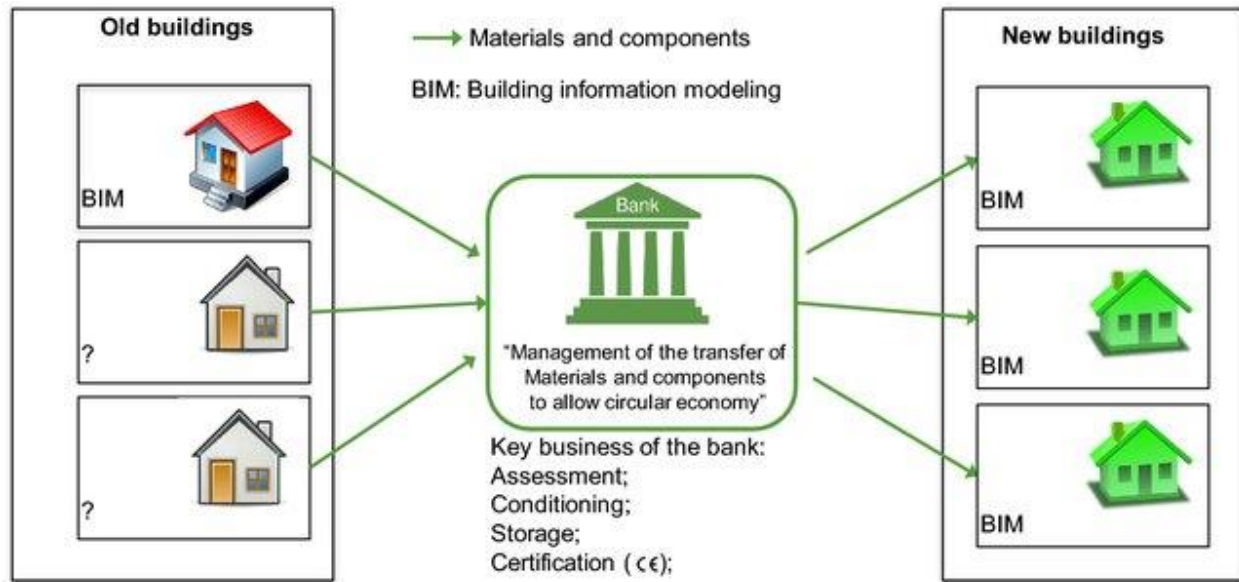


Figure 3: Conceptual schematic of a material bank showing stored data (Geometry, Material Grade, dimensions) and its application in new structures [10].

1.3 Objectives

The research focused on creating an **optimisation algorithm** using **Grasshopper-Rhino** that sources these components from a **theoretical material bank**. This theoretical material bank stores the geometry, cross-sectional properties, material grade properties, and dimensions for reusable structural elements. The main aim is an optimisation technique that efficiently selects these reusable structural components with precision to be used in new structures without compromising Eurocode standards [11].

The algorithm will be used in two study cases to **design a section of a simple frame structure**, check its adequacy for specified load conditions, and identify the optimal solutions. By coupling it with building information modelling, future developments can be achieved, which allows seamless selection and integration of reused structural components.

Another objective of the study report is to conduct a thorough literature review of the role of materials banks in promoting a circular economy and expounding on case studies that have successfully implemented reusable structural elements [12]. The study will also further expound

on the circular economy in the construction industry and how structural reusability can minimise waste while meeting performance standards [13].

2. Literature review

2.1 Role of circular economy in construction

The **circular economy** is a system where materials never become waste and nature is regenerated. The linear economy, on the other hand, has the take-make-dispose principle. In contrast, the circular economy emphasises resource recovery, material reuse, recycling, and increasing the material life cycle [13]. The circular economy principles emphasise the recovery of resources and material reuse, which is essential due to the significant consumption of raw materials and waste production.

In the construction industry, circular economy principles come into play when integrating **sustainable design** of buildings and infrastructure. The end goal is to conserve the value of materials for an extended period. Sustainable design can be achieved by reusing these structural components from deconstructed buildings for new projects or recycling them for new applications. Unlike recycling, reusing in construction aims to take and use the structural components from deconstructed buildings and reintegrate them into new projects without degrading their functionality. Reusing is better than recycling as it preserves the embedded energy of the materials and reduces the intensive work and energy required in recycling. This approach reduces the demand for new raw materials and the carbon footprint of construction activities [14].

Evidence of this is the Venlo city hall project in the Netherlands, where circular design principles have been integrated. A technical and biological system is continuously recovered and re-utilised with the cradle-to-cradle design. Through a well-thought material choice and design for disassembly, at a later date on disassembly, it is possible to reuse the material components through a ‘buy and buy-back’ scheme and ultimately reuse them again. The components in the building are documented in a digital ‘material passport’ that discloses the material constituents, along with how to disassemble, recycle, or return them to the manufacturer - thereby recouping a proportion of the original investment. Creating a log of the residual material value within the building makes it possible to quantify the potential value of buildings as material banks [15]. A

prime example of the circular economy's potential to reshape the construction industry practices, which highly relies on sustainability and efficient use of resources.



Figure 4: Figure that illustrates the Venlo City Hall [16]

Earlier case studies of the circular economy display promising results, but the concept constantly evolves in the construction industry. The Ellen Macarthur Foundation has several reports of projects that have been successfully implemented, such as 1 Triton Square, where, with the circular economy approach, much of the frame and facade was retained or reused, saving 3,300 m² of limestone, 35,000 tonnes of concrete, and 1,900 tonnes of steel. It minimised the redevelopments' carbon footprint, thus reducing its impact on climate change. It was deemed to have achieved 54% carbon saving in construction and operation [17].

2.2 Material Banks: Theory and Practice

A material bank is a repository of construction materials recovered from an existing decommissioned building through redevelopment, demolition, or other means. It stores and catalogues reusable components recovered from existing buildings decommissioned through redevelopment, demolition, or other means. The main goal of material banks is to provide an organised platform for the reuse of structural components to prevent these materials from being deposited in a landfill.

Material banks play a crucial component in the circular economy in construction by extending the life cycle of elements. Components like beams, columns, and slabs are stored and made accessible through material passports with detailed information about their characteristics.

Material banks are central to the future of sustainable construction, acting as repositories for reusable structural components and enabling more efficient material management. Well-organised material banks provide reliable information on the structural elements' availability, properties, and qualities. This transparency and efficiency are essential for designers and architects to use these structural components when designing new structures. Furthermore, delays in getting and transporting the reusable elements will be reduced, ensuring a more efficient construction process. The benefits of material banks are that they help eliminate waste and reduce emissions.

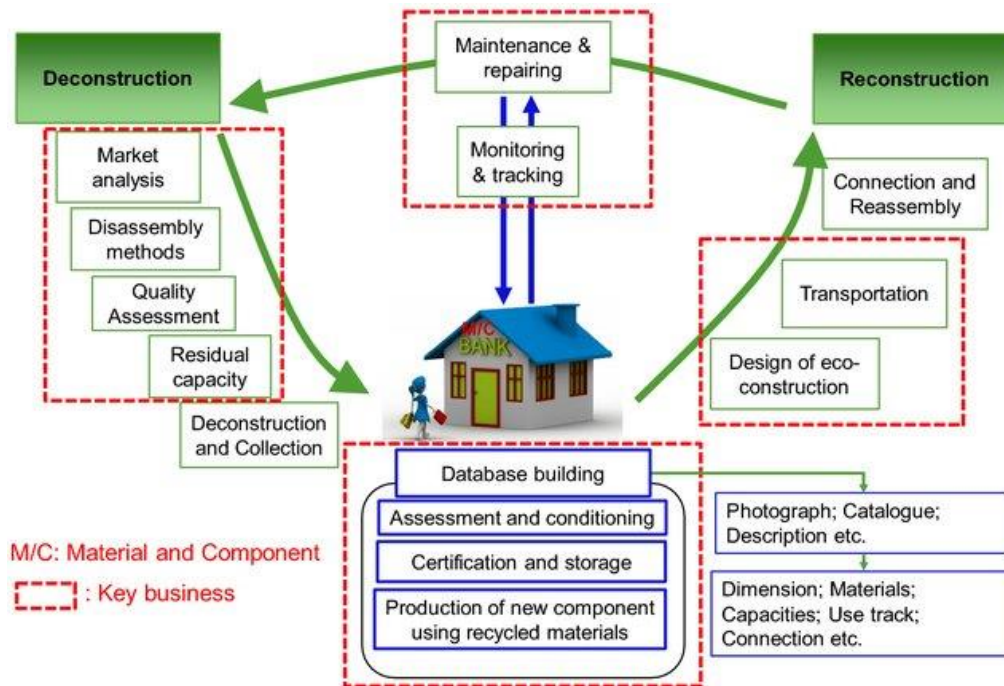


Figure 5: The flow of materials from decommissioning to storage in material banks and back to new constructions [18].

However, the concept of material banks is compelling but bears challenges and requires constant engagement throughout the material chains. Material passports currently need to be standardised for the management of material banks, which can create challenges in implementing these and inconsistencies between different material bank marketplaces [19]. However, as the awareness of material banks continues to intensify and more digital tools (BIM) are integrated into the construction industry, so does the role of material banks in promoting sustainability.

Establishing an **open data-sharing network** between different countries and regions can help increase the accessibility and overall distribution of reusable elements [20]. Establishing policy

intensives that promote the use of material banks by governments and construction industry leaders, such as giving tax subsidies or credits or targeting material reuse in public projects, will foster an expansion in the market of reusable elements and expand reuse in the construction industry [21-22].

Furthermore, further research should consider more sustainability metrics to get the overall environmental impact of material banks. Some include tracking the energy used during deconstruction, transporting and storing reused elements, and in-depth Life-Cycle Assessments(LCA). This in-depth analysis helps quantify the environmental benefits of re-use, making it much more clear how it contributes to the overall reduction of carbon emissions and depletion of resources [22-23].

The high growth of infrastructure increases the demand for resources. Material banks can be vital as they provide a resource-efficient way to garner reusable elements. With proper working systems, material banks will reduce the dependence on raw virgin materials in new construction projects, revamping the way structures are constructed around the world[20-22-24].

Case studies of material banks

Material banks are gaining traction, with Europe at the forefront, where sustainability is implemented into public policy. **The Resource Rows project in Denmark** is an example of using reclaimed bricks and timber from demolished buildings with the help of material banks, saving 463 tonnes of waste into materials. With an upcycle percentage of 29% CO₂ saving per/m² (Life Cycle Assessment), LCA clearly shows the impact of effective planning and use of material banks in reducing material waste and minimising the environmental footprint of construction [20].

Another example is the implementation of material banks in Belgium, in the Flanders region, where the material bank is used as a platform for keeping track of and managing the reuse of building materials throughout the region or country [21]. Therefore, material banks offer several advantages by storing material characteristics, thus making it easier to ensure that reused components meet safety and structural design standards. Furthermore, this will lower construction costs as they provide an alternative to sourcing new raw materials. Moreover, it reduces the demand for raw materials, significantly lowering the construction industry's impact on the manufacturing and extraction of raw materials.

2.3 Structural reusability

Structural reusability integrates deconstructed structural components such as beams, columns, and slabs for new construction projects. Specific criteria and requirements must be met to ensure they are applicable in geometry, material grade properties, and overall structural performance. To ensure efficiency, the geometry (size, shape, and configuration) must fit the new design with minimal cutting or reshaping (Best-fit criteria). Furthermore, the component's resistance - the ability to withhold structural loads without failure - and its stiffness, or ability to resist deformation. The material strength should also be checked to ensure the structural component can withhold the design loads. These factors ensure that the reused components meet the ultimate limit state and the serviceability limit state requirements of structural design. Prior analysis and testing, including non-destructive testing (NDT), is crucial to check whether the structural component's adequacy is suitable for reuse. Research by Cecilia Braendstrup introduces a new NDT method that complements existing practices by helping designers confront the age-old question of exceeding design loads and potential fatigue load damage in the re-assessment of steel structures [22].

The flowchart below (Figure 6) shows the re-using process from the start of deconstruction to the end of the process and its usage in new structures.

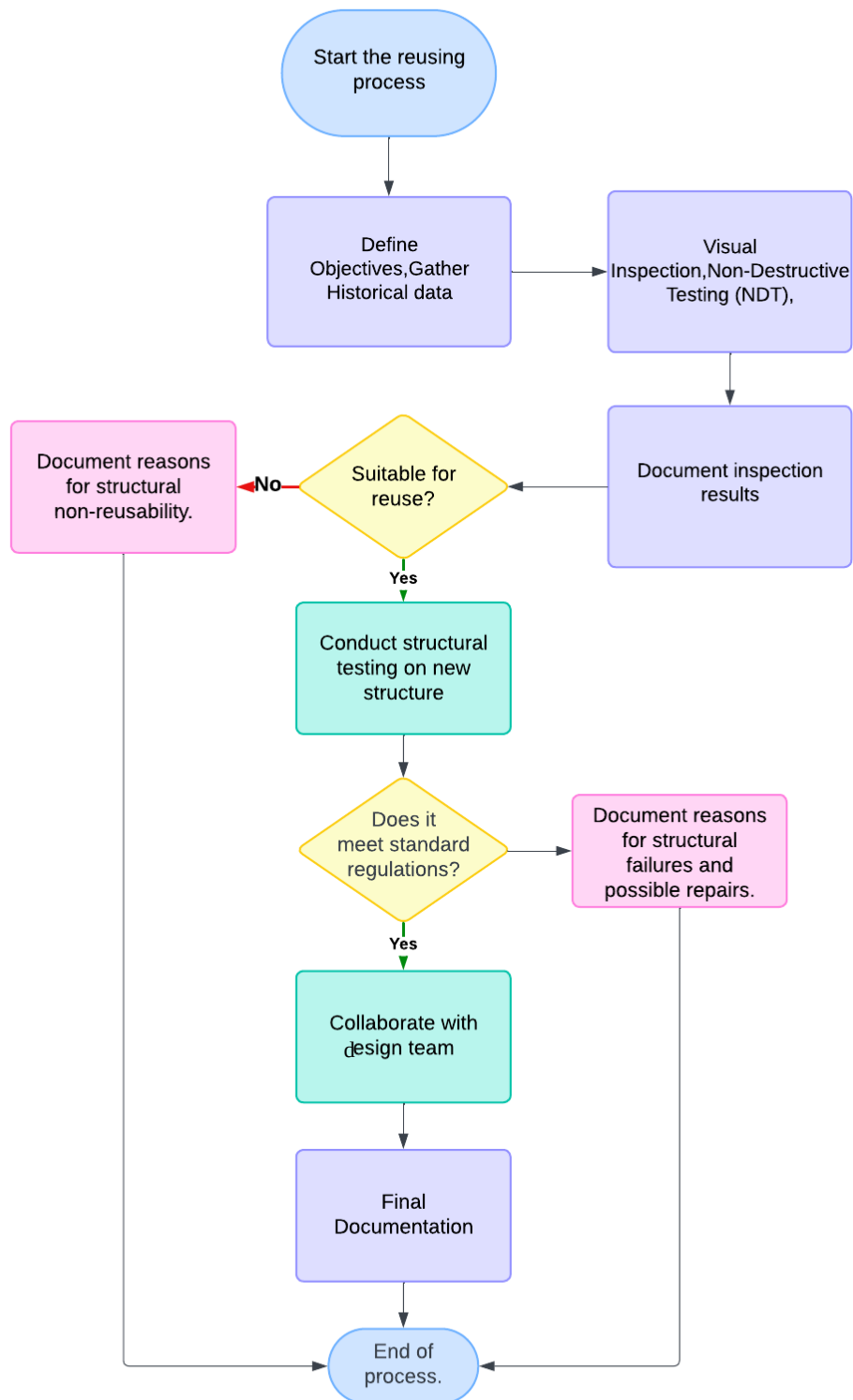


Figure 6: Flowchart that illustrates the selection of reusable elements.

2.4 Trade-off between recycling and reuse

Reusing building components and construction products affects the overall life cycle and environmental performance of construction activities. Despite an increase in transportation needs, approximately 40% of **embodied energy** can be saved, and more than 60% of the carbon footprint of the concrete structure can be saved when reusing prefabricated slabs (Roth and Eklund, 2003) [19]. Reusing has significant benefits compared to recycling, which entails separating the materials into their raw form using energy and resources.

However, reusing structural components has a downside, as quality assurance and logistical issues must be handled. They may require thorough testing and quality inspection to check whether they meet the required safety standards. Furthermore, transportation and storage between the periods of deconstruction and demolition can be a hurdle. Material banks are required to make this process easier; they provide a reliable system for keeping track of the storage and distribution of structural components. Furthermore, the deconstruction process and techniques must be carefully performed to avoid the destruction of the structural elements [28]. The figure below (Figure 7) explains the life cycle stages of building materials and compares the typical cycles.

Explanation of the Life Cycles: Classic, recycled, ex-situ reused, and in-situ reused.

- The **classic life-cycle** has the **Product Stage(A1-A3)**, where raw material extraction, transportation of these materials to the industry, and manufacturing are done. The **construction stage (A4-A5)** entails transporting the manufactured materials to the sites and the actual construction. The **Use Stage(B1-B7) is a period during which the building** operates, including maintenance and repair. The **End of Life Stage(C2-C4)** shows the deconstruction, processing of waste, and disposal. From the classic life cycle, it is typical for new materials to be used in the new life cycle.
- **The recycled Life Cycle** has the initial stages of **A1-C4. However**, processing is needed at the end of its life to ensure the material is recovered and used in new construction life cycles. This ensures re-entry and recovery to a new life cycle.
- **Ex-situ Reused Life Cycle:** The same stages, **A1-C4** are valid. However, instead of being thrown away or re-manufactured like recycling, the components are extracted and used as they are in new projects.

- In-situ Reused Life Cycle:** This cycle is similar to ex-situ in that the materials are used within the same site or project, thus lessening the need for transportation and its associated impacts. There is no reprocessing, as the next life cycle begins immediately at A5.

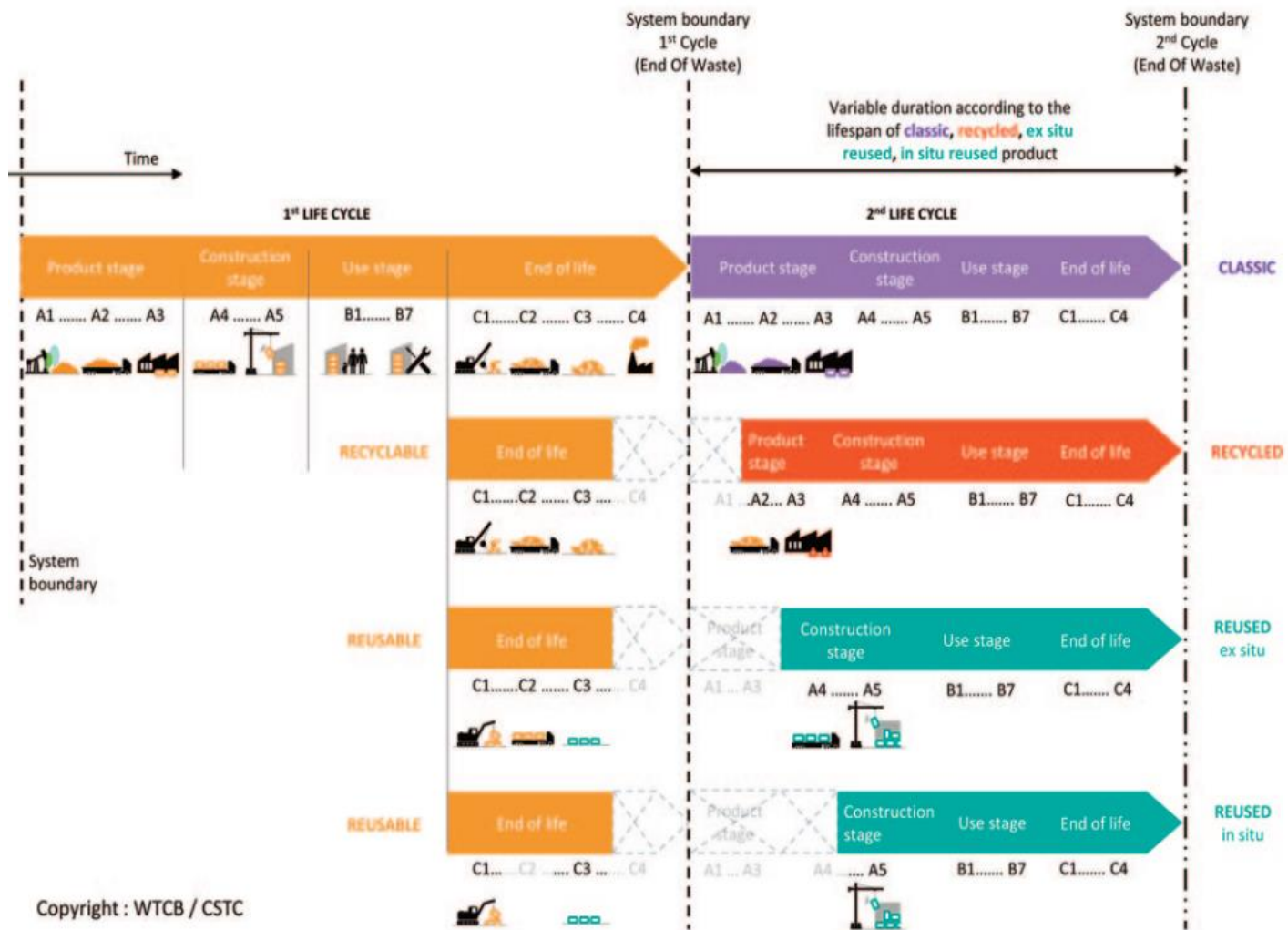


Figure 7: Comparisons of different Life Cycles.

Table 1: Comparing the environmental and economic trade-offs between recycling and reusing structural components [25]

aspect	recycling	reusing
Energy Consumption	High energy is required in the processing and breakdown of materials	Lower energy is due to minimal processing for reuse.
Carbon Footprint	Material breakdown and transportation significantly contributes	Less impact as components are reused in their original form
Material Waste	Some material loss during the recycling process	Reduced waste as components are kept in their original form.
Economic Cost	Higher costs and processing, sorting, and reprocessing are involved.	Lower costs as components are in a good state for re-using.
Labor & Time	Very labour intensive and time-consuming	Less time and labour required
Material Quality	Quality degradation for some materials.	Retains initial form and quality of material
Environmental Impact	Moderately effective as less raw material extraction is required	Prevents waste and reduces consumption, thus making it more highly effective.
Scalability	Easily scaled	Limited scalability depends on the availability of reusable elements.

2.5 Eurocode reference and how Eurocode standards apply to reused materials

The Eurocode provides standards and a comprehensive set of guidelines for the design of safe and reliable structures. It applies to new and reused components, although additional caution should be taken with reused materials. **Eurocode 3** (design of steel structures) and **Eurocode 2** (design of concrete structures) are used as guidelines for assessing the mechanical properties of materials and ensuring they meet load-bearing and deformation requirements [26-27].

These standards should be used to evaluate reused components, checking their structural soundness and meeting the resistance and stiffness requirements.

Furthermore, the CEN/TS 1090-201 further provides supplementary provisions for reusing reclaimed structural components in the execution of steel structures in EXEC1 to EXEC3 structures to be designed according to Eurocode 3 without seismic and fatigue design. The CEN/TS specifies requirements for the reusability of structural components and the declaration of mechanical and geometrical properties and weldability. The properties to be declared are those listed as required relevant properties to be specified according to clause 5.1 of **EN 1090-2**:

- strength (yield and tensile);
- elongation;
- tolerances on dimensions and shape;
- heat treatment delivery conditions;
- weldability.

This CEN/TS applies to reclaimed hot rolled profiles and hot-finished or cold-formed hollow sections used as constituent products according to EN 1090-2[27].

3. Methodology and Algorithm Development

This section describes an algorithm that maximises the reusability of structural elements with data from a theoretical material bank. The main goal is to reduce the cutting of structural components from a material bank and minimise the usage of new materials. Through this approach, the algorithm reduces the excessive usage of resources by reducing material wastage and promotes the construction industry's circular economy.

Algorithm Development

The logic starts with importing material elements from a theoretical material bank stored in a database to Grasshopper Rhino. It contains the cross-sectional properties according to the Eurocode 3 of steel cross sections. The process is simply broken down into these steps:

- **The algorithm takes the following inputs:**
 - **Geometry: Length** available for reuse.
 - **Material Grade:** Steel section material grades.
 - **Cross-section Sizes and their parameters:** Weight (kg/m), Area (mm²), Inertia Y (mm⁴), Modulus Y (mm³), Inertia Z (mm⁴), Modulus Z (mm³), Shear Area (mm²), Torsional Inertia (mm⁴), and Warping Inertia (mm⁶).
- **The algorithm performs four significant checks:**

The first two aimed at ensuring the reused elements meet the structural integrity

- **ULS checks** of the cross-sections
- **SLS checks** of the cross-sections
- **Length check** to ensure it is satisfactory for the required length
- **Minimising Cutting Waste** by ensuring the chosen cross sections have minimal cutting waste, checked and calculated according to weight.

Flowchart showing the algorithm's steps.

A flowchart (Figure 8) illustrates the algorithm's step-by-step process. It shows how the inputs are fed into the system, how the optimization process occurs (balancing reusability with structural demands), and how the output provides an optimised design solution.

Flowchart

This visual map shows the process of the algorithm

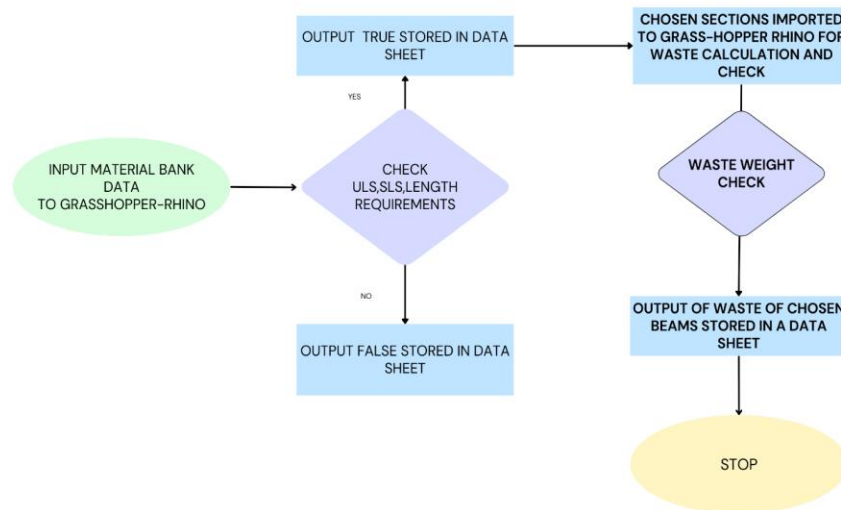


Figure 8:Flowchart that illustrates the Grasshopper Algorithm

The following steps outline the algorithm's work in more detail, demonstrating how it operates from importing the material to the analysis and, finally, the output data.

STEP 1: IMPORTING MATERIAL BANK

The algorithm begins with importing data from the theoretical material bank, which includes a list of cross-sections with key properties such as length, cross-sectional area, and material grade. This database serves as the input from which all potential structural elements are selected.

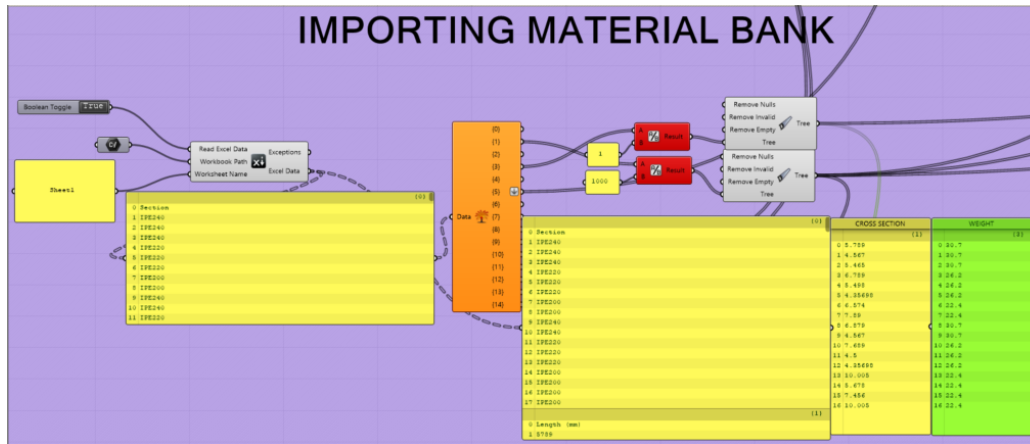


Figure 9: Step 1: Importing the theoretical data bank.

STEP 2: ULS AND SLS CHECKS OF THE CROSS SECTIONS FROM THE MATERIAL BANK

A performance check of the ULS and SLS checks on each cross-section within the material bank to ensure that each section meets the criteria. The check verifies whether the sections can withstand design loads and remain within the limits of deflections, filtering out sections that do not satisfy the requirements.

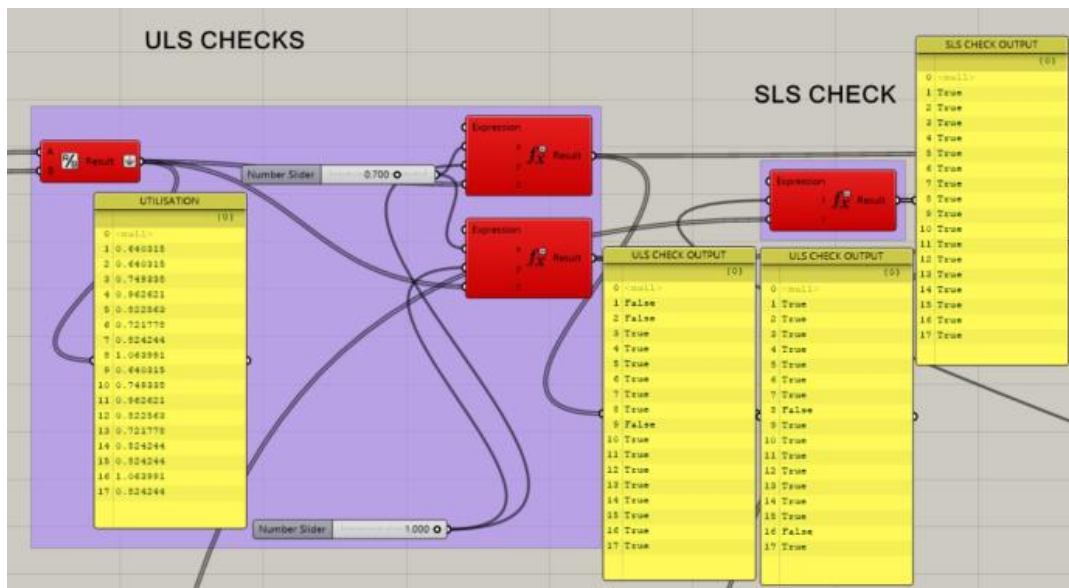


Figure 10: Figure illustrates the first two checks in the algorithm.

STEP 3: GEOMETRY CHECK (Compares the required length with the length from the material bank)

A comparison of the required structural and available lengths from the material bank. This step ensures that the chosen cross-sections closely align with the length requirements, allowing for optimal reuse with minimal cutting.

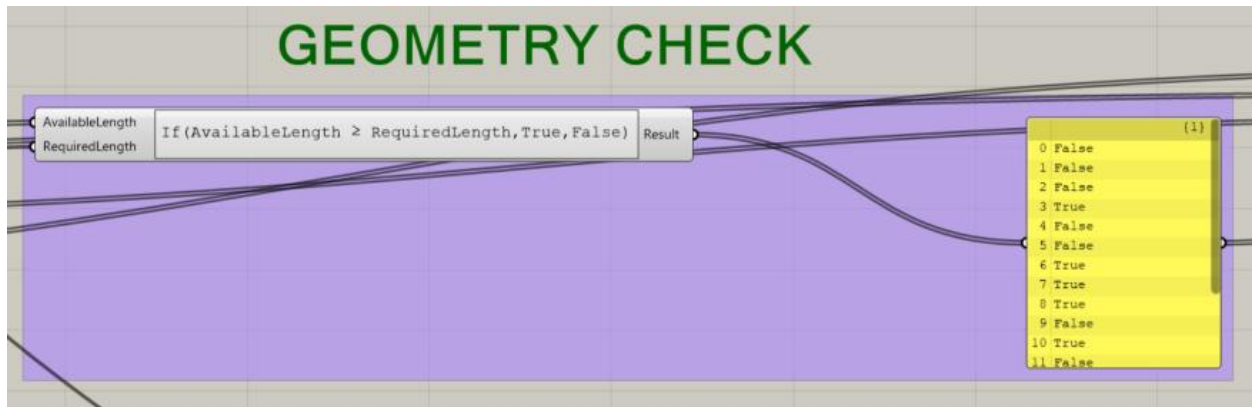


Figure 11: Figure illustrates the geometry check in the algorithm.

STEP4: EXPORT TO DATA SHEET FOR FURTHER ANALYSIS

The filtered list of cross-sections is exported to a datasheet, where further analysis and processing can enable a more detailed assessment.

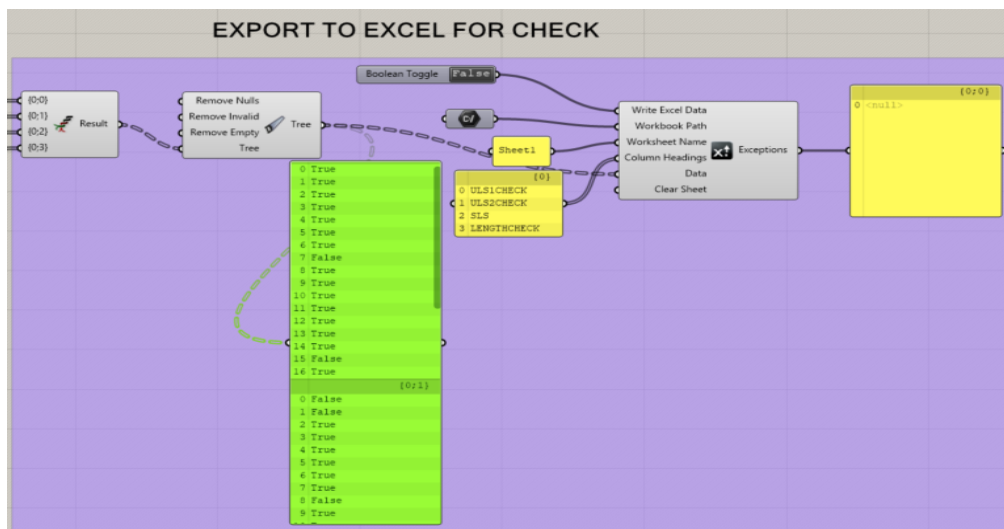


Figure 12: Figure illustrates the algorithm's export of data to an external database.

	A	B	C	D	E	F	G	H
1	ULS1CHEC	ULS2CHEC	SLS	LENGTHCHECK	Section	Length (mm)	aterial Gra	eight (kg/m)
2	TRUE	FALSE	TRUE	FALSE	IPE240	5789.00	S235	30.70
3	TRUE	FALSE	TRUE	FALSE	IPE240	4567.00	S235	30.70
4	TRUE	TRUE	TRUE	FALSE	IPE240	5465.00	S275	30.70
5	TRUE	TRUE	TRUE	TRUE	IPE220	6789.00	S235	26.20
6	TRUE	TRUE	TRUE	FALSE	IPE220	5498.00	S275	26.20
7	TRUE	TRUE	TRUE	FALSE	IPE220	4356.98	S355	26.20
8	TRUE	TRUE	TRUE	TRUE	IPE200	6574.00	S335	22.40
9	FALSE	TRUE	TRUE	TRUE	IPE200	7890.00	S275	22.40
10	TRUE	FALSE	TRUE	TRUE	IPE240	6879.00	S235	30.70
11	TRUE	TRUE	TRUE	FALSE	IPE240	4567.00	S275	30.70
12	TRUE	TRUE	TRUE	TRUE	IPE220	7689.00	S235	26.20
13	TRUE	TRUE	TRUE	FALSE	IPE220	4500.00	S275	26.20
14	TRUE	TRUE	TRUE	FALSE	IPE220	4356.98	S355	26.20
15	TRUE	TRUE	TRUE	TRUE	IPE200	10005.00	S335	22.40
16	TRUE	TRUE	TRUE	FALSE	IPE200	5678.00	S335	22.40
17	FALSE	TRUE	TRUE	TRUE	IPE200	7456.00	S275	22.40
18	TRUE	TRUE	TRUE	TRUE	IPE200	10005.00	S335	22.40

Figure 13: Figure illustrating a sample of the extracted data for assessment by the algorithm.

STEP 5: WASTE CALCULATION WITH CHOSEN CROSS SECTIONS CHECK

From the filtered cross-sections, the algorithm calculates potential material waste. After all the other requirements are satisfied, an evaluation of how much material weight waste remains.

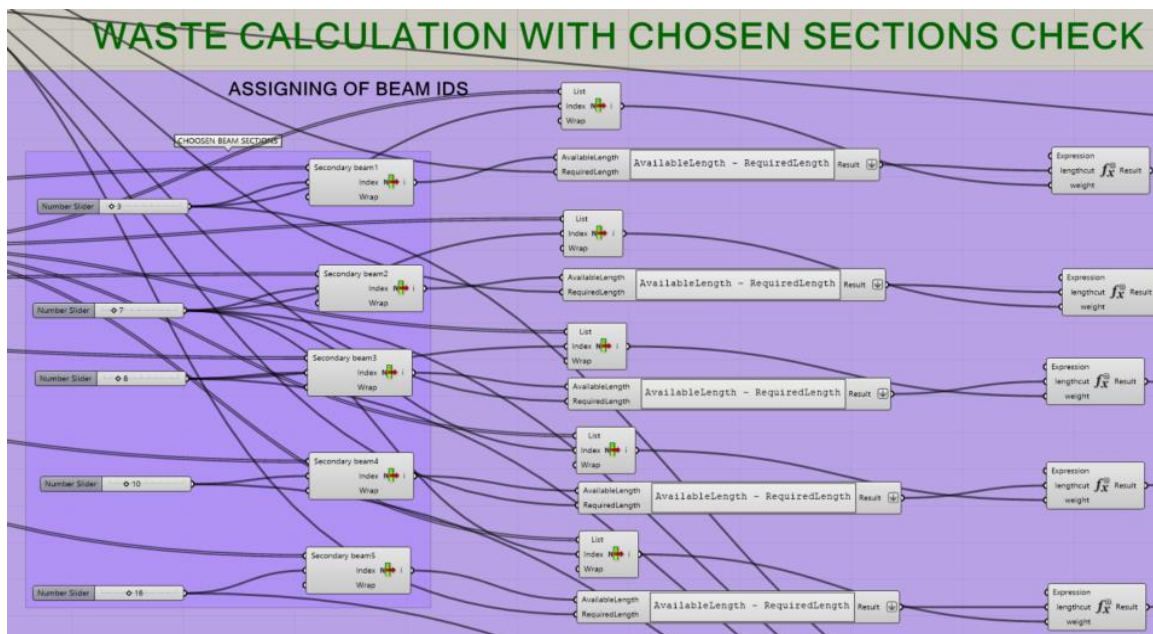


Figure 14: Figure illustrates the waste calculation by the algorithm for the chosen cross-section check.

STEP6: EXPORT OF FINAL CALCULATED WASTE TO DATASHEET

The final waste calculations are then exported to a datasheet for a further comprehensive review.

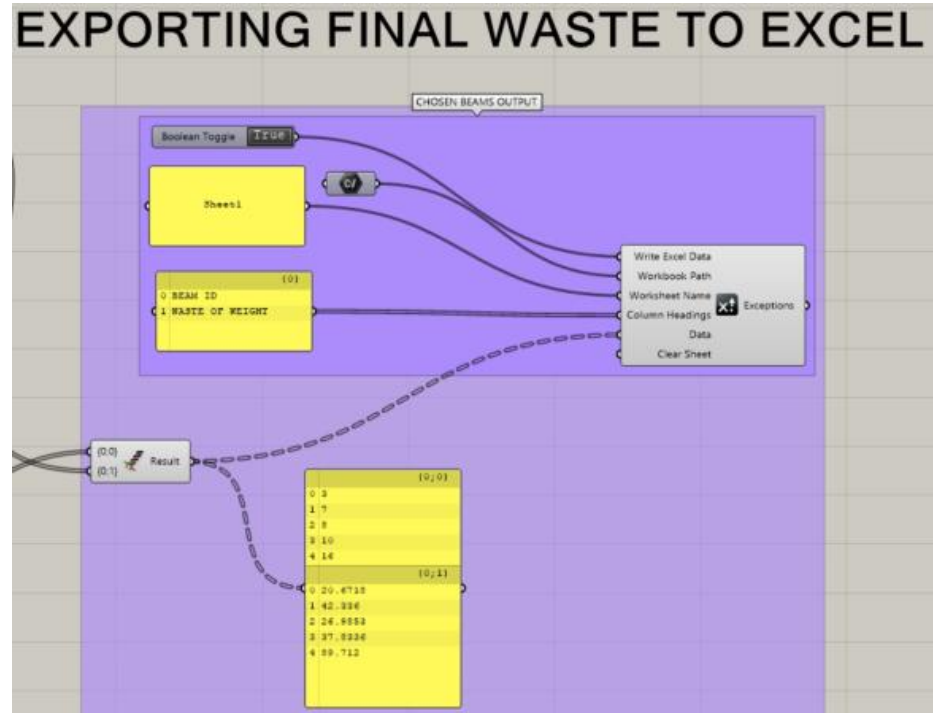


Figure 15: Figure illustrates the exportation of final material waste by the algorithm for further evaluation.

The next chapter outlines the comprehensive algorithm's structure and principles and outlines a case study to explore its practical application.

4. Case Studies

Simple Frame Structure Design

A simple frame structure is incorporated into the study, demonstrating the algorithm's effectiveness in the reusability of structural elements. It aims to minimise the cutting of reused structural elements from the material bank and the use of new materials with two sets of data. The initial checks of the Ultimate Limit State and the Serviceability Limit State are performed on the cross-sections with different lengths and sizes from the material bank, which will be used as beams of the simple frame structure. The structural 3D **model** of the parametric frame is visualised in Rhino and parametrically designed with Grasshopper-AXISVM plugins. A sketch

will visualise the chosen material grade, cross-section, and placement of the reused components. This section will summarise the algorithm's performance and how the material bank is crucial in achieving this. The main objectives are the output of the material waste and the material saved, new elements used, if any, and how the design using the reusable elements can meet the structural requirement according to the Eurocode Standards.

4.1 Structural Design Calculations

Initial structural hand load calculations in compliance with the Eurocode are performed to ensure the re-used elements meet the structural requirements criteria. This section outlines the procedure and initial assumptions.

The initial **assumptions** are that lateral torsional buckling does not occur as the top flange of the primary and secondary beams are supported.

A summary of the structural calculations and drawings illustrating the concepts are shown below. The secondary and primary beam layout is illustrated in (Figure 16) below.

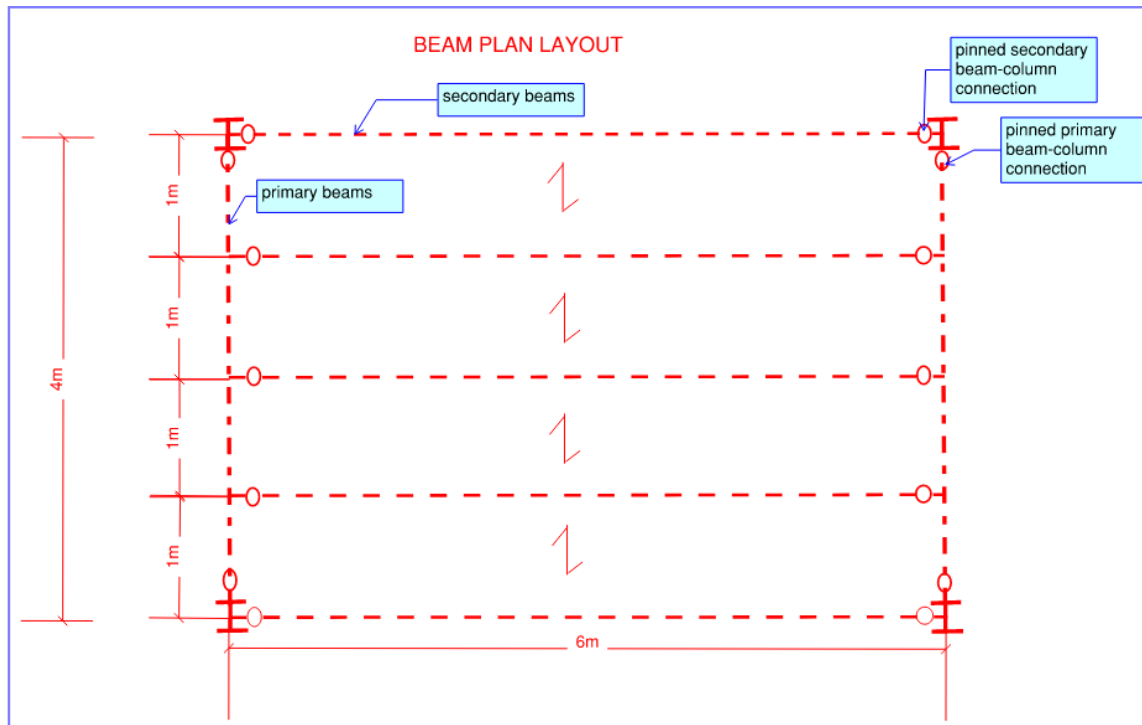


Figure 16: The beam plan layout

A section of the floor arrangement and two connections, column-primary beam, and primary-secondary beams, are shown below (Figure 17) to illustrate the pinned column-beam connections and secondary-beam-to-primary beam connections.

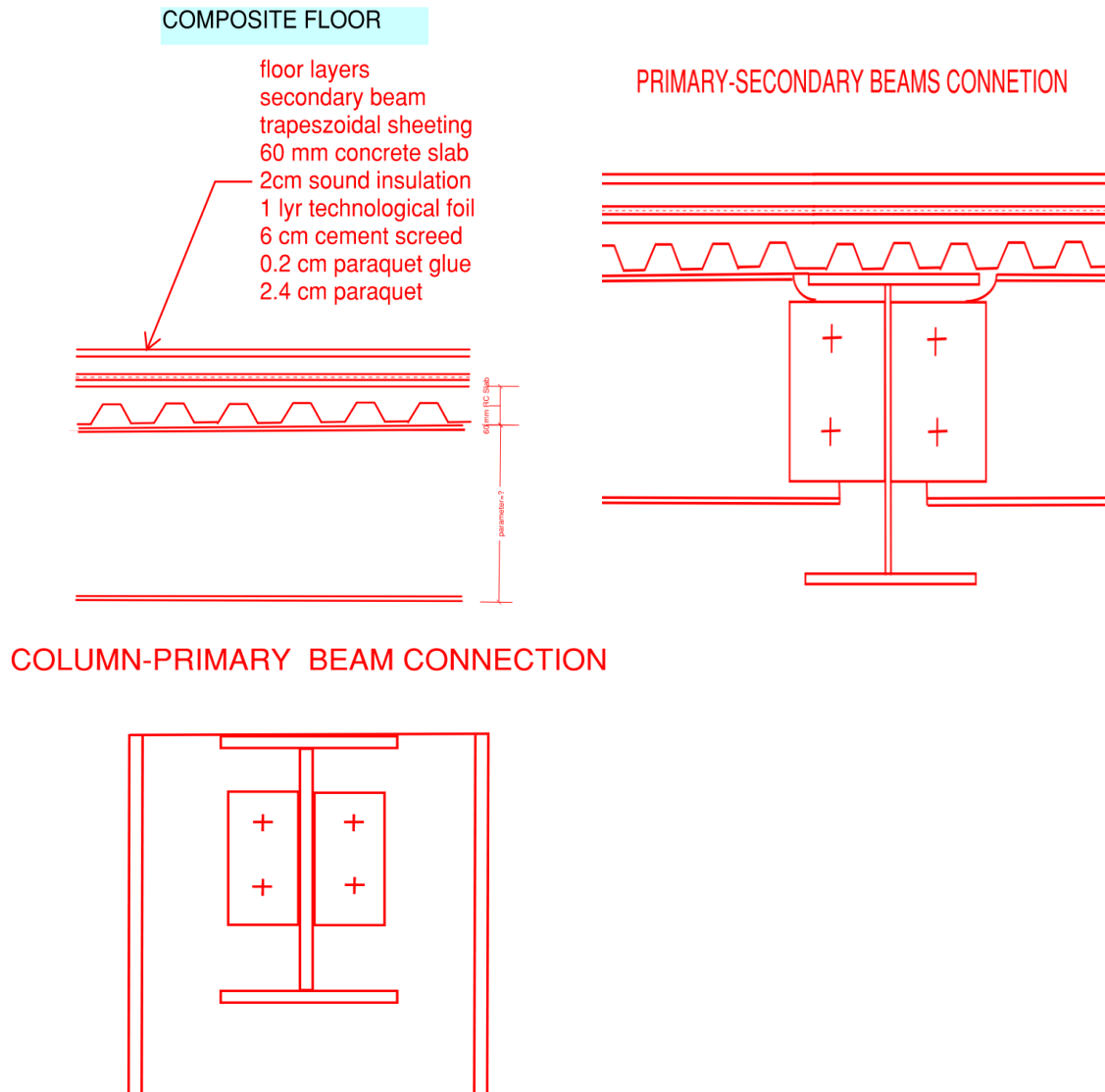


Figure 17: Figures illustrate structural sketches of the column-primary beam, primary-secondary beam connection, and the composite floor.

The loads and effects hand calculations are provided in the annex which are done according to the Eurocode standards.

After the algorithm performs structural load calculations for both ULS and SLS, a check of the cross-section capacity (utilisation) is performed. A length check is then performed to check the use of reused elements with the waste and new elements, if any.

4.2 Performance of the Algorithm with Case Studies.

The algorithm

The algorithm incorporates structural load design calculations to evaluate the re-used elements' structural integrity. The Eurocode design standards are used to assess the safety and reliability of the structural elements. The **stiffness** of the structural elements is checked to ensure adequacy to resist the deformation under the loads. In addition, the **resistance** of the components to withstand the loads is checked to ensure that they withstand the **vertical** loads and do not fail under ultimate state conditions. The performance of the material bank algorithm is evaluated based on crucial output metrics and adherence to structural design standards. This study illustrates how the algorithm can adapt to changes in element lengths and further filters based on cross-section.

Case study 1:

First Material Bank Variant for Primary Beams

	Section	Length (mm)	Material Grade	Weight (kg/m)	Area (mm ²)	Inertia Y (mm ⁴)	Modulus Y (mm ³)	Inertia Z (mm ⁴)	Modulus Z (mm ³)	Shear Area (mm ²)	Torsional Inertia (mm ⁴)	Warping Inertia (mm ⁶)	Mrd	Med	Utilisation
1															
2	HEA220	7980.00	S235	50.5	6434.00	54100000	919800	36680000	270600	2067.00	280900	1.9E+11	133.59	86.064	0.64423984
3	HEA240	5694.00	S235	60.3	7684.00	77630000	744600	27690000	351700	2518.00	410300	3.22E+11	174.99	86.064	0.49182239
4	HEA220	8759.00	S275	50.5	6434.00	54100000	919800	36680000	270600	2067.00	280900	1.9E+11	156.33	86.064	0.55052773
5	HEA240	9605.00	S275	60.3	7684.00	77630000	744600	27690000	351700	2518.00	410300	3.22E+11	204.77	86.064	0.42029594
6	HEA180	4567.00	S235	35.5	4525.00	25100000	324900	624815.1	156500	3420.00	146600	5.9E+10	76.34	86.064	1.12737752
7	HEA200	6589.00	S235	42.3	5383.00	36920000	429500	19550000	203800	1808.00	204300	1.06E+11	100.93	86.064	0.8527098
8	HEA180	9856.00	S275	35.5	4525.00	25100000	324900	624815.1	156500	3420.00	146600	5.9E+10	89.33	86.064	0.96343893
9	HEA160	8960.00	S275	30.4	3877.00	16730000	245100	6156000	76950	1321.00	118400	3.06E+10	67.42	86.064	1.27653515
10	HEB160	4676.00	S235	42.6	5245.00	24920000	354000	8892000	170000	1759.00	312400	4.67E+10	83.18	86.064	1.0346718
11	HEB180	7656.00	S235	51.2	6525.00	38310000	481400	13630000	231000	2024.00	422400	9.17E+10	113.14	86.064	0.76068588
12	HEB160	8645.00	S275	42.6	5245.00	24920000	354000	8892000	170000	1759.00	312400	4.67E+10	97.34	86.064	0.88415862
13	HEA200	6543.00	S235	42.3	5383.00	36920000	429500	19550000	203800	1808.00	204300	1.06E+11	100.93	86.064	0.8527098
14	HEA180	6473.00	S275	35.5	4525.00	25100000	324900	624815.1	156500	3420.00	146600	5.9E+10	89.33	86.064	0.96343893
15	HEA160	10586.00	S275	30.4	3877.00	16730000	245100	6156000	76950	1321.00	118400	3.06E+10	67.42	86.064	1.27653515

Figure 18: Figure illustrates the data table for the primary beams' first theoretical material bank variant.

Output 1 shows the ULS, SLS, and Length Check.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
	ULS1CHECK	ULS2CHECK	SLS	LENGTHCHECK	Section	Length (mm)	Material Grade	Weight (kg/m)	Area (mm ²)	Inertia Y (mm ⁴)	Modulus Y (mm ³)	Inertia Z (mm ⁴)	Modulus Z (mm ³)	Shear Area (mm ²)	Torsional Inertia (mm ⁴)	Warping Inertia (mm ⁶)	Mrd	Med	Utilisation
1																			
2	FALSE	TRUE	TRUE	TRUE	HEA220	7980.00	S235	50.5	6434.00	54100000	919800	36680000	270600	2067.00	280900	1.8961E+11	133.59	86.064	0.64423984
3	FALSE	TRUE	TRUE	TRUE	HEA240	5694.00	S235	60.3	7684.00	77630000	744600	27690000	351700	2518.00	410300	3.2164E+11	174.99	86.064	0.49182239
4	FALSE	TRUE	TRUE	TRUE	HEA220	8759.00	S275	50.5	6434.00	54100000	919800	36680000	270600	2067.00	280900	1.8961E+11	156.33	86.064	0.55052773
5	FALSE	TRUE	TRUE	TRUE	HEA240	9605.00	S275	60.3	7684.00	77630000	744600	27690000	351700	2518.00	410300	3.2164E+11	204.77	86.064	0.42029594
6	TRUE	FALSE	TRUE	TRUE	HEA180	4567.00	S235	35.5	4525.00	25100000	324900	624815.1	156500	3420.00	146600	59014000000	76.34	86.064	1.12737752
7	TRUE	TRUE	TRUE	TRUE	HEA200	6589.00	S235	42.3	5383.00	36920000	429500	19550000	203800	1808.00	204300	1.0558E+11	100.93	86.064	0.8527098
8	TRUE	TRUE	TRUE	TRUE	HEA180	9856.00	S275	35.5	4525.00	25100000	324900	624815.1	156500	3420.00	146600	59014000000	89.33	86.064	0.96343893
9	TRUE	FALSE	TRUE	TRUE	HEA160	8960.00	S275	30.4	3877.00	16730000	245100	6156000	76950	1321.00	118400	30615000000	67.42	86.064	1.27653515
10	TRUE	FALSE	TRUE	TRUE	HEB160	4676.00	S235	42.6	5245.00	24920000	354000	8892000	170000	1759.00	312400	46667000000	83.18	86.064	1.0346718
11	TRUE	TRUE	TRUE	TRUE	HEB180	7656.00	S235	51.2	6525.00	38310000	481400	13630000	231000	2024.00	422400	91728000000	113.14	86.064	0.76068588
12	TRUE	TRUE	TRUE	TRUE	HEB160	8645.00	S275	42.6	5245.00	24920000	354000	8892000	170000	1759.00	312400	46667000000	97.34	86.064	0.88415862
13	TRUE	TRUE	TRUE	TRUE	HEA200	6543.00	S235	42.3	5383.00	36920000	429500	19550000	203800	1808.00	204300	1.0558E+11	100.93	86.064	0.8527098
14	TRUE	TRUE	TRUE	TRUE	HEA180	6473.00	S275	35.5	4525.00	25100000	324900	624815.1	156500	3420.00	146600	59014000000	89.33	86.064	0.96343893
15	TRUE	FALSE	TRUE	TRUE	HEA160	10586.00	S275	30.4	3877.00	16730000	245100	6156000	76950	1321.00	118400	30615000000	67.42	86.064	1.27653515

Figure 19: Illustrates a table output of the first three checks (ULS, SLS, Length check) for the primary beams.

The beams fulfilling the conditions are further analysed for waste calculation check within Grasshopper. The question of whether the selection of optimum waste is based on weight or length becomes questionable but the former is preferred; as the cross-section material grade and geometrical properties vary. From the chosen list of primary beams that satisfy the conditions, the algorithm chooses a variety of elements that satisfy the conditions prior but never the same element twice; this is identified by the element ID.

Output 2 shows the two chosen beams for this case study with the waste of weight and used weight.

BEAM ID	WASTE OF WEIGHT	USED WEIGHT
11	107.5689	169.2
12	87.7915	142

Figure 20: Figure illustrates a data table output of the waste of weight and used weight for the two chosen primary beam elements.

The amount of reused material is the total weight of the reused element used by the two primary beams in this case. **Waste Generated** quantifies material waste by the weight identified for the two primary beams. A comparison of the waste weight based on further filters such as the

same cross sections and materials are applied to do a comparison. In this case, for the two primary beams, the selected beams are row 7 (Beam ID 11) and 13(Beam ID 5), respectively, as they fulfil both conditions.

BEAM ID	WASTE OF WEIGHT	USED WEIGHT
11	107.5689	169.2
5	109.5147	169.2

Figure 21: Figure illustrates a data table output of the waste of weight and used weight for the two primary beam elements with similar cross-sectional types and materials.

Based on the table above, it is clear that although the reusable elements used in this case are far more favourable in structural design practice as they have the same cross-section sizes and material grade, a compromise must be made depending on the design situation. In my case, optimisation based on the reduced weight is necessary. Thus, the first two beam outputs are favourable in terms of the least total material waste and the used weight.

First material bank variant secondary beams:

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
	Section	Length (mm)	Material Grade	Weight (kg/m)	Area (mm ²)	Inertia Y (mm ⁴)	Modulus Y (mm ³)	Inertia Z (mm ⁴)	Modulus Z (mm ³)	Shear Area (mm ²)	Torsional Inertia (mm ⁴)	Warping Inertia (mm ⁶)	Mrd(kNm)	Med(kNm)	utilisation
1															
2	IPE240	6789.00	S235	30.70	3912.00	38920000.00	366600.00	2836000.00	73920.00	1914.00	127400.00	366800000000.00	100.83	64.56	0.64
3	IPE240	7809.00	S235	30.70	3912.00	38920000.00	366600.00	2836000.00	73920.00	1914.00	127400.00	366800000000.00	100.83	64.56	0.64
4	IPE240	5465.00	S275	30.70	3912.00	38920000.00	366600.00	2836000.00	73920.00	1914.00	127400.00	366800000000.00	86.16	64.56	0.75
5	IPE220	10698.00	S235	26.20	3337.00	27920000.00	285400.00	2049000.00	58110.00	2754.00	89820.00	223100000000.00	67.07	64.56	0.96
6	IPE220	6556.00	S275	26.20	3337.00	27920000.00	285400.00	2049000.00	58110.00	2754.00	89820.00	223100000000.00	78.49	64.56	0.82
7	IPE220	9768.00	S355	26.20	3337.00	27920000.00	285400.00	2049000.00	58110.00	2754.00	89820.00	223100000000.00	89.45	64.56	0.72
8	IPE200	9785.00	S335	22.40	2848.00	19430000.00	194300.00	1424000.00	44610.00	2848.00	68460.00	127460000000.00	78.33	64.56	0.82
9	IPE200	6543.00	S275	22.40	2848.00	19430000.00	194300.00	1424000.00	44610.00	2848.00	68460.00	127460000000.00	60.68	64.56	1.06
10	IPE240	7578.00	S235	30.70	3912.00	38920000.00	366600.00	2836000.00	73920.00	1914.00	127400.00	366800000000.00	100.83	64.56	0.64
11	IPE240	10984.00	S275	30.70	3912.00	38920000.00	366600.00	2836000.00	73920.00	1914.00	127400.00	366800000000.00	86.16	64.56	0.75
12	IPE220	11567.00	S235	26.20	3337.00	27920000.00	285400.00	2049000.00	58110.00	2754.00	89820.00	223100000000.00	67.07	64.56	0.96
13	IPE220	9867.00	S275	26.20	3337.00	27920000.00	285400.00	2049000.00	58110.00	2754.00	89820.00	223100000000.00	78.49	64.56	0.82
14	IPE220	4500.00	S355	26.20	3337.00	27920000.00	285400.00	2049000.00	58110.00	2754.00	89820.00	223100000000.00	89.45	64.56	0.72
15	IPE200	10005.00	S335	22.40	2848.00	19430000.00	194300.00	1424000.00	44610.00	2848.00	68460.00	127460000000.00	78.33	64.56	0.82
16	IPE200	5678.00	S335	22.40	2848.00	19430000.00	194300.00	1424000.00	44610.00	2848.00	68460.00	127460000000.00	78.33	64.56	0.82
17	IPE200	7456.00	S275	22.40	2848.00	19430000.00	194300.00	1424000.00	44610.00	2848.00	68460.00	127460000000.00	60.68	64.56	1.06
18	IPE200	11984.00	S335	22.40	2848.00	19430000.00	194300.00	1424000.00	44610.00	2848.00	68460.00	127460000000.00	78.33	64.56	0.82

Figure 22:Figure illustrates the data table for the secondary beams' first theoretical material bank variant.

Output 1 shows the ULS, SLS, and Length Check.

	ULS1CHE CK	ULS2CHE CK	SLS	LENGTHCHEC K	Section	Length (mm)	Material Grade	Weight (kg/m)	Area (mm ²)	Inertia Y (mm ⁴)	Modulus Y (mm ³)	Inertia Z (mm ⁴)	Modulus Z (mm ³)	Shear Area (mm ²)	Torsional Inertia (mm ⁴)	Warping Inertia (mm ⁶)	Mrd(kNm)	Med(kNm)	utilisatio n
2	TRUE	FALSE	TRUE	TRUE	IPE240	6789	S235	30.7	3912	38920000	366600	2836000	73920	1914	127400	3.67E+10	100.83	64.563	0.640315
3	TRUE	FALSE	TRUE	TRUE	IPE240	7809	S235	30.7	3912	38920000	366600	2836000	73920	1914	127400	3.67E+10	100.83	64.563	0.640315
4	TRUE	TRUE	TRUE	FALSE	IPE240	5465	S275	30.7	3912	38920000	366600	2836000	73920	1914	127400	3.67E+10	86.16	64.563	0.749338
5	TRUE	TRUE	TRUE	TRUE	IPE220	10698	S235	26.2	3337	27920000	285400	2049000	58110	2754	89820	2.23E+10	67.07	64.563	0.962621
6	TRUE	TRUE	TRUE	TRUE	IPE220	6556	S275	26.2	3337	27920000	285400	2049000	58110	2754	89820	2.23E+10	78.49	64.563	0.822563
7	TRUE	TRUE	TRUE	TRUE	IPE220	9768	S355	26.2	3337	27920000	285400	2049000	58110	2754	89820	2.23E+10	89.45	64.563	0.721778
8	TRUE	TRUE	TRUE	TRUE	IPE200	9785	S335	22.4	2848	19430000	194300	1424000	44610	2848	68460	1.27E+10	78.33	64.563	0.824244
9	FALSE	TRUE	TRUE	TRUE	IPE200	6543	S275	22.4	2848	19430000	194300	1424000	44610	2848	68460	1.27E+10	60.68	64.563	1.063991
10	TRUE	FALSE	TRUE	TRUE	IPE240	7578	S235	30.7	3912	38920000	366600	2836000	73920	1914	127400	3.67E+10	100.83	64.563	0.640315
11	TRUE	TRUE	TRUE	TRUE	IPE240	10984	S275	30.7	3912	38920000	366600	2836000	73920	1914	127400	3.67E+10	86.16	64.563	0.749338
12	TRUE	TRUE	TRUE	TRUE	IPE220	11567	S235	26.2	3337	27920000	285400	2049000	58110	2754	89820	2.23E+10	67.07	64.563	0.962621
13	TRUE	TRUE	TRUE	TRUE	IPE220	9867	S275	26.2	3337	27920000	285400	2049000	58110	2754	89820	2.23E+10	78.49	64.563	0.822563
14	TRUE	TRUE	TRUE	FALSE	IPE220	4356.98	S355	26.2	3337	27920000	285400	2049000	58110	2754	89820	2.23E+10	89.45	64.563	0.721778
15	TRUE	TRUE	TRUE	TRUE	IPE200	10005	S335	22.4	2848	19430000	194300	1424000	44610	2848	68460	1.27E+10	78.33	64.563	0.824244
16	TRUE	TRUE	TRUE	FALSE	IPE200	5678	S335	22.4	2848	19430000	194300	1424000	44610	2848	68460	1.27E+10	78.33	64.563	0.824244
17	FALSE	TRUE	TRUE	TRUE	IPE200	7456	S275	22.4	2848	19430000	194300	1424000	44610	2848	68460	1.27E+10	60.68	64.563	1.063991
18	TRUE	TRUE	TRUE	TRUE	IPE200	11984	S335	22.4	2848	19430000	194300	1424000	44610	2848	68460	1.27E+10	78.33	64.563	0.824244

Figure 23:Figure illustrating a table output of the first three checks (ULS, SLS, Length check) for the secondary beams.

Output 2 shows the chosen secondary beams with the waste of weight and used weight.

	A	B	C
1	BEAM ID	WASTE OF WEIGHT	USED WEIGHT
2	3	123.0876	157.2
3	4	14.5672	157.2
4	6	84.784	134.4
5	11	101.3154	157.2
6	13	104.931	157.2

Figure 24:Figure illustrates a data table output of the waste of weight and used weight for the chosen five secondary beam elements.

The amount of reused material compared to the total weight of the reused element used by the five secondary beams is shown above. The **Waste Generated quantification** of the material waste by the weight is identified for the re-used elements chosen. In the case of the secondary beam's first material bank variant, further filtration is based on the same cross-sectional properties, and a comparison to the previous material waste generated and used material weight is made.

Output 2 shows the chosen beams with the waste of weight and used weight.

	A	B	C
1	BEAM ID	WASTE OF WEIGHT	USED WEIGHT
2	3	123.0876	157.2
3	4	14.5672	157.2
4	5	98.7216	157.2
5	10	145.8554	157.2
6	11	101.3154	157.2

Figure 25: Figure illustrates a data table output of the waste of weight and used weight for the five secondary beam elements with similar cross-sectional properties.

The results with these different sets of sections show a higher amount of waste and used weight compared to the first set of chosen sections. Thus, in this study case, an optimisation based on less material waste is preferable, so the first set of sections will be applied for the secondary beams. The final layout below visualises the chosen primary and secondary beams in the first material bank variant. From the final beam configuration in (Figure 26), it is an optimal configuration to the weight and not the constructibility. Further optimisation parameters ought to be developed in later development phases of the algorithm to create a more balanced and easily assembled structure.

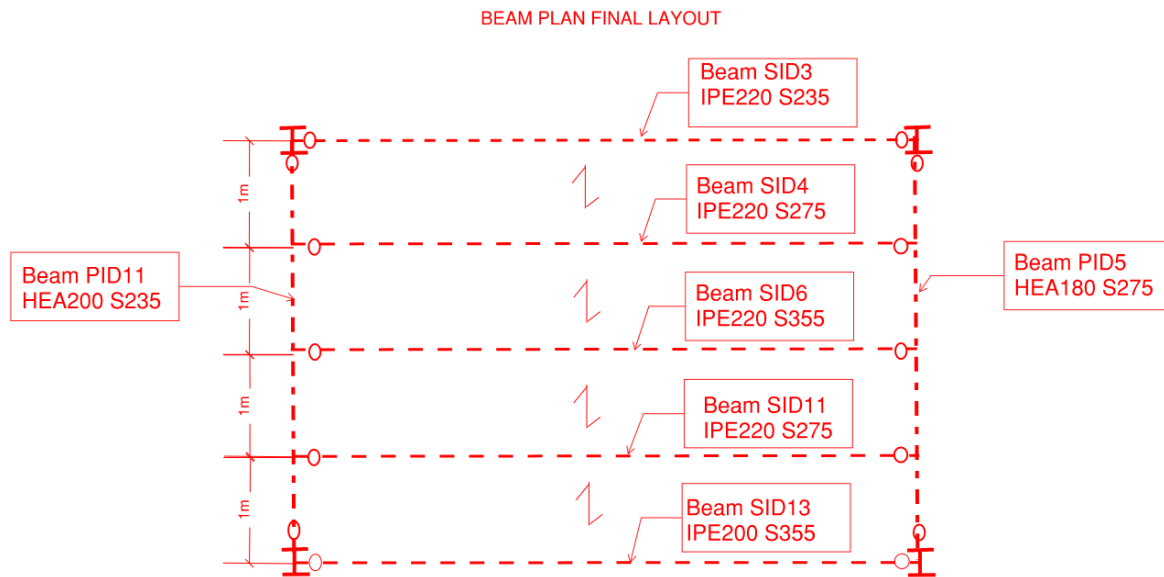


Figure 26: Final beam arrangement layout for the first case study.

Case study 2:

The second case study provides a second set of material bank with a wider range of lengths allowing for flexibility in selection and many more filtering options.

Second Material Bank Variant Primary Beams

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
	Section	Length (mm)	Material Grade	Weight (kg/m)	Area (mm ²)	Inertia Y (mm ⁴)	Modulus Y (mm ³)	Inertia Z (mm ⁴)	Modulus Z (mm ³)	Shear Area (mm ²)	Torsional Inertia (mm ⁴)	Warping Inertia (mm ⁶)	Mrd	Med	Utilisation
1															
2	HEA220	10968.00	S235	50.5	6434.00	54100000	919800	36680000	270600	2067.00	280900	1.9E+11	133.59	86.064	0.64423984
3	HEA240	5879.00	S235	60.3	7684.00	77630000	744600	27690000	351700	2518.00	410300	3.22E+11	174.99	86.064	0.49182239
4	HEA220	8905.00	S275	50.5	6434.00	54100000	919800	36680000	270600	2067.00	280900	1.9E+11	156.33	86.064	0.55052773
5	HEA240	6453.00	S275	60.3	7684.00	77630000	744600	27690000	351700	2518.00	410300	3.22E+11	204.77	86.064	0.42029594
6	HEA180	5345.00	S235	35.5	4525.00	25100000	324900	624815.1	156500	3420.00	146600	5.9E+10	76.34	86.064	1.12737752
7	HEA200	9348.00	S235	42.3	5383.00	36920000	429500	19550000	203800	1808.00	204300	1.06E+11	100.93	86.064	0.8527098
8	HEA180	8475.00	S275	35.5	4525.00	25100000	324900	624815.1	156500	3420.00	146600	5.9E+10	89.33	86.064	0.96343893
9	HEA160	7847.00	S275	30.4	3877.00	16730000	245100	6156000	76950	1321.00	118400	3.06E+10	67.42	86.064	1.27653515
10	HEB160	5385.00	S235	42.6	5245.00	24920000	354000	8892000	170000	1759.00	312400	4.67E+10	83.18	86.064	1.0346718
11	HEB180	6843.00	S235	51.2	6525.00	38310000	481400	13630000	231000	2024.00	422400	9.17E+10	113.14	86.064	0.76068588
12	HEB160	4560.00	S275	42.6	5245.00	24920000	354000	8892000	170000	1759.00	312400	4.67E+10	97.34	86.064	0.88415862
13	HEA200	9483.00	S235	42.3	5383.00	36920000	429500	19550000	203800	1808.00	204300	1.06E+11	100.93	86.064	0.8527098
14	HEA180	9685.00	S275	35.5	4525.00	25100000	324900	624815.1	156500	3420.00	146600	5.9E+10	89.33	86.064	0.96343893
15	HEA160	8756.00	S275	30.4	3877.00	16730000	245100	6156000	76950	1321.00	118400	3.06E+10	67.42	86.064	1.27653515

Figure 27: Figure illustrates the data table for the primary beams' second theoretical material bank variant.

Output1 shows the ULS, SLS, and Length Check.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	ULS1CHE CK	ULS2CH ECK	SLS	LENGTH HECK	Section	Length (mm)	Material Grade	Weight (kg/m)	Area (mm ²)	Inertia Y (mm ⁴)	Modulus Y (mm ³)	Inertia Z (mm ⁴)	Modulus Z (mm ³)	Shear Area (mm ²)	Torsional Inertia (mm ⁴)
2	FALSE	TRUE	TRUE	TRUE	HEA220	8607.00	S235	50.5	6434.00	54100000	919800	36680000	270600	2067.00	280900
3	FALSE	TRUE	TRUE	TRUE	HEA240	5879.00	S235	60.3	7684.00	77630000	744600	27690000	351700	2518.00	410300
4	FALSE	TRUE	TRUE	TRUE	HEA220	8905.00	S275	50.5	6434.00	54100000	919800	36680000	270600	2067.00	280900
5	FALSE	TRUE	TRUE	TRUE	HEA240	9570.00	S275	60.3	7684.00	77630000	744600	27690000	351700	2518.00	410300
6	TRUE	FALSE	TRUE	TRUE	HEA180	9305.00	S235	35.5	4525.00	25100000	324900	624815.1	156500	3420.00	146600
7	TRUE	TRUE	TRUE	TRUE	HEA200	8576.00	S235	42.3	5383.00	36920000	429500	19550000	203800	1808.00	204300
8	TRUE	TRUE	TRUE	TRUE	HEA180	5069.00	S275	35.5	4525.00	25100000	324900	624815.1	156500	3420.00	146600
9	TRUE	FALSE	TRUE	TRUE	HEA160	9758.00	S275	30.4	3877.00	16730000	245100	6156000	76950	1321.00	118400
10	TRUE	FALSE	TRUE	TRUE	HEB160	4856.00	S235	42.6	5245.00	24920000	354000	8892000	170000	1759.00	312400
11	TRUE	TRUE	TRUE	TRUE	HEB180	5960.00	S235	51.2	6525.00	38310000	481400	13630000	231000	2024.00	422400
12	TRUE	TRUE	TRUE	TRUE	HEB160	4560.00	S275	42.6	5245.00	24920000	354000	8892000	170000	1759.00	312400
13	TRUE	TRUE	TRUE	TRUE	HEA200	6978.00	S235	42.3	5383.00	36920000	429500	19550000	203800	1808.00	204300
14	TRUE	TRUE	TRUE	TRUE	HEA180	9867.00	S275	35.5	4525.00	25100000	324900	624815.1	156500	3420.00	146600
15	TRUE	FALSE	TRUE	TRUE	HEA160	6970.00	S275	30.4	3877.00	16730000	245100	6156000	76950	1321.00	118400

Figure 28: Figure illustrates a table output of the first three checks (ULS, SLS, Length check) for the primary beams.

Output 2 shows the chosen beams with the waste of weight and used weight.

	A	B	C
1	BEAM ID	WASTE OF USED WEIGHT	
2	10	23.856	170.4
3	9	145.5616	204.8

Figure 29: Figure illustrates a data table output of the waste of weight and used weight for the two chosen primary beam elements for the second material bank variant.

The amount of Reused Material is the total weight of the reused element used by the two primary beams with the second material bank variant. The **waste generated** quantifies the material waste by the weight identified for the two primary beams with the second material bank variant. A comparison of the waste weight based on further filters such as the same cross sections and materials are applied to do a comparison. In this case, for primary beams, the selected beams are row 8(Beam ID 6)and 14(Beam ID 12), respectively, as they fulfil both conditions.

	A	B	C
1	BEAM ID WASTE OF USED WEIGHT		
2	6	158.8625	142
3	12	201.8175	142

Figure 30: Figure illustrates a data table output of the waste of weight and used weight for the two primary beam elements with similar cross-section types and material properties.

The results with these different sets of sections show a higher amount of waste and used weight compared to the first set of chosen sections. In the second variant material bank, the results for the primary beams are shown below. The results with these different sets of sections show more waste and used weight than the first set of chosen primary beam sections. Thus, in this study case, an optimisation based on less material waste is preferable, so the applied set is the first set of sections for the primary beams.

Second Material Bank Variant Secondary Beams

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Section	Length (mm)	Material Grad	Weight (kg/m)	Area (mm ²)	Inertia Y (mm ⁴)	Modulus Y (mm ³)	Inertia Z (mm ⁴)	Modulus Z (mm ³)	Shear Area (mm ²)	Torsional Inertia (mm ⁴)	Warping Inertia (mm ⁶)	Mrd(kN m)	Med(kN m)	utilisation
2	IPE240	6789.00	S235	30.70	3912.00	38920000.00	366600.00	2836000.00	73920.00	1914.00	127400.00	36680000000.00	100.83	64.56	0.64
3	IPE240	7809.00	S235	30.70	3912.00	38920000.00	366600.00	2836000.00	73920.00	1914.00	127400.00	36680000000.00	100.83	64.56	0.64
4	IPE240	5465.00	S275	30.70	3912.00	38920000.00	366600.00	2836000.00	73920.00	1914.00	127400.00	36680000000.00	86.16	64.56	0.75
5	IPE220	10698.00	S235	26.20	3337.00	27920000.00	285400.00	2049000.00	58110.00	2754.00	89820.00	22310000000.00	67.07	64.56	0.96
6	IPE220	6556.00	S275	26.20	3337.00	27920000.00	285400.00	2049000.00	58110.00	2754.00	89820.00	22310000000.00	78.49	64.56	0.82
7	IPE220	9768.00	S355	26.20	3337.00	27920000.00	285400.00	2049000.00	58110.00	2754.00	89820.00	22310000000.00	89.45	64.56	0.72
8	IPE200	9785.00	S335	22.40	2848.00	19430000.00	194300.00	1424000.00	44610.00	2848.00	68460.00	12746000000.00	78.33	64.56	0.82
9	IPE200	6543.00	S275	22.40	2848.00	19430000.00	194300.00	1424000.00	44610.00	2848.00	68460.00	12746000000.00	60.68	64.56	1.06
10	IPE240	7578.00	S235	30.70	3912.00	38920000.00	366600.00	2836000.00	73920.00	1914.00	127400.00	36680000000.00	100.83	64.56	0.64
11	IPE240	10984.00	S275	30.70	3912.00	38920000.00	366600.00	2836000.00	73920.00	1914.00	127400.00	36680000000.00	86.16	64.56	0.75
12	IPE220	11567.00	S235	26.20	3337.00	27920000.00	285400.00	2049000.00	58110.00	2754.00	89820.00	22310000000.00	67.07	64.56	0.96
13	IPE220	9867.00	S275	26.20	3337.00	27920000.00	285400.00	2049000.00	58110.00	2754.00	89820.00	22310000000.00	78.49	64.56	0.82
14	IPE220	4500.00	S355	26.20	3337.00	27920000.00	285400.00	2049000.00	58110.00	2754.00	89820.00	22310000000.00	89.45	64.56	0.72
15	IPE200	10005.00	S335	22.40	2848.00	19430000.00	194300.00	1424000.00	44610.00	2848.00	68460.00	12746000000.00	78.33	64.56	0.82
16	IPE200	5678.00	S275	22.40	2848.00	19430000.00	194300.00	1424000.00	44610.00	2848.00	68460.00	12746000000.00	78.33	64.56	0.82
17	IPE200	7456.00	S335	22.40	2848.00	19430000.00	194300.00	1424000.00	44610.00	2848.00	68460.00	12746000000.00	60.68	64.56	1.06
18	IPE200	11984.00	S355	22.40	2848.00	19430000.00	194300.00	1424000.00	44610.00	2848.00	68460.00	12746000000.00	78.33	64.56	0.82

Figure 31: Figure illustrates the data table for the secondary beams' second theoretical material bank variant.

Output 1 shows the ULS, SLS, and Length Check.

	A	B	C	D	E	F	G	H	I	J	K	L
	ULS1CHE CK	ULS2CHE CK	SLS	LENGTHCHECK	Section	Length (mm)	Material Grade	Weight (kg/m)	Area (mm ²)	Inertia Y (mm ⁴)	Modulus Y (mm ³)	Inertia Z (mm ⁴)
1												
2	TRUE	FALSE	TRUE	TRUE	IPE240	10967.00	S235	30.70	3912.00	38920000.00	366600.00	2836000.0
3	TRUE	FALSE	TRUE	TRUE	IPE240	11985.00	S235	30.70	3912.00	38920000.00	366600.00	2836000.0
4	TRUE	TRUE	TRUE	FALSE	IPE240	9857.00	S275	30.70	3912.00	38920000.00	366600.00	2836000.0
5	TRUE	TRUE	TRUE	TRUE	IPE220	8574.00	S235	26.20	3337.00	27920000.00	285400.00	2049000.0
6	TRUE	TRUE	TRUE	TRUE	IPE220	7923.00	S275	26.20	3337.00	27920000.00	285400.00	2049000.0
7	TRUE	TRUE	TRUE	TRUE	IPE220	5069.00	S355	26.20	3337.00	27920000.00	285400.00	2049000.0
8	TRUE	TRUE	TRUE	TRUE	IPE200	8493.00	S335	22.40	2848.00	19430000.00	194300.00	1424000.0
9	FALSE	TRUE	TRUE	TRUE	IPE200	8465.00	S275	22.40	2848.00	19430000.00	194300.00	1424000.0
10	TRUE	FALSE	TRUE	TRUE	IPE240	7543.00	S235	30.70	3912.00	38920000.00	366600.00	2836000.0
11	TRUE	TRUE	TRUE	TRUE	IPE240	8654.00	S275	30.70	3912.00	38920000.00	366600.00	2836000.0
12	TRUE	TRUE	TRUE	TRUE	IPE220	7845.00	S235	26.20	3337.00	27920000.00	285400.00	2049000.0
13	TRUE	TRUE	TRUE	TRUE	IPE220	9467.00	S275	26.20	3337.00	27920000.00	285400.00	2049000.0
14	TRUE	TRUE	TRUE	FALSE	IPE220	11464.00	S355	26.20	3337.00	27920000.00	285400.00	2049000.0
15	TRUE	TRUE	TRUE	TRUE	IPE200	11975.00	S335	22.40	2848.00	19430000.00	194300.00	1424000.0
16	TRUE	TRUE	TRUE	FALSE	IPE200	9567.00	S335	22.40	2848.00	19430000.00	194300.00	1424000.0
17	FALSE	TRUE	TRUE	TRUE	IPE200	9765.00	S275	22.40	2848.00	19430000.00	194300.00	1424000.0
18	TRUE	TRUE	TRUE	TRUE	IPE200	7356.00	S335	22.40	2848.00	19430000.00	194300.00	1424000.0

Figure 32: Figure illustrates a table output of the first three checks (ULS, SLS, Length check) for the secondary

Output 2 shows the chosen beams with the waste of weight and used weight.

	A	B	C
1	BEAM ID	WASTE OF USED WEIGHT	
2	4	14.5672	157.2
3	5	98.7216	157.2
4	6	84.784	134.4
5	13	104.931	157.2
6	11	101.3154	157.2

Figure 33: Figure illustrates a data table output of the waste of weight and used weight for the chosen secondary beam elements.

The amount of reused material compared to the total weight of the reused element used by the five secondary beams is shown above for the second material bank variant. **Waste Generated quantification** of the material waste by the weight is identified for the re-used elements chosen for the second material bank variant. In the case of the secondary beams variant, further filtration is based on the same cross-sectional properties, and a comparison to the previous material waste generated and used material weight is made.

	A	B	C
1	BEAM ID	WASTE OF USED WEIGHT	
2	4	14.5672	157.2
3	3	123.0876	157.2
4	5	98.7216	157.2
5	10	145.8554	157.2
6	11	101.3154	157.2

Figure 34: Figure illustrates a data table output of the waste of weight and used weight for the secondary beam elements.

The results with these different sets of sections show a higher amount of waste and used weight compared to the first set of chosen sections. Thus, in this study case, an optimisation based on less material waste is preferable, so the applied set of sections is the first set of sections for the secondary beams. The final layout is displayed below, visualising the chosen primary beams and secondary beams in the second material bank variant subject to further improvements at later stages of the algorithm.

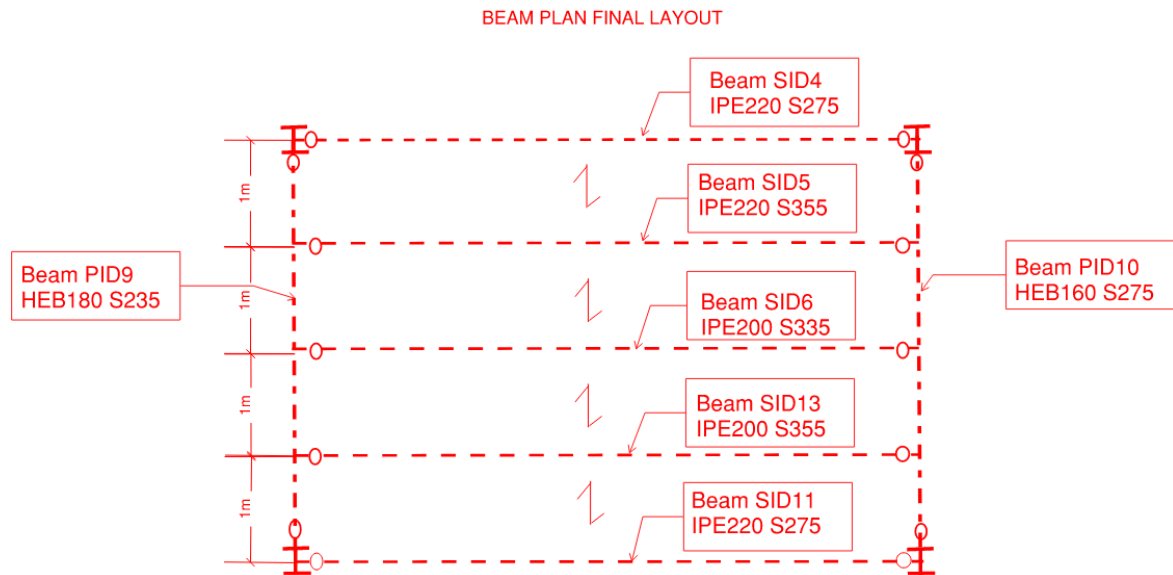


Figure 35: The primary and secondary beams chosen in the second material bank variant.

Eurocode compliance:

From the two case studies performed on the two material bank variants, the algorithm emphasises ensuring the structure meets both the Ultimate and Serviceability Limit States conditions. The reused components undergo a check for the specific load-bearing requirement. The checks ensure that despite using the reusable structural components, structural integrity is not compromised. Only the elements that satisfy the conditions are considered to be reused in the structure.

Optimisation Results:

From the two case studies, the optimisation process aimed to ensure the maximum reuse of structural elements with minimal waste. Further analysis and breakdown of applying the algorithm to demonstrate its effectiveness in achieving this is presented in the section below. Two key outputs are highlighted: the total waste from the reused elements and the material utilisation weight from the reused elements. These provide a better insight into the efficiency achieved by the algorithm. **Material utilisation weight from the Reused Components** is the weight value of the reused components from the material bank that provides insight into the quantifiable materials saved in contrast to the resources that would have been newly acquired.

Furthermore, the **total waste from the reused elements** shows that although the aim was to maximise the reuse of the structural components, some elements might still be cut and discarded due to length mismatches. The algorithm can show this, giving insight into further optimisation techniques that might be applied to reduce waste, such as reusing the cut elements in other parts of the structure making it more sustainable by creating a closed-loop reuse system. It is worth noting that the optimum beam configurations on the two case studies are designed with the least cutting waste as a parameter, further future development of the algorithm will be aimed at optimising based on ease of constructibility(similar cross-section properties). A visualisation with bar graphs showing the total volume of reused material, new material acquired, and waste generated from the two case studies is presented in (Figure 36) for the first material bank case study and (Figure 37) for the second material bank case study.

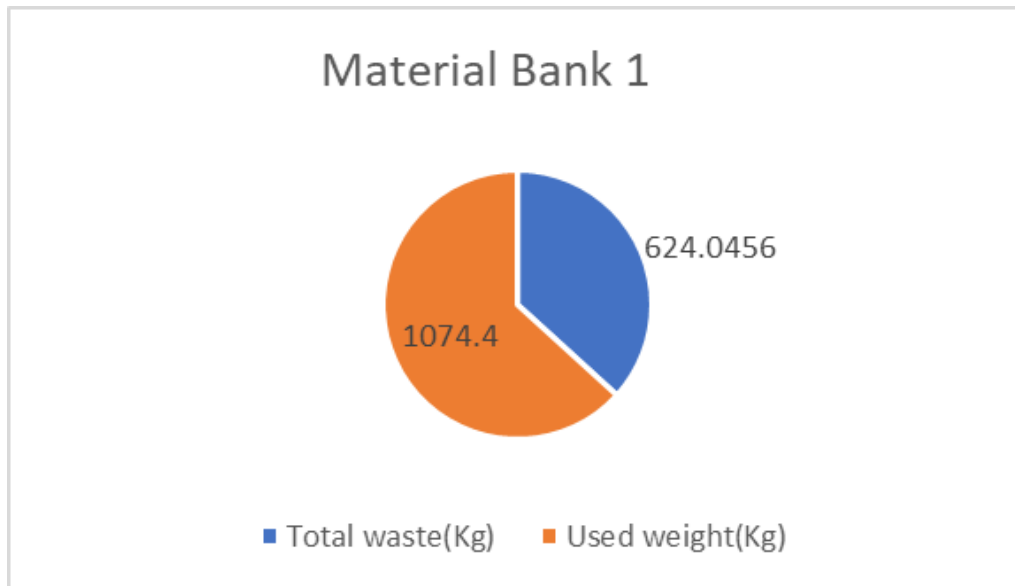


Figure 36: Pie chart showing the used weight and the total waste in kg of the first material bank variant.

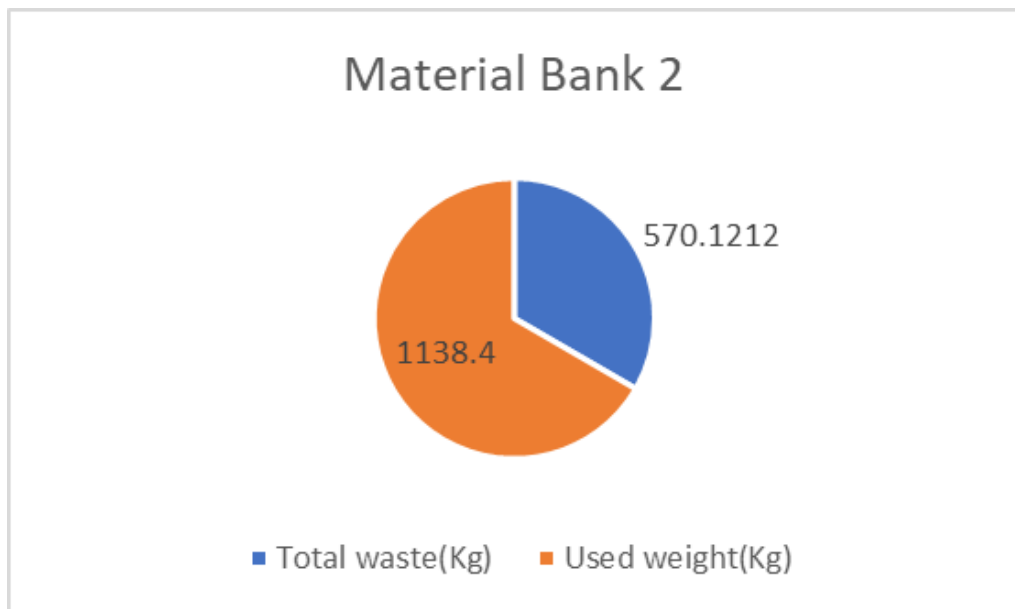


Figure 37: Pie chart showing the used weight and the total waste in kg of the second material bank variant.

5. Discussion

This section explains the broader implications of the study of sustainable construction practices and the future role of the material banks in the reusability of structural elements. It also discusses the problems facing the reuse of structural elements and ways to address them to scale the approach.

5.1 Implications for the Construction Industry

The need for new materials is minimised by reusing materials, promoting resource efficiency, and reducing the carbon footprint of the construction sector, contributing to the circular economy [26]. Prior studies indicate that the construction industry accounts for 24-40% of global carbon dioxide emissions [27]. Reducing dependency on new structural components can be vital to high-cost reduction. Reusing structural components can lower project costs by reducing the need for new materials purchases, which contributes significantly to overall costs. In addition, reducing dependency on natural resources means lower exposure to the adverse effects of resource price shocks [28]. Reusing structural components addresses one of the biggest challenges in the construction industry's **waste management**, as fewer materials will be diverted to landfills [29]. In the circular economy, great emphasis is laid on extending the lifecycle of materials by minimising construction waste [30]. By reusing structural elements, the construction industry's practices align more with the waste hierarchy principles [31].

Scalability of the Approach: The algorithm above was considered for study cases for a simple frame structure; however, the methodology and thought process is possible for more significant and complex projects such as industrial halls and commercial buildings. The reuse of sheet pile walls in foundation design shows how adaptable reuse of foundational elements can be cost—and material-saving. However, highly standardised protocols are required to check the structural integrity and quality of the reusable elements. Constantly updating the building design codes associated with the reusable elements is crucial to achieving their wide adoption.

Automation and integration of technology: The advancement of digital tools such as Building Information Management is essential to keep a record of the life-cycle of elements used, therefore making it easier to catalog and ensure optimal reuse of structural components [31].

5.2 Potential Areas for Improvement in the Construction Industry

Even though the study evaluates the usefulness of the proposed algorithm, certain limitations need to be addressed to adopt it further. The **component's structural integrity** is fundamental, so to verify the material and cross-section properties, the structural integrity of older structural components must be robustly checked through test methods. This is crucial to developing trust in the quality of the reused elements [31]. The availability of reusable elements depends on the frequency and scale of deconstruction projects. Therefore, this limitation is important for certain areas, making it important for **logistics and supply management** to properly store and transport the structural elements [32]. Despite the flexibility of reusable structural components, there are mismatches between their availability and applicability in old and new buildings. Therefore, optimisation in material selection to reduce cutting waste is important to enhance efficiency in reusing [30].

6. Summary

Material reuse is becoming more prevalent in the construction industry, as reducing the environmental impact is very important. However, unlike recycling reusing does not involve processing before the materials are used again saving considerable energy costs. Reusing structural components lowers resource usage and reduces waste. As explained in Chapter 2, reuse results in sustainable practises by increasing the life-cycle of materials, conserving resources, and ultimately reducing the carbon footprint associated with new material production. With this in mind, an algorithm in Grasshopper-Rhino to optimise the selection and reuse of structural components with the least cutting waste. The algorithm incorporated the material bank as its input which has the geometry, material grade, and cross-section, allowing it to evaluate the material bank and choose configurations that minimise the cutting waste. The algorithm was run on two case studies to design a section of a simple frame structure, particularly the primary and secondary beams.

Through this, the algorithm's ability to use reusable elements in the frame structure at a substantial level was demonstrated. The reused components met the performance requirements under the Eurocode standards, both in the Ultimate Limit State (ULS) and Serviceability Limit State (SLS). By optimising the structural elements by selecting the minimum waste weight, there was less overall material waste and thus a lower carbon footprint. Further optimisation

parameters to ease constructibility such as the same section, and the material selection will be performed at later stages of the algorithm.

These findings show that optimising reuse through a well-structured material bank is a viable pathway to sustainability in the construction industry. It sets a benchmark for reducing new material purchases and supporting the industry-wide effort to reduce the environmental impact.

7. References

- [1] Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, 114, 11-32. <https://doi.org/10.1016/j.jclepro.2015.09.007>
- [2] Commission of European Communities. (2014). Communication No. 398: Towards a Circular Economy: A Zero Waste Programme for Europe. *European Commission*. Retrieved from <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52014DC0398>
- [3] Padeglob@ESSEC. (n.d.). *Linear vs. circular economy*. Retrieved from https://media.licdn.com/dms/image/v2/C5612AQEWXOWPRzTRgw/article-cover_image-shrink_720_1280/article-cover_image-shrink_720_1280/0/1542109580007?e=1733356800&v=beta&t=AEjTZ12G1i36Q2PwMtAtYE5zNV9dsUCIzgVnz16VspI
- [4] Techno-economic and environmental assessment of construction and demolition waste management in the European Union, Cristóbal García, J., Caro, D., Foster, G., Pristerà, G., Gallo, F., Tonini, D.
- [5] https://www.mdpi.com/sustainability/sustainability-14-13918/article_deploy/html/images/sustainability-14-13918-g001-550.jpg
- [6] Ellen MacArthur Foundation. Reports on Circular Economy and Building Reuse. <https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview>
- [7] Minunno, R., O'Grady, T., Morrison, G. M., & Gruner, R. L. (2020). Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. *Resources, Conservation and Recycling*, 160, 104855. <https://doi.org/10.1016/j.resconrec.2020.104855>
- [8] Akbarnezhad, A., & Xiao, J. (2017). Estimation and Minimization of Embodied Carbon of Buildings: A Review. *Buildings*, 7(1), 5. <https://doi.org/10.3390/buildings7010005>

- [9] Tang, Z., Li, W., Tam, V. W. Y., & Xue, C. (2020). Advanced progress in recycling municipal and construction solid wastes for manufacturing sustainable construction materials. *Resources, Conservation and Recycling: X*, 6, 100033.
- [10] https://www.researchgate.net/profile/Gaochuang-Cai-2/publication/335830974/figure/fig9/AS:960342976897038@1605975016156/Concept-of-the-material-and-component-bank_W640.jpg
- [11] CEN (European Committee for Standardization). Eurocode standards.CEN/TS 1090-201:2024
- [12] Heinrich, M., Lang, W., & Kranzl, L. (2019). Material reuse in building construction: Case studies and prospects.
- [13] Ellen MacArthur Foundation. Introduction to the Circular Economy.
- [14] European Commission. Circular Economy and the Construction Sector.
- [15] Venlo city hall, Netherlands. Case study on circular building design. <https://knowledge-hub.circle-economy.com/article/5975?n=Venlo-Cradle-to-Cradle-City-Hall>
- [16] <https://images.app.goo.gl/iRZkfHsdXBqRgjYD9>
- [17] Ellen MacArthur Foundation. Reports on Circular Economy and Building Reuse. <https://www.ellenmacarthurfoundation.org/circular-examples/refurbishing-buildings-to-alleviate-environmental-pressures-1-triton-square>
- [18] https://www.researchgate.net/profile/Gaochuang-Cai-2/publication/335830974/figure/fig11/AS:960342976917516@1605975016386/Main-businesses-of-material-and-component-bank_W640.jpg
- [19] Material banks explained: could they be the path to a circular economy?
- [20] Chini, A. R., & Bruening, S. (2003). *Deconstruction and Materials Reuse in the United States*. The Future of Sustainable Construction, 12-14.
- [21] Cheshire, D. (2016). Building revolutions: Applying the circular economy to the built environment. RIBA Publishing.
- [22] World Green Building Council. (2019). *Bringing Embodied Carbon Upfront: Coordinated Action for the Building and Construction Sector to Tackle Embodied Carbon*.
- [23] Akbarnezhad, A., Ong, K.C.G., & Chandra, L.R. (2014). Economic and environmental assessment of deconstruction strategies using building information modeling. **Automation in Construction*, 37*, 131-144. <https://doi.org/10.1016/j.autcon.2013.10.017>

- [24] Resource Rows Project, Denmark. Case study on material reuse and material banks.
<https://lendager.com/project/resource-rows/>
- [25] Gorgolewski, M. (2017). *Resource Salvation: The Architecture of Reuse*. Wiley.
- [26] Galle, Waldo & Vandervaeren, Camille & Denis, Francois & Paduart, Anne & Cambier, Charlotte & Temmerman, Niels. (2017). Flanders' and Brussels' emerging businesses and products for a circular construction economy.
- [27] Van Es, S., Braendstrup, C., Slot, H., Seinen, J., & Dekker, R. (n.d.). *Determination of actual material properties in existing structures using small specimens*.
- [28] Gálvez-Martos, J., Styles, D., Schoenberger, H., & Zeschmar-Lahl, B. (2018). Construction and demolition waste best management practice in Europe. *Resources, Conservation and Recycling*, 136, 166-178. <https://doi.org/10.1016/j.resconrec.2018.04.016>
- [29]https://opal.is.eu/sites/default/files/2022-02/FCRBE-booklet-01-environmental_impact-EN.pdf
- [30]CEN (European Committee for Standardization). Eurocode 3: Design of Steel Structures.
- [31] Eurocode 4:design of concrete structures.
- [32] CEN/TS 1090-201:2024
Execution of steel and aluminium structures - Reuse of structural steel CEN/TS 1090-201:2024.Publication date:Jun26,2024<https://genorma.com/en/standards/fprcen-ts-1090-201>
- [33] Ma, W., & Hao, J. L. (2024). Enhancing a circular economy for construction and demolition waste management in China: A stakeholder engagement and key strategy approach. **Journal of Cleaner Production*, 450*, 141763. <https://doi.org/10.1016/j.jclepro.2024.141763>
- [34] Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. **Journal of Cleaner Production*, 143*, 710–718.
<https://doi.org/10.1016/j.jclepro.2016.12.055>
- [35] Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. **Journal of Cleaner Production*, 114*, 11-32. <https://doi.org/10.1016/j.jclepro.2015.09.007>
- [36] Webster, M. D. (2007). **Structural design for adaptability and deconstruction: A strategy for closing the materials loop and increasing building value.** *Building Research & Information*, 35(6), 602–615.

[37] Tebbatt Adams, K., Osmani, M., Thorpe, T., & Thornback, J. (2017). Circular economy in construction: Current awareness, challenges, and enablers. *Proceedings of the Institution of Civil Engineers - Waste and Resource Management*, 170(1), 15-24.

<https://doi.org/10.1680/jwarm.16.00011>

ANNEX

Load identification and sample calculation

$$g_{kconcrete} := \gamma_{concrete} \cdot t_{concrete} = 1.5 \frac{kN}{m^2}$$

trapezoidal sheeting:

$$\gamma_{steel} := 78.5 \frac{kN}{m^3} \quad t_{trapezoidalsheeting} := 0.0008 \text{ m}$$

$$g_{ktrapezoidalsheeting} := \gamma_{steel} \cdot t_{trapezoidalsheeting} = 0.063 \frac{kN}{m^2}$$

reinforcement

$$\rho := 0.01$$

$$g_{kreinforcement} := \rho \cdot \gamma_{steel} \cdot t_{concrete} = 0.047 \frac{kN}{m^2}$$

characteristic load on secondary beam:

$$g_{ksbeam} := g_{kreinforcement} + g_{ktrapezoidalsheeting} + g_{kconcrete} + g_{ksoundinsulation} + g_{ktechnological} + g_{kscreed} + g_{kmortar} + g_{kparq}$$

design load on the secondary beams

$$g_{dsbeam} := g_{ksbeam} \cdot \gamma_g = 4.427 \frac{kN}{m^2}$$

design dead load on the most loaded secondary beam:

$$g_{dsecondary} := g_{dsbeam} \cdot d = 4.427 \frac{kN}{m} \quad g_{ksecondary} := g_{ksbeam} \cdot d = 3.279 \frac{kN}{m}$$

live load on the office floor slab:

characteristic live load on floor slab:

$$q_k := 3.0 \frac{kN}{m^2}$$

design load on slab:

$$q_d := q_k \cdot \gamma_q = 4.5 \frac{kN}{m^2}$$

design live load on the most loaded secondary beam:

$$q_{dsecondary} := q_d \cdot d = 4.5 \frac{kN}{m} \quad q_{ksecondary} := q_k \cdot d = 3 \frac{kN}{m}$$

dead load of the secondary beam:(This is an input parameter)

self-weight of the secondary beam

$$g_{ksecondarybeam} := 90.698 \frac{kg}{m} \cdot g = 0.889 \frac{kN}{m} \quad g_{dsecondarybeam} := g_{ksecondarybeam} \cdot \gamma_g = 1.201 \frac{kN}{m}$$

Total dead load acting on the primary beam:

$$g_{dprimary} := g_{dsecondarybeam} + g_{dsecondary} = 5.628 \frac{kN}{m}$$

$$g_{kprimary} := g_{ksecondarybeam} + g_{ksecondary} = 4.169 \frac{kN}{m}$$

Load combination: secondary beam

ULS Limit state

$$\gamma_{G.sup} := 1.35$$

$$\gamma_{Q.sup} := 1.5$$

$$q_{uls} := \gamma_{G.sup} \cdot g_{dprimary} + \gamma_{Q.sup} \cdot q_{dsecondary} = 14.347 \frac{kN}{m}$$

$$q_k := g_{kprimary} + q_{ksecondary} = 7.169 \frac{kN}{m}$$

$$V_d := \frac{g_{kprimary} \cdot l}{2} = 12.506 \text{ kN}$$

$$M_{eduls} := \frac{q_{uls} \cdot l^2}{8} = 64.563 \text{ m} \cdot \text{kN}$$

$$V_{eduls} := \frac{q_{uls} \cdot l}{2} = 43.042 \text{ kN}$$

SLS Limit State $q_{ksecondary} = 3 \frac{kN}{m}$

$$q_{sls} := g_{kprimary} + q_{ksecondary} = 7.169 \frac{kN}{m}$$

$$V_l := \frac{q_{ksecondary} \cdot l}{2} = 9 \text{ kN}$$

$$\delta := \frac{(5 \cdot q_{sls} \cdot l^4)}{384 \cdot \left(210000 \frac{N}{mm^2} \cdot 4.82 \cdot 10^8 \text{ mm}^4 \right)} = 1.195 \text{ mm}$$

allowable deflection:

$$l := \frac{l}{250} = 24 \text{ mm}$$

$$\delta < l = 1$$

Therefore the deflection is within the SLS limit.

Calculation of loads on the primary beams:

The number of secondary beams loading the primary beams as point loads is 5 in my case. Therefore the calculated reaction on each point of the primary beams are as follows:

loads and effects calculation.

Length between primary beams:

$$l := 6 \text{ m}$$

Width of the building:

$$w := 4 \text{ m}$$

Distance between the secondary beams:

$$d := 1 \text{ m}$$

weights of composite floor and the layers of the floor

$$\gamma_g := 1.35$$

$$\gamma_q := 1.5$$

floor slab

parquet flooring:

$$\gamma_{\text{parquet}} := 11.76 \frac{\text{kN}}{\text{m}^3} \quad t_{\text{parquet}} := 2.4 \text{ cm}$$

$$g_{k\text{parquet}} := \gamma_{\text{parquet}} \cdot t_{\text{parquet}} = 0.282 \frac{\text{kN}}{\text{m}^2}$$

sticking mortar

$$\gamma_{\text{mortar}} := 16 \frac{\text{kN}}{\text{m}^3} \quad t_{\text{mortar}} := 0.2 \text{ cm}$$

$$g_{k\text{mortar}} := \gamma_{\text{mortar}} \cdot t_{\text{mortar}} = 0.032 \text{ m} \cdot \frac{\text{kN}}{\text{m}^3}$$

cement screed

$$\gamma_{\text{screed}} := 22 \frac{\text{kN}}{\text{m}^3} \quad t_{\text{screed}} := 6.0 \text{ cm}$$

$$g_{k\text{screed}} := \gamma_{\text{screed}} \cdot t_{\text{screed}} = 1.32 \frac{\text{kN}}{\text{m}^2}$$

technological foil

$$\gamma_{\text{technologicalfoil}} := 0.02548 \frac{\text{kN}}{\text{m}^3}$$

$$t_{\text{foil}} := 0.1 \text{ cm}$$

$$g_{k\text{technological}} := \gamma_{\text{technologicalfoil}} \cdot t_{\text{foil}} = (2.548 \cdot 10^{-5}) \frac{\text{kN}}{\text{m}^2}$$

sound insulation

$$\gamma_{\text{soundinsulation}} := 0.7 \frac{\text{kN}}{\text{m}^3} \quad t_{\text{soundinsulation}} := 5 \text{ cm}$$

$$g_{k\text{soundinsulation}} := \gamma_{\text{soundinsulation}} \cdot t_{\text{soundinsulation}} = 0.035 \frac{\text{kN}}{\text{m}^2}$$

60 mm concrete slab

$$\gamma_{\text{concrete}} := 25 \frac{\text{kN}}{\text{m}^3} \quad t_{\text{concrete}} := 6 \text{ cm}$$

Reaction on point 1: Above the column it is loaded directly to the column below thus no reaction force on the primary beam

Dead load

Live load

$n := 3$

$$V_d := \frac{g_{kprimary} \cdot l \cdot n}{2} = 0.15 \text{ kN} \quad V_l := \frac{q_{ksecondary} \cdot l \cdot n}{2} = 0.108 \text{ kN}$$

Reaction on each primary beam

Reactions on each support point above column:

$$R := \frac{V_{eduls} \cdot n}{2} = 64.563 \text{ kN}$$

Moment at the first point:

Shear at the first point:

$$M_0 := 0 \text{ kN} \cdot \text{m}$$

$$V_0 := -R = -64.563 \text{ kN}$$

Moment at the second point:

Shear at the second point:

$$M_1 := R \cdot d = 64.563 \text{ kN} \cdot \text{m}$$

$$V_1 := -R + V_{eduls} = -21.521 \text{ kN}$$

Moment at the third point :

Shear at the third point:

$$M_2 := R \cdot 2d - V_{eduls} \cdot d = 86.084 \text{ kN} \cdot \text{m} \quad V_2 := -R + 2 \cdot V_{eduls} = 21.521 \text{ kN}$$

Moment at the fourth point :

Shear at the fourth point:

$$M_3 := M_1 = 64.563 \text{ kN} \cdot \text{m}$$

$$V_3 := R - V_{eduls} = 21.521 \text{ kN}$$

Moment at the fifth point :

Shear at the fifth point:

$$M_5 := 0 \text{ kN} \cdot \text{m}$$

$$V_0 := R = 64.563 \text{ kN}$$

Deflection calculation of primary beam with smeared loads:

$$q_{slsp} := g_{ksecondary} + q_{ksecondary} = 6.279 \frac{\text{kN}}{\text{m}}$$

$$\delta_{max} := \frac{(5 \cdot q_{slsp} \cdot l^4)}{384 \cdot \left(210000 \frac{\text{N}}{\text{mm}^2} \cdot 4.82 \cdot 10^8 \text{ mm}^4 \right)} = (2.68 \cdot 10^{-10}) \text{ mm}$$

Allowable deflection:

$$l := \frac{w}{250} = 16 \text{ mm}$$

$$\delta_{max} < l = 1$$

Allowable