Developing a methodology for selective disassembly planning for building components to reduce the environmental impact at the End-of-Life scenario

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Abstract

This study addresses the pressing need in the construction industry to develop methodologies that optimize the environmental impact of building end-of-life scenarios through systematic disassembly planning and accurate carbon footprint calculations. The research proposes a framework integrating Disassembly Sequence Structure Graphs (DSSG) with detailed CO2 emission calculations to support decision-making in disassembly processes. Key objectives include linking DSSG models with carbon footprint calculations to evaluate the environmental impacts of different disassembly scenarios. The methodology is applied to a specific case study involving the disassembly of building components, focusing on windows. Findings demonstrate significant variations in carbon emissions based on the selected disassembly direction, underscoring the framework's efficacy in guiding sustainable practices. The study faces challenges such as data gaps in emission factor databases and methodological complexities in scaling to broader applications. This research provides a systematic approach to optimize disassembly processes through DSSG and minimize environmental impact based on a linked methodology of DSSG and LCA. Through accurate carbon footprint calculations, including fasteners and disassembly machines impacts, this leads to well-informed decision-making. Future directions include enhancing data availability, integrating automation tools for improved scalability, and validating the framework through broader case studies in the construction sector.

Keywords: Selective Disassembly Planning, Life Cycle Assessment (LCA), Disassembly Sequence Structure Graph (DSSG), Decision-Making Support

1. Introduction

The construction industry is a significant contributor to environmental degradation, primarily through waste generation and carbon emissions. Current practices often prioritize linear construction models, resulting in extensive waste and limited consideration for sustainable end-of-life options beyond demolition. This is particularly problematic for buildings and its components, where deconstruction lacks robust tools for assessing environmental impacts, hindering the widespread adoption of sustainable practices (Ruocco et al. (2023)). Therefore, there is a critical need for innovative methodologies that enable comprehensive evaluation and optimization of deconstruction methods within building practices. Reducing the environmental impact of the construction industry necessitates both methodological advancements and practical applications to assess the sustainability of product life cycles and building systems. Key to this effort is critically evaluating the End-of-Life phase, specifically the management of selective disassembly and demolition plans to facilitate material reuse and recycling. Existing approaches lack a unified methodology for effectively linking disassembly sequences with carbon footprint calculations, particularly concerning building components. This study seeks to address the following research questions: How can a methodology effectively link DSSG with carbon footprint calculations to support decision-making in end-of-life scenarios for buildings and building components? How can the developed methodology be applied and implemented for specific disassembly cases in buildings or building components, like windows? There is a need to develop a framework that integrates DSSG with detailed CO2 emission calculations. Methodologies for linking disassembly sequences with carbon footprint calculations within the construction industry are underdeveloped. Especially the End-of-Life scenario lacks standardized approaches for calculating emissions, highlighting a potential area for adaptation and improvement. This study seeks to fill this gap by proposing and implementing a robust methodology. This report is structured as follows to explore these questions and contribute to sustainable construction practices. First the current state of methodologies related to sustainable construction practices will be reviewed, with a focus on disassembly processes and carbon footprint calculations. Afterwards a methodology based on the DSSG approach will be developed. This section will include detailed CO2 emission calculations and the establishment of boundaries for LCA, introducing a linked methodology for DSSG and LCA. A specific case study will define the disassembly process of a aluminium framed window. Matrices for implementation, along with a database containing environmental impact emission factors and material quantities, will be detailed. The developed methodology will be applied using a Python-based tool, demonstrating comparisons of carbon emissions across different disassembly scenarios and visualizing DSSG models. The results will be critically discussed, emphasizing both the strengths and limitations of the study. This section will address challenges encountered in methodology implementation and propose avenues for future research and application. By systematically addressing these components, this study aims to advance methodologies for sustainable construction practices. This study aims to optimize the environmental impact of building end-of-life scenarios by implementing systematic selective disassembly planning and precise carbon footprint calculations in a linked methodology, thereby enhancing decision-making in the construction industry.

2. Literature Review

There is a growing body of research on Design for Disassembly (DfD) in the architecture, engineering, and construction (AEC) industry, yet practical case studies and applications remain underrepresented in scientific literature. Ostapska et al. (2024) highlight the need for a more uniform definition of DfD and the development of indicators and quantifications to compare the effectiveness of different designs. The study provides a comprehensive overview of the current DfD building stock and identifies emerging areas of research and development, such as tool development, BIM integration, and reversible connection design. As part of DfD, multiple disassembly planning approaches for buildings and products have been developed over the past years, categorized into destructive and non-destructive disassembly, further defined as temporary, selective, and complete disassembly (Sanchez and Haas (2018)). Disassembly planning can be achieved through different methodologies. Fazio et al. (2021) describe the development of a method called the "Disassembly Map", which visually maps the disassembly of a product and guides product design for repairability. The method considers four main design parameters to assess the ease of disassembly: disassembly sequence/depth, type of tools, fastener reusability/reversibility, and disassembly time. The Disassembly Map method is not based on an algorithm for automatic calculation but instead asks designers and engineers to analyze each disassembly step using standardized visual elements. Formentini and Ramanujan (2023) propose a novel approach called Design of Circular Disassembly, along with a corresponding model, the Parent-Action-Child model, to address the limitations of current disassembly methods in modeling the impacts of a product's end-of-life status on the disassembly process. Earlier, Smith et al. (2012) introduced the Disassembly Sequence Structure Graph (DSSG) methodology, which addresses the limitations of prior disassembly graphs by introducing a more efficient approach to creating and optimizing disassembly sequences. The DSSG model is characterized by its ability to handle single and multiple target components within a single graph, minimizing the number of nodes and links necessary for the disassembly process. While the approaches of Fazio et al. (2021) and Formentini and Ramanujan (2023) were only tested on products, the DSSG approach of Smith et al. (2012) has already been applied to building components. Using this as a foundation of the research, Sanchez and Haas (2018) expanded on the concept of selective disassembly by developing a rule-based recursive analysis method for planning the recovery of target components from building subsystems. This approach integrates various matrices, such as the contact constraint matrix (CC), motion constraint matrix (MC), and environmental constraint matrix (EnvC), to optimize the disassembly sequence. The study emphasized the importance of considering multiple objectives, including carbon footprint and cost, in the disassembly planning process. Sanchez et al. (2020) further explored the environmental impact of selective disassembly through multi-objective optimization (MOO). Their study included detailed equations for calculating the LCA of building components during various life cycle stages. Sanchez et al. (2020) highlighted the challenges in obtaining accurate data for end-of-life (EOL) scenarios and the complexity of modeling the system boundaries for different EOL options. Despite these challenges, the study demonstrated that selective disassembly could lead to significant environmental benefits, particularly when components are reused with minimal refurbishments. EOL scenarios for buildings and components are still simplified due to a lack of data and knowledge. Calculating the environmental impact at the EOL stage can be approached in various ways. Queheille et al. (2022) proposed a comprehensive LCA model to estimate the environmental impacts of EOL scenarios for buildings. This model is applicable to various building types and EOL strategies, covering stages C (demolition/deconstruction) and D (benefits and loads beyond the system boundaries). The study utilized OpenLCA and the ecoinvent 3.3 database to provide detailed insights into the environmental impacts associated with different EOL activities, such as waste transport, processing, and disposal. The findings surprisingly indicated that deconstruction often results in higher environmental impacts compared to demolition, particularly in stages C3 (waste processing) and D (benefits from waste recovery). Durmisevic et al. (2017) emphasized the importance of designing buildings for disassembly to enhance the reuse potential and transformability of building components. This framework includes assessing the technical composition and quality of elements, developing certification protocols for reusable elements, and establishing decision-making tools to support disassembly preparation. Similarly, Melella et al. (2021) provided insights into CO2 calculations for the disassembly and deconstruction of steel structures. Recent studies further illustrate the environmental benefits of selective disassembly. Ruocco et al. (2023) developed a methodology to mitigate CO2 emissions during the decommissioning and disposal of timber building systems. Their quantitative model considers the CO2 emissions rates in the C and D life cycle phases of building sustainability assessment. Applied to two wooden buildings with different structures, the study demonstrates the possibility of achieving circularity in wood construction through a zero-emission approach through deconstruction planning. Similarly, Diyamandoglu and Fortuna (2015) demonstrated that deconstruction of wooden structures for material recovery and reuse can significantly reduce greenhouse gas (GHG) emissions, though the environmental impact of deconstruction depends on various factors such as the model used, treatment processes, and transportation distances. The literature demonstrates various advancements in selective disassembly planning and environmental impact assessment in the AEC industry. Sanchez and Haas (2018) and Sanchez et al. (2020) show that integrating DSSG methodologies with CO2 calculations is effective for selective disassembly planning, but the methodology only includes the carbon footprint for components and not for fasteners and disassembly processes. The studies focus more on automated search for the best disassembly sequences and particularly don't prioritize carbon footprint calculations. Queheille et al. (2022), Durmisevic et al. (2017), and Melella et al. (2021) focus on broader building components and systems, rather than specific types. Furthermore, studies like those by Ruocco et al. (2023) and Diyamandoglu and Fortuna (2015) highlight the environmental benefits of disassembly in wood construction. While these studies only focused on wood construction, the use of LCA in disassembly processes for generic building components is not mentioned. There remains a significant research gap in methodologies that combine detailed approaches in selective disassembly processes and carbon calculations for specific building components or buildings. To address this gap, this research will show a systematic approach to link the DSSG with LCA models in a linked methodology, to optimize disassembly processes and minimize environmental impact through accurate carbon footprint calculations, including fasteners and disassembly machines impacts. Through consistent information by using the framework, the methodology should be used to apply informed decision-making for every possible disassembly scenario based on the environmental impact.

3. Research Methodology

3.1. DSSG approach

The DSSG approach presented in this study is a simplified and modified version of the one proposed in Smith et al. (2012), but the methodology still is a similar framework. DSSG describes the methodology to generate disassembly sequences, means the order of how to remove components and fasteners to disassemble a target component. This is important to present optimal solutions in selective disassembly planning to make informed decisions on the disassembly order. In Smith et al. (2012) a single- and multiple-target component approach were developed. This study uses the single target component approach because of the small scope of the research and the assumption, that only one target component has to be changed or disassembled at a time. Starting point is to create an inverted tree model. Root nodes represent the target component, while leaf nodes represent parts that constrain the target component. The process of creating a single-target DSSG involves arranging and ordering parts in constraint levels, starting from the target component. Removing parts in reverse order provides an optimized disassembly sequence for minimizing the number of removed parts, part order, and part disassembly directions. Through pre-defined expert rules based on physical constraints the methodology receives its priorities and the quality of solutions can be improved. Some rules are defined in Smith et al. (2012) and will be used for this study, two more are added:

- **Rule 1:** Choosing the disassembly direction with the least number of blocking components.
- **Rule 2:** Removing all fasteners that constrain a component before removing the component.
- **Rule 3:** Removing all components that constrain a part in the direction of disassembly before removing the part.
- **Rule 4:** Selecting the best direction for removing all parts unless pre-assigned disassembly directions exist.
- **Rule 5:** Incorporating carbon footprint calculations.
- **Rule 6:** Considering the life cycle impact of components and prioritizing disassembly sequences to minimize carbon emissions.

To create a DSSG several matrices have to be defined, which record various constraints for components and fasteners. These matrices facilitate the identification of the optimal disassembly path by considering the dependencies and constraints associated with each component and fastener. The matrices are separated for components and fasteners and have to be created for each case individually. Further descriptions for the structure of each matrix are in Smith et al. (2012).

- CC: contact constraints for components
- MC: motion constraints for components
- CF: contact constraints for fasteners
- MF: motion constraints for fasteners
- PC: projection constraints to account for blocking components

3.2. Impact Calculations

In the context of the EOL scenario, the LCA focuses on the disassembly, transportation, and treatment of the product or system components. For this study the LCA methodology is based on stages C (end of life) and D (benefits and loads beyond the system boundaries) of the standard DIN EN 15804. For fasteners and components which have to be manufactured again, the product stage A has to be included as well. The functional unit is "kgCO2e per disassembly sequence per component". For the LCA calculations a proper database with all the necessary information about the in the product/building included components and materials has to be defined. In fig. 1 the considered life cycle stages and its definitions can be seen.

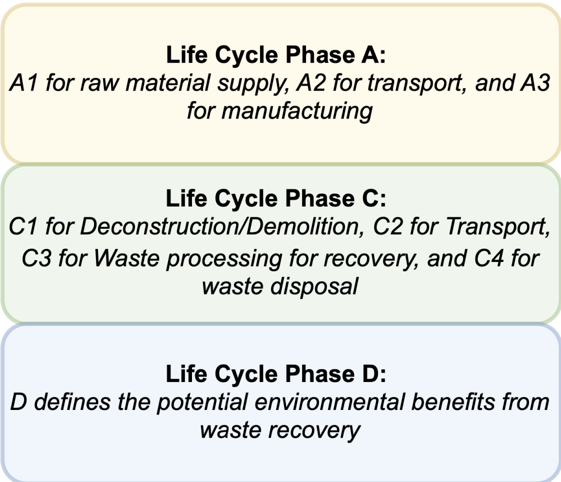

Figure 1: System boundaries LCA

The LCA will be calculated for several different components and processes of the building/building component. The calculations for products and disassembly processes consider the carbon emissions associated with the energy consumption of disassembly machines and the material emissions for each component and fastener. Detailed assumptions for these calculations include that components are always renewed upon disassembly, thus considering life cycle phases C, D, and A, while fasteners are generally reused, except for those involving glue, which are considered for phase C only. The equations below for components, fasteners and machines show the methodology. For each disassembly sequence the total amount of CO2 will be summed up.

Disassembly CO2 impact component:

$$GWP_{\text{comp}} = (EF_{\text{A1toA3}} + EF_{\text{C}} + EF_{\text{D}}) \times \text{quantity}$$

Disassembly CO2 impact fastener:

$$GWP_{\text{fast}} = (EF_{\text{C}}) \times \text{quantity}$$

Disassembly CO2 impact glue:

$$GWP_{\text{glue}} = (EF_{\text{A1toA3}} + EF_{\text{C}} + EF_{\text{D}}) \times \text{quantity}$$

Disassembly CO2 impact machine:

$$GWP_{\text{machine}} = (EF_{\text{energy}}) \times \text{power} \times \text{quantity}$$

Disassembly CO2 impact total:

$$GWP_{\text{total}} = (GWP_{\text{comp}} + GWP_{\text{glue}} + GWP_{\text{fast}} + GWP_{\text{machine}})$$

3.3. Linked methodology

To link the DSSG approach with the LCA for a single target component the framework in fig. 2 has been developed. The methodology is centered around a semi-automated approach. Mandatory for this methodology is that the matrices described in section 3.1 and environmental data with an appropriate approach for the units are defined. Also the disassembly graph (DG), means all the components and fasteners of the product/building, is clarified. The methodology is based on several algorithms and dependencies between components and fasteners and their disassembly directions. The initial step involves selecting the target component and assigning it a disassembly direction, which marks the commencement of the analysis. A root node is established for the target component within the DSSG. This node is classified as a component and is assigned a specific disassembly direction. The target component is then added to the processing queue. The core of the methodology lies in a processing loop that iteratively handles parts from the queue. For each part, the method first determines whether the part is a component or a fastener and then retrieves the corresponding material information. If the part is a component, the method calculates the product emissions considering all relevant life cycle phases (A, C, and D). The emission factors for these phases are derived from specific databases that provide product-specific emission factors. When handling a fastener, the methodology calculates both product emissions and machine emissions. These emissions are then aggregated in their respective lists for subsequent analysis. Each part is then added as a node in the DSSG graph. For components, the methodology applies Step 2 to process connected components and fasteners. This involves retrieving relevant data from the CC and MC matrices to identify and process any connected parts. For each connected component or fastener that is not already included in the DSSG, the method determines the appropriate disassembly direction, incorporates it into the DSSG, and adds it to the processing queue (Step 3). An edge is also added to the graph to represent the connection between parts. When handling fasteners, a specific rule is applied to retrieve data from the CF and MF matrices to identify any connected components (Step 4). The method ensures that each identified component is processed only if it can be disassembled in the same direction as the fastener or if it meets specific criteria related to disassembly constraints. Identified components are then incorporated into the DSSG and added to the processing queue, with the appropriate edges added to the graph. After processing all parts in the queue, the methodology finalizes the DSSG by updating each component's blocked components based on data from the PC matrix. The final step involves calculating the overall emissions by combining the product and machine emissions for the entire disassembly sequence.

3.4. Scenario Analysis

The scenario analysis aims to provide users with comprehensive information about the carbon footprint associated with each possible disassembly direction for a selected target component. The process involves running the carbon footprint calculations for each disassembly sequence stored in the queue. For each sequence, the tool calculates the emissions based on the data and assumptions made for the studied case. Through results visualization the carbon impact of each possible disassembly direction is presented. This detailed scenario analysis allows users to compare different disassembly paths and select the one with the lowest carbon footprint, thereby delivering a systematic and quantitative approach for assessing environmental impacts for disassembly scenarios, and supporting more sustainable disassembly practices.

4. Case Study

4.1. Model implementation

In this study, the test case is a window model. This window model serves as an example to demonstrate the linked methodology of the DSSG creation and LCA. The exploded view of the window model, as shown in fig. 3, illustrates all the fasteners and components involved. This detailed visualization is essential for understanding the disassembly process and create the necessary matrices like described in section 3.1.

The disassembly graph (DG) contains 24 components and 17 fasteners. table 1 gives an overview of the chosen materials for each component as well as the quantities and the unit. The quantities for the model are roughly assumed, as the window model is a synthetic case.

table 2 shows the fasteners and its quantities. These are based on the drawing in fig. 3 as well as in RAICO (2015), as there are two screws per frame component and 4 nails. The glue is roughly assumed per corner and given es part of a full glue package.

To test the methodology for the case study - described in section 3.3 - the framework is implemented in *Python3.12*, as a user-friendly tool. The matrices were created based on the materials, quantities and DG and are shown in the

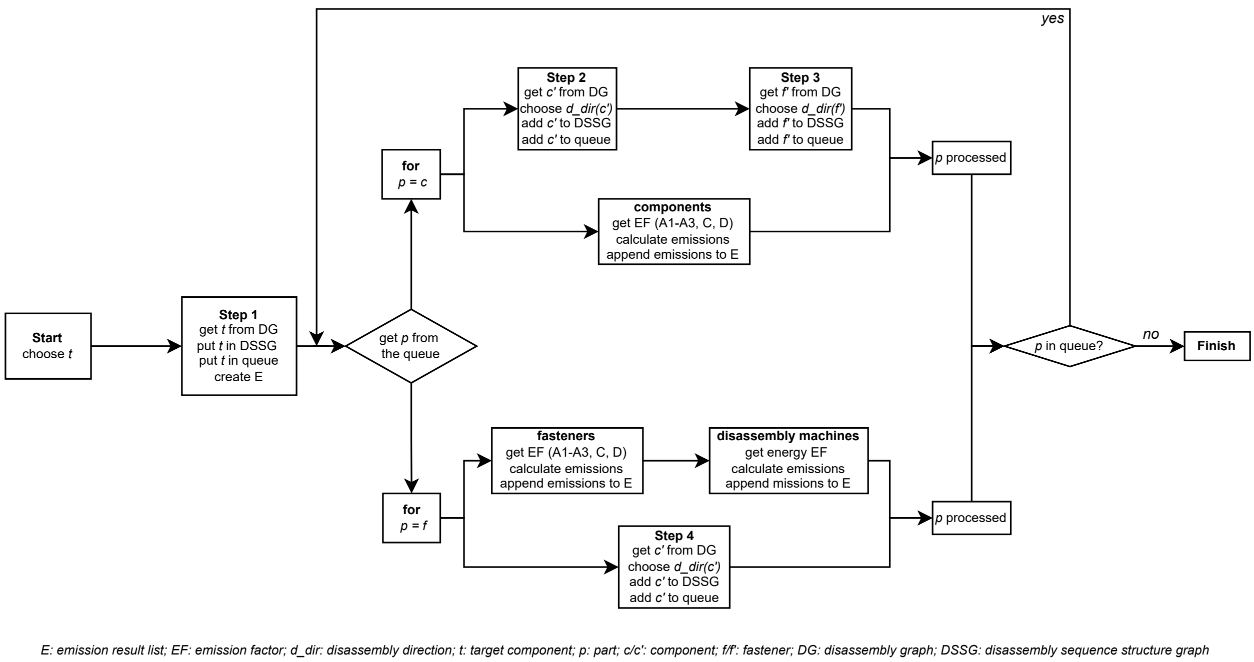

Figure 2: Single-target DSSG approach

key	part	material	quantities	unit
1	frame	alu	1.2	m
2	frame	alu	1.2	m
3	frame	alu	1.2	m
4	frame	alu	1.2	m
5	cornerbracket	alu	0.17	m
6	cornerbracket	alu	0.17	m
7	cornerbracket	alu	0.17	m
8	cornerbracket	alu	0.17	m
9	frame	alu	1.2	m
10	frame	alu	1.2	m
11	frame	alu	1.2	m
12	frame	alu	1.2	m
13	cornerbracket	alu	0.17	m
14	cornerbracket	alu	0.17	m
15	cornerbracket	alu	0.17	m
16	cornerbracket	alu	0.17	m
17	gasket	tape	0.000032	m3
18	window	glass	0.64	m2
19	gasket	tape	0.000032	m3
20	gasket	tape	0.000032	m3
21	glazingbead	alu	1.2	m
22	glazingbead	alu	1.2	m
23	glazingbead	alu	1.2	m
24	glazingbead	alu	1.2	m

Table 1: Component materials and quantities

key	type	quantities
f1	screws	2
f2	screws	2
f3	screws	2
f4	screws	2
f5	glue	0.1
f6	glue	0.1
f7	glue	0.1
f8	glue	0.1
f9	screws	2
f10	screws	2
f11	screws	2
f12	screws	2
f13	glue	0.1
f14	glue	0.1
f15	glue	0.1
f16	glue	0.1
f17	nails	4

Table 2: Fastener types and quantities

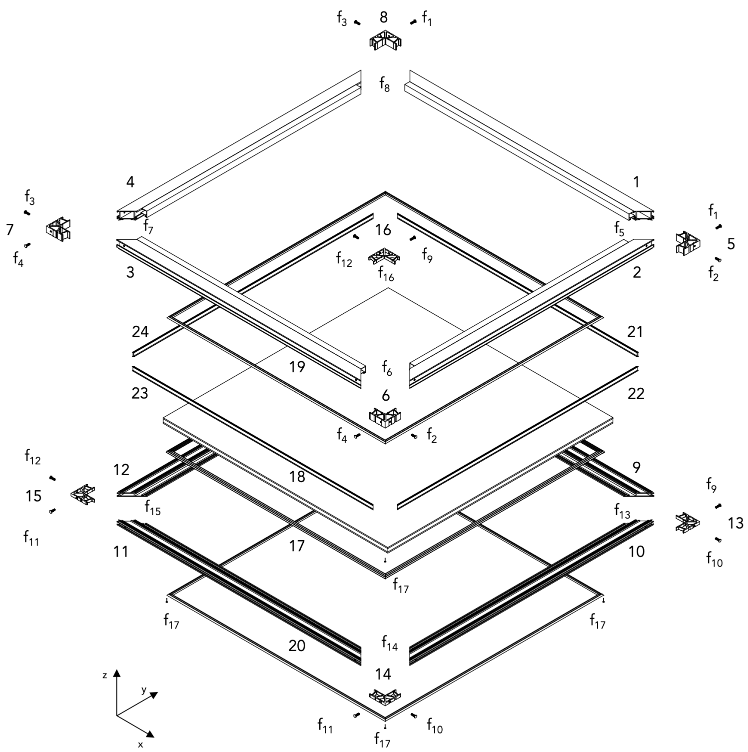

Figure 3: Exploded view of the window model

Appendix - section 7. As an input for the tool the following information is mandatory: possible disassembly directions (1: +x, 2: -x, 3: +y, 4: -y, 5: +z, 6: -z), DG (24 components, 17 fasteners), target component, component materials and quantities as well as fastener materials and quantities.

4.2. Data collection

Data collection took process in collecting necessary data for the window materials as well as for machines to disassemble it. The data was found in the *oekobaudat* for components and fasteners. The window components dataset has multiple options for the frame to show the different environmental impacts for different materials.

fastener	A1-A3	C	D
screws	0.00549024	-	-0.00166539
nails	0.00645736	5.824E-07	-0.00252616
bolts	0.005688	-	-0.0029022
glue	0.06103692	-	0.00835396

Table 3: Fastener emission factors for life cycle phases in kgCO2e/pc

component	material	A1-A3	C	D	unit
window	glass	13.35	0.219	0	/m2
frame	alu	17.04	0.592	-9.588	/m
gasket	tape	284.69	212.978	-62.174	/m3
glazing bead	alu	12.45	0.00318	-7.131	/m
corner bracket	alu	12.45	0.00318	-7.131	/m
sealing	epdm	1.331	2,722	-1.117	/m
pre-sealant	silicone	9232.8	1221.061	-355.32	/m3

Table 4: Component emission factors for life cycle phases in kgCO2e/unit

For machines the data is taken from Queheille et al. (2022), shown in table 5. The emission factor is the electricity mix scenario of Germany of the *oekobaudat*.

fastener -	machine -	emission factor (kgCO2e/kWh)	power (kWh)
screws	drill	0.3557	0.066
nails	nail puller	-	-
bolts	impact wrench	0.3557	0.114
glue	-	-	-

Table 5: Data for machine calculations

5. Results

The primary objective of this study was to evaluate the carbon footprint associated with different disassembly sequences for selected target components using the DSSG approach integrated with LCA, as detailed in section 3.3. The results provide insights into the environmental impacts of disassembly processes, supporting decision-making by identifying the most sustainable practices. This section presents the detailed findings for three target components, illustrating their disassembly graphs and corresponding carbon emissions to provide an overview of various components. In the DSSGs the components and fasteners to be removed are shown, connected with arrows. The number next to the arrow defines the disassembly direction of the part.

5.1. Target component 2 - frame

For the first analysis, frame part 2, shown in fig. 3, was chosen. This component was selected due to its structural importance and complexity in the disassembly process. Through the carbon footprint comparison in fig. 4 one can see that the CO2 emissions for disassembly direction 1 (+x) have the lowest environmental impact with a value of 29.48 kgCO2e, while direction 2 (-x) and 6 (-z) have the highest impact with 119.12 kgCO2e. The disassembly of target component 2 in the directions 3 (+y), 4 (-y) and 5 (+z) show impacts between 39.13 kgCO2e and 42.35 kgCO2e.

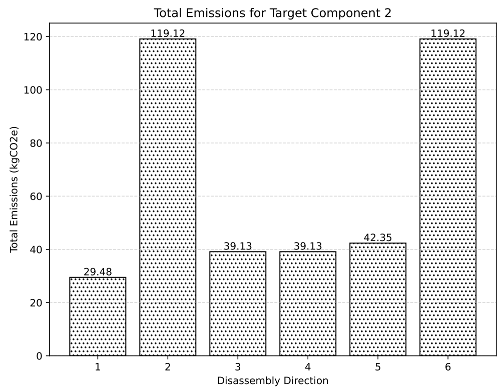

Figure 4: CO2 emissions for disassembly of target component 2

To show the difference in the DSSG models for sequences with the lowest and the highest environmental impact fig. 5 and fig. 6 are presented. fig. 6 shows that the disassembly of the frame in direction 6 (-z) includes the disassembly of multiple components and fasteners, due to its blocking components in the direction.

5.2. Target component 13 - cornerbracket

The second target component selected for analysis is the corner bracket 13. This component is crucial for understanding the disassembly of joints and connections, as

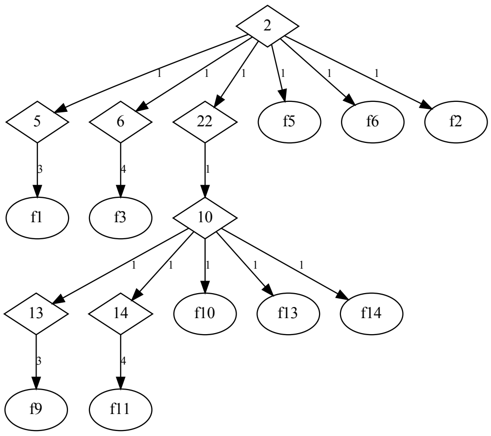

Figure 5: DSSG for disassembly of target component 2 - direction 1

it is between to frame parts and blocks the components to be disassembled without being disassembled itself. fig. 7 shows the carbon emissions for the six possible directions. Direction 1 (+x) and 3 (+y) show the lowest environmental impact with 29.48 kgCO2e, resulting from the least components and fasteners have to be removed. For disassembly direction 5 (+z) and 6 (-z) the diagram shows an impact of 119.09 kgCO2e, indicating a high amount of components and fasteners to be removed before the target component.

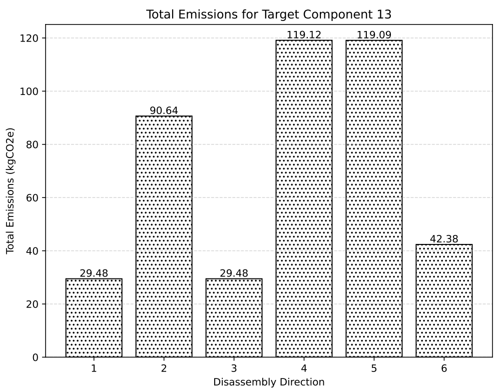

Figure 7: CO2 emissions for disassembly of target component 13

All the products of the window to be removed are shown in fig. 8 and fig. 9, while fig. 8 shows the DSSG for direction 3 (+y) with the least amount of components and fasteners to be removed, and fig. 9 the highest amount of products to be removed.

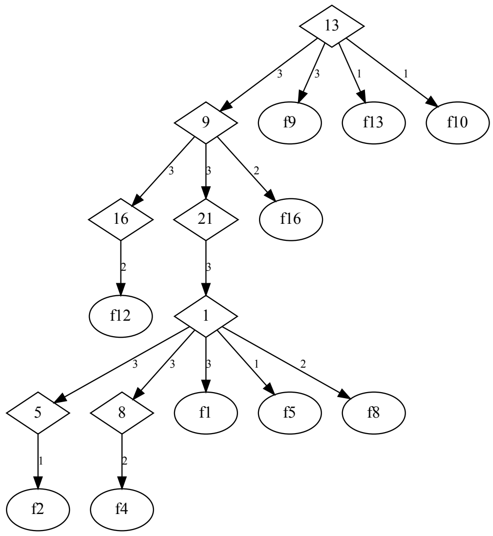

Figure 8: DSSG for disassembly of target component 13 - direction 3

5.3. Target component 18 - glass

The final target component analyzed is the glass, which is component 18. fig. 10 shows that environmental impact of removing the glass component through all directions is between 38.30 kgCO2e and 64.02 kgCO2e. For disassembly direction 5 (+z) and 6 (-z) the emissions are 51.17 kgCO2e or 51.20 kgCO2e. The highes amount of CO2 emissions shows the disassembly in direction 2 (-x) with 64.02 kgCO2e.

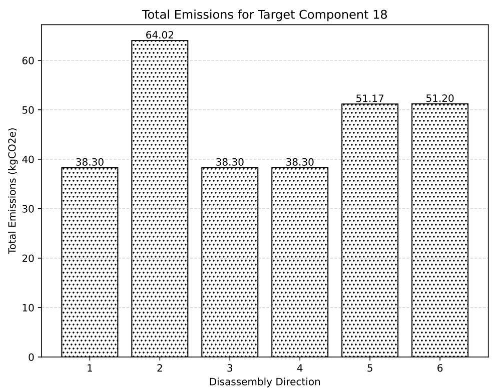

Figure 10: CO2 emissions for disassembly of target component 18

The difference in the amount of components and fasteners to be removed before the target component shown in fig. 11 and fig. 12 is less and than for the other target components, shows that the amount of blocking components and connected fasteners are similar. This can also be seen in the difference in the environmental impact, shows

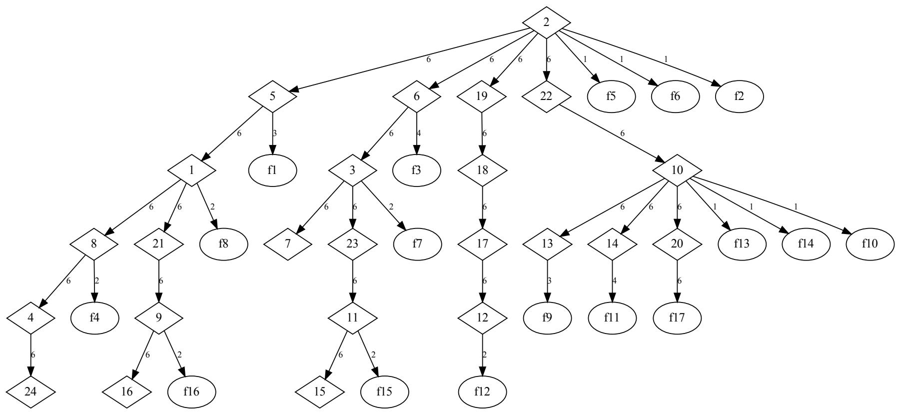

Figure 6: DSSG for disassembly of target component 2 - direction 6

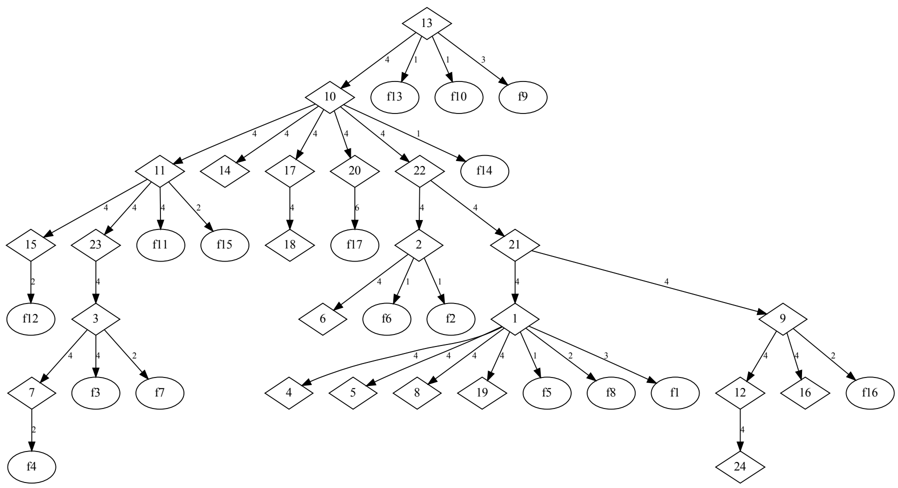

Figure 9: DSSG for disassembly of target component 13 - direction 4

a range of 38.30 to 64.02, while for target component 2 the range was 29.48 to 119.12 and for target component 13 29.48 to 119.02.

6. Discussion

6.1. Framework Evaluation

The results from this study demonstrate the efficacy of the developed framework in linking DSSG models with detailed carbon footprint calculations. By evaluating different disassembly sequences for three target components, it was evident that the methodology can provide an overview of sustainable disassembly practices and comparisons, highlighting its practical application for decision-making in disassembly processes. The detailed analysis of the three target components — frame (component 2), corner bracket (component 13), and glass (component 18) — revealed significant variations in carbon emissions based on the disassembly direction. The DSSG models facilitated a clear visualization of these sequences, illustrating the components and fasteners involved in each disassembly path. This visualization is crucial for understanding the complexity and dependencies in the disassembly process, thereby aiding in the selection of the optimal disassembly path. For the frame (component 2), the results indicated that disassembly direction 1 (+x) had the lowest carbon footprint at 29.48 kgCO2e, whereas directions 2 (-x) and 6 (-z) had the highest impacts at 119.12 kgCO2e. This substantial difference underscores the importance of selecting the optimal disassembly direction to minimize environmental impact. This is similar for the corner bracket (component 13), directions 1 (+x) and 3 (+y) were the most sustainable, each with 29.48 kgCO2e, while directions 5 (+z) and 6 (-z) had the highest impacts at 119.09 kgCO2e. The glass component (component 18) showed a narrower range of emissions, from 38.30 kgCO2e to 64.02 kgCO2e, indicating less variation but still highlighting the importance of direction

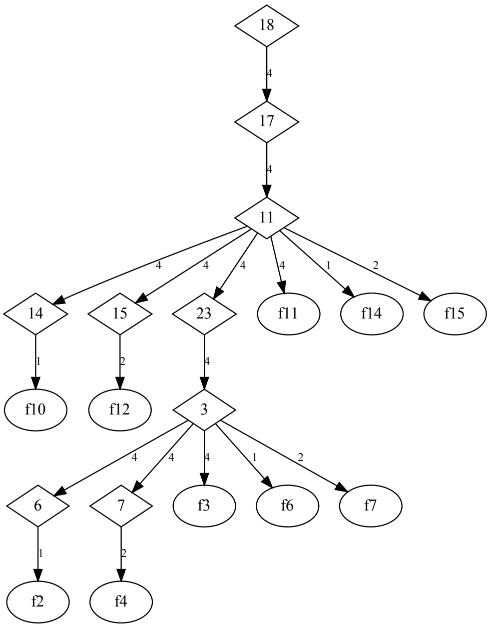

Figure 11: DSSG for disassembly of target component 18 - direction 4

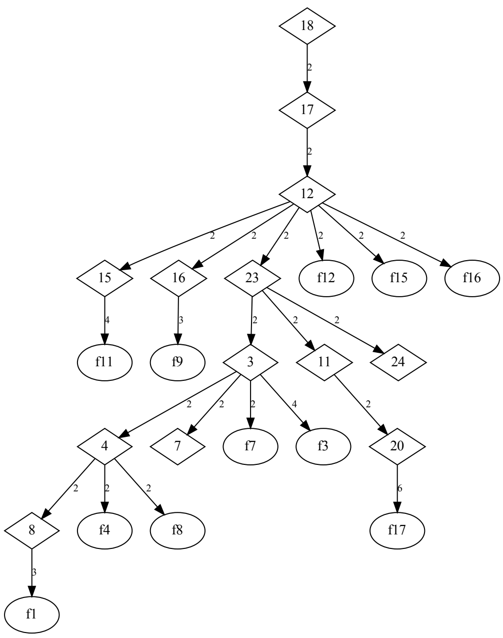

Figure 12: DSSG for disassembly of target component 18 - direction 2

selection. Comparing these findings with previous studies, the framework developed here demonstrates a more detailed approach in terms of linking detailed carbon footprint calculations with DSSG models. Unlike the study by Sanchez and Haas (2018), which linked a more generic carbon emission calculation approach to DSSG models for multiple target components, this research focused on a detailed methodology for CO_2 calculations for individual disassembly processes. This included the emissions for components, fasteners, and disassembly machines, offering a more granular analysis. Sanchez and Haas (2018) provided carbon footprint data only for components, not for fasteners and machines, underscoring the enhanced detail and scope of the present study. The methodology in this study also shows a simplified approach to finding the best disassembly sequences across all possible directions, supporting decision-making by presenting detailed carbon footprint comparisons. Unlike the automatic algorithm used in Sanchez and Haas (2018) to find the optimal disassembly sequence, this framework explicitly shows all possible directions and what is necessary for disassembly in each direction. This allows for a transparent and informed evaluation of each disassembly scenario and considers all potential environmental impacts, as well as full control above the results and all options. By evaluating every potential scenario, this methodology enables better decision-making for optimizing the disassembly process and minimizing carbon emissions, which is supporting more sustainable and circular product design and end-of-life management. It can be beneficial for selective disassembly planning for building components, as shown for window disassembly processes, supporting sustainable decision-making through integrated environmental impact assessments. The methodology's capacity to incorporate both component-level and fastener-level emissions, as well as machine energy consumption, ensures a comprehensive environmental impact analysis, setting a new standard for disassembly process optimization.

6.2. Limitations of the study

The study faces several limitations that impact its practical application and reliability. A primary challenge identified is the insufficient availability of emission factor data in existing databases. This gap hinders the ability to accurately quantify emissions for individual materials, machines, and fasteners, and leads to educated assumptions. This complexity not only complicates emission attribution but also introduces uncertainties into the analysis. To cover data gaps other detailed models could be used through databases like *ecoinvent*, to calculate the carbon footprint based on processes. Applying the framework to larger case studies like buildings proves challenging due to the intricate nature of systems such as windows. The manual effort required to create necessary matrices for the DSSG approach and integrate them into tools is huge. This manual work not only demands extensive time and resources but also increases the potential for errors, especially for complex systems. The study suggests future integration with automation tools like AECData through APIs to streamline data integration to not use manual created databases. However, implementing automation via APIs necessitates robust data standards and compatibility across platforms, which may pose additional challenges. Scaling the framework to larger case studies requires overcoming data and methodological challenges while ensuring findings' applicability across diverse contexts and project scales. The resource-intensive nature of applying the framework further limits its adoption speed and breadth, especially in settings with limited resources or tight project timelines. The initial plan of this study was to create a BIM-based disassembly tool, which should use IFC files as an input and applies the methodology with the data provided in the IFC model. Due to the lack of common IFC models in the industry it was not possible to continue to work on this specific topic and the study showed an approach to use and apply the methodology with manual integrated matrices. A further point for automation should be to do research in how to use IFC models in such methodologies/tools to directly receive the data about connections of fasteners and components of it. While the study presents a promising framework for analyzing CO2 emissions at a detailed level and shows satisfying results like described in section 5 and section 6, its practical implementation is constrained by data gaps, methodological complexities, and significant manual effort. Addressing these limitations through improved data availability, enhanced automation, and validated case studies will be crucial for enhancing the robustness and applicability of the approach in real-world applications.

7. Conclusion

The framework successfully links DSSG models with detailed carbon footprint calculations, offering a valuable tool for optimizing disassembly processes. The findings highlight the significant impact that disassembly direction can have on carbon emissions and demonstrate the practical utility of this methodology in supporting sustainable decision-making. By providing a comprehensive analysis of disassembly sequences and their environmental impacts, this framework supports in disassembly process optimization and well-informed decision-making. The methodology demonstrates a simplified yet comprehensive approach to identifying the best disassembly sequences. By not relying solely on automated algorithms, it ensures that all possible disassembly directions are considered, providing a robust comparison of carbon footprints. This detailed approach supports the selection of the most sustainable disassembly practices, which is crucial for reducing the overall environmental impact of products at the end of their life cycle.

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Annexes

$$CF = \begin{bmatrix} CF1 \\ CF2 \\ CF3 \\ CF4 \\ CF5 \\ CF6 \\ CF7 \\ CF8 \\ CF9 \\ CF10 \\ CF11 \\ CF12 \\ CF13 \\ CF14 \\ CF15 \\ CF16 \\ CF17 \end{bmatrix} = \begin{bmatrix} 3 \\ 1 \\ 4 \\ 2 \\ 1 \\ 1 \\ 2 \\ 2 \\ 3 \\ 1 \\ 4 \\ 2 \\ 1 \\ 1 \\ 2 \\ 2 \\ 6 \end{bmatrix}$$

$$MF = \begin{bmatrix} MF1 \\ MF2 \\ MF3 \\ MF4 \\ MF5 \\ MF6 \\ MF7 \\ MF8 \\ MF9 \\ MF10 \\ MF11 \\ MF12 \\ MF13 \\ MF14 \\ MF15 \\ MF16 \\ MF17 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 4 & 0 & 0 & 0 & 0 \\ 0 & 4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 4 & 0 & 0 & 0 & 0 \\ 0 & 4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$PC = \begin{bmatrix} PC1 \\ PC2 \\ PC3 \\ PC4 \\ PC5 \\ PC6 \\ PC7 \\ PC8 \\ PC9 \\ PC10 \\ PC11 \\ PC12 \\ PC13 \\ PC14 \\ PC15 \\ PC16 \\ PC17 \\ PC18 \\ PC19 \\ PC20 \\ PC21 \\ PC22 \\ PC23 \\ PC24 \end{bmatrix} = \begin{bmatrix} 3 & 3 & 3 & 13 & 2 & 10 \\ 3 & 13 & 3 & 3 & 2 & 10 \\ 3 & 3 & 13 & 3 & 2 & 10 \\ 13 & 3 & 3 & 3 & 2 & 10 \\ 2 & 9 & 2 & 9 & 2 & 7 \\ 2 & 9 & 9 & 2 & 2 & 7 \\ 9 & 2 & 9 & 2 & 2 & 7 \\ 9 & 2 & 2 & 9 & 2 & 7 \\ 4 & 4 & 3 & 14 & 10 & 3 \\ 3 & 14 & 4 & 4 & 10 & 3 \\ 4 & 4 & 14 & 3 & 10 & 3 \\ 14 & 3 & 4 & 4 & 10 & 3 \\ 2 & 9 & 2 & 9 & 7 & 2 \\ 2 & 9 & 9 & 2 & 7 & 2 \\ 9 & 2 & 9 & 2 & 7 & 2 \\ 9 & 2 & 2 & 9 & 7 & 2 \\ 1 & 1 & 1 & 1 & 6 & 5 \\ 1 & 1 & 1 & 1 & 5 & 6 \\ 1 & 1 & 1 & 1 & 4 & 7 \\ 1 & 1 & 1 & 1 & 11 & 0 \\ 2 & 2 & 2 & 16 & 3 & 3 \\ 2 & 16 & 2 & 2 & 3 & 3 \\ 2 & 2 & 16 & 2 & 3 & 3 \\ 16 & 2 & 2 & 2 & 3 & 3 \end{bmatrix}$$

$$\mathrm{CC} = \begin{bmatrix} \mathrm{CC1} \\ \mathrm{CC2} \\ \mathrm{CC3} \\ \mathrm{CC4} \\ \mathrm{CC5} \\ \mathrm{CC6} \\ \mathrm{CC7} \\ \mathrm{CC8} \\ \mathrm{CC9} \\ \mathrm{CC10} \\ \mathrm{CC11} \\ \mathrm{CC12} \\ \mathrm{CC13} \\ \mathrm{CC14} \\ \mathrm{CC15} \\ \mathrm{CC16} \\ \mathrm{CC17} \\ \mathrm{CC18} \\ \mathrm{CC19} \\ \mathrm{CC20} \\ \mathrm{CC21} \\ \mathrm{CC22} \\ \mathrm{CC23} \\ \mathrm{CC24} \end{bmatrix} = \begin{bmatrix}
2,5,f5 & 4,8,f8 & f1,f5,f8,5,8,21 & 2,4,5,8,18,19,21,f5,f8 & 5,8,f5,f8 & 5,8,21,19,f5,f8 \\
f2,f5,f6,5,6,22 & f5,f6,5,6,1,3,22,18,19 & 1,5,f5 & 3,6,f6 & 5,6,f5,f6 & 5,6,22,19,f5,f6 \\
2,6,f6 & 4,7,f7 & 2,4,6,7,18,19,23,f6,f7 & f3,f6,f7,6,7,23 & 6,7,f6,f7 & 6,7,23,19,f6,f7 \\
1,3,7,8,18,19,24,f7,f8 & f4,f7,f8,7,8,24 & 1,8,f8 & 3,7,f7 & 7,8,f7,f8 & 7,8,24,19,f7,f8 \\
2,f2,f5 & 1,f5 & 1,f1,f5 & 2,f5 & 1,2,f5 & 1,2,f5 \\
2,f2,f6 & 3,f6 & 2,f6 & 3,f3,f6 & 2,3,f6 & 2,3,f6 \\
3,f7 & 4,f4,f7 & 4,f7 & 3,f3,f7 & 3,4,f7 & 3,4,f7 \\
1,f8 & 4,f4,f8 & 1,f1,f8 & 4,f8 & 1,4,f8 & 1,4,f8 \\
10,13,17,20,21,f13 & 12,16,17,20,21,f16 & f9,f13,f16,13,16,21 & 10,12,13,16,20,21,17,18,f13,f16 & 13,16,21,f13,f16,17 & 13,16,20,f13,f16 \\
f10,f13,f14,13,14,22 & 9,11,13,14,17,18,20,22,f13,f14 & 9,13,17,20,22,f13 & 11,14,17,20,22,f14 & 13,14,22,f13,f14,17 & 13,14,20,f13,f14 \\
10,14,23,17,20,f14 & 12,15,17,20,23,f15 & 10,12,14,1517,18,20,23,f14,f15 & 14,15,23,f11,f14,f15 & 14,15,23,f14,f15,17 & 14,15,20,f14,f15 \\
9,11,15,16,17,18,20,24,f15,f16 & 15,16,23,f12,f15,f16 & 9,16,17,18,20,24,f16 & 11,15,17,18,20,24,f15 & 15,16,24,f15,f16,17 & 15,16,20,f15,f16 \\
10,f10,f13 & 9,f13 & 9,f9,f13 & 10,f13 & 9,10,f13 & 9,10,f13 \\
10,f10,f14 & 11,f14 & 10,f14 & 11,f11,f14 & 10,11,f14 & 10,11,f14 \\
11,f15 & 12,f12,f15 & 12,f15 & 11,f11,f15 & 11,12,f15 & 11,12,f15 \\
9,f16 & 12,f12,f16 & 9,f9,f16 & 12,f16 & 9,12,f16 & 9,12,f16 \\
10,18 & 12,18 & 9,18 & 11,18 & 18 & 9,10,11,12 \\
17 & 17 & 17 & 17 & 19 & 17 \\
2,18 & 4,18 & 1,18 & 3,18 & 1,2,3,4 & 18 \\
10 & 12 & 9 & 11 & 9,10,11,12 & f17 \\
1,9,22 & 1,9,24 & 1,9 & 1,9 & 1 & 9 \\
2,10 & 2,10 & 2,10,23 & 2,10,21 & 2 & 10 \\
3,11,22 & 3,11,24 & 3,11 & 3,11 & 3 & 11 \\
4,12 & 4,12 & 4,12,21 & 4,12,23 & 4 & 12
\end{bmatrix}$$

$$\mathrm{MC} = \begin{bmatrix} \mathrm{MC1} \\ \mathrm{MC2} \\ \mathrm{MC3} \\ \mathrm{MC4} \\ \mathrm{MC5} \\ \mathrm{MC6} \\ \mathrm{MC7} \\ \mathrm{MC8} \\ \mathrm{MC9} \\ \mathrm{MC10} \\ \mathrm{MC11} \\ \mathrm{MC12} \\ \mathrm{MC13} \\ \mathrm{MC14} \\ \mathrm{MC15} \\ \mathrm{MC16} \\ \mathrm{MC17} \\ \mathrm{MC18} \\ \mathrm{MC19} \\ \mathrm{MC20} \\ \mathrm{MC21} \\ \mathrm{MC22} \\ \mathrm{MC23} \\ \mathrm{MC24} \end{bmatrix} = \begin{bmatrix}
f1,f2,21,22 & f1,f4,21,24 & 0 & 3,7,6,23,22,24,f6,f7,f2,f3,f4 & f1,f2,f4 & f1,9,13,16,f13,f16,f2,f4,f10,f12,f9,18,17,20,f17 \\
0 & 21,23,24,4,7,8,f1,f3,f7,f8 & f2,21,22,f1 & f2,22,23,f3 & f2,f8,f1,f3 & f2,10,f10,14,13,f13,f14,f9,f11,f1,f3,18,17,20,f17 \\
f3,f6,f2,23,22 & f3,f4,23,24 & f2,f4,1,f1,5,8,f5,f8,22,24,21 & 0 & f3,f2,f4 & f3,11,f11,15,f15,14,f14,18,17,20,f17,f2,f4,f10,f12 \\
f1,f3,2,f2,5,f5,6,f6,21,23,22 & 0 & f4,f1,24,21 & f4,f3,24,23 & f4,f1,f3 & f4,f3,f1,12,f12,f15,15,f16,16,f11,f9,18,17,20,f17 \\
f1,22 & f1,17,18,19,21,24,4,f4,8,f8,2,f2,22 & 21,f2 & 1,f1,19,18,17,f2,22,6,f6,3,f3,23,21 & f1,f2,21,22 & f1,f2,21,22,13,f13,f9,f10,9,10 \\
f3,22 & 2,f2,22,f3,23,4,f4,24,7,f7,19,18,17 & 19,18,17,23,22,21,1,f1,f2,5,f5,f3 & f2,23 & f2,f3,22,23 & f2,f3,22,23,14,f14,11,f11,10,f10 \\
4,f4,24,f3,23,6,f6,2,f2,22,19,18,17 & f3,24 & 19,18,17,24,21,23,3,f3,f4,1,f1,8,f8 & f4,23 & f3,f4,23,24 & f3,f4,23,24,12,f12,11,f11,15,f15 \\
4,f4,24,f1,21,5,f5,2,f2,19,18,17,22 & f1,24 & f4,21 & 1,f1,21,f4,24,7,f7,3,f3,23,19,18,17 & f4,f1,24,21 & f1,f4,21,24,16,f16,9,f9,12,f12 \\
f9,f10,22 & f9,f12,24 & 0 & f17,f10,f12,11,f11,14,f14,15,f15,22,23,24 & f1,1,5,8,f5,f8,9,f2,f4,f10,f12,f9,18 & f9,f10,f12 \\
21 & 23,24,21,f17,f11,f9,15,f15,16,f16,12,f12 & f10,f9,21 & f10,f11,23 & f2,2,5,6,f10,f5,f6,f9,f11,f1,f3,19,18,20,f17 & f10,f11,f9 \\
f11,f10,22 & f11,f12,24 & 23,f17,12,f12,f10,9,f9,13,f13,16,f16,22,21,24 & 0 & f3,3,6,f6,7,f7,f11,19,18,17,20,f17,f2,f4,f10,f12 & f11,f12,f10 \\
f12,f9,21,f11,23,14,f14,13,f13,10,f10,22,f17 & 24 & f12,14,21,f9 & f11,12,23 & f4,4,7,f7,8,f8,f3,f1,f12,f11,f9,19,18,20,f17 & f12,f11,f9 \\
22,f9 & f9,21,24,12,f12,16,f16,10,f10,22 & 21,f10 & 9,f9,f10,22,14,f14,11,f11,23,21 & 1,f1,2,f2,21,22,13,f9,f10 & f9,f10,21,22 \\
f11,22 & 10,f10,22,f11,23,12,f12,24,15,f15 & 23,22,21,9,f9,f10,13,f13,f11 & f10,23 & 2,3,f2,f3,22,23,14,f11,f10 & f10,f11,22,23 \\
12,f12,24,f11,23,14,f14,10,f10,22 & f11,24 & 24,21,23,11,f11,f12,9,f9,16,f16 & f12,23 & 3,4,f3,f4,23,24,15,f12,f11 & f11,f12,23,24 \\
12,f12,24,f9,21,13,f13,10,f10,22 & f9,24,f15 & f12,21 & 9,f9,21,f12,24,15,f15,11,f11,23 & 1,f1,4,f4,21,24,16,f9,f12 & f12,f9,24,21 \\
13,f13,14,f14,f10,f11,f9,22 & 15,16,f15,f16,f12,24,f9,f11 & 13,16,f13,f16,f9,21,f10,f12 & f11,15,f15,14,f14,f10,f12,23 & 19,1,2,3,4,f1,f2,f3,f4 & f9,f10,f11,f12,20,f17,21,22,23,24 \\
10,13,f13,14,f14,f10,f11,f9,2,f2,5,f5,f1,6,f6,f3,22 & 24,12,f12,15,f15,16,f16,11,f11,9,f9,4,f4,7,f7,8,f8,f3,f1 & 9,f9,13,f13,16,f16,21,1,f1,5,f5,8,f8,f4,f2,f10,f12 & 11,f11,14,f14,15,f15,7,f7,6,f6,3,f3,f4,f2,23,f12,f10 & 1,2,3,4,f1,f2,f3,f4 & 9,10,11,12,f9,f10,f11,f12,20,f17,21,22,23,24 \\
f1,f3,6,f6,5,f5,f2,22,1,4,f4,3 & f4,7,f7,8,f8,f3,f1,24,1,3,2,f2 & f1,2,f2,3,f3,4,f4,5,f5,8,f8,21 & 1,f1,2,f2,f3,4,f4,6,f6,7,f7,23 & f1,f2,f3,f4 & 9,10,11,12,f9,f10,f11,f12,20,f17,21,22,23,24,19 \\
13,f13,14,f14,f10,f11,f9,22,f17 & f12,16,f16,15,f15,f11,f9,24,f17 & f9,21,13,f13,16,f16,f10,f12,f17 & f11,14,f14,15,f15,f12,f10,f17,23 & f9,f10,f11,f12,17,18,19,1,2,3,4,f1,f2,f3,f4 & 0 \\
f2,5,f5,13,f13 & 4,f4,8,f8,16,f16 & f1,f9 & 17,18,19,24,22,2,4,f2,f4,3,11,23,10,12,f10,f12,f11,f1 & f1,5,f5,8,f8 & f9,13,f13,16,f16 \\
f2,f10 & 17,18,19,3,1,f3,f1,4,f4,12,f12 & 1,f1,21,5,f5,13,f13 & 3,f3,f6,6,23,14,f14 & f2,5,f5,6,f6 & f10,13,f13,14,f14 \\
6,f6,2,f2,10,f10,14,f14 & f11,f3,f7,7,15,f15 & 4,f4,12,f12,2,f2,10,f10,22,24,21,17,18,19,1,f1 & f3,f11 & f3,7,f7,6,f6 & f11,14,f14,15,f15 \\
17,18,19,1,f1,9,f9,11,f11,3,f3,10,f10,22,2,f2 & f4,f12 & 1,f1,9,f9,8,f8,16,f16 & 15,f15,7,f7,f12,f4 & f4,8,f8,7,f7 & f12,15,f15,16,f16
\end{bmatrix}$$