Master's Thesis

Mitigating Thermal Bridges in Renovation: Strategies and Environmental Impacts

Rojvan Amin

Building Energy Design 2025

Master's Degree, 4th Semester Project
The Faculty of Engineering and Science Department of the Built Environment

STUDENT REPORT
AALBORG UNIVERSITY

Department of the Built Environment
Aalborg University
http://www.aau.dk

AALBORG UNIVERSITY
STUDENT REPORT

Title:
Mitigating Thermal Bridges in Renovation: Strategies and Environmental Impacts

Project Period:
October 2024 – May 2025

Participant(s):
Rojvan Amin

Supervisor(s):
Endrit Hoxha
Rasmus Lund Jensen

Copies: 1

Page Numbers: 115

Date of Completion:
May 21, 2025

Abstract:

Thermal bridges significantly contribute to heat loss in buildings, increasing energy demand and environmental impact. This study evaluates the effectiveness of thermal bridge mitigation strategies in renovation projects across three building types: a single-family house (new building for comparison), a multi-storey residential building, and a kindergarten. Using **HT-flux simulations, transmission loss calculations, and life cycle assessment (LCA) via LCAbyg**, the research quantifies the impact of thermal bridges and assesses the trade-offs between insulation improvements and embodied carbon emissions.
Findings show that **thermal bridges account for 30–52% of total transmission losses**, excluding point losses, which could further increase this percentage. Implementing optimized solutions reduces **global warming potential (GWP) by 3.96–10.95%**, demonstrating that thermal bridge optimization is a viable strategy for sustainable renovations. While additional insulation reduces operational energy demand, it slightly increases embodied emissions. However, the **net impact remains positive**, supporting the integration of thermal bridge mitigation in energy-efficient renovations. The study provides **practical recommendations** for balancing building performance and environmental sustainability.

Contents

Preface

This report is the culmination of my 4th semester master's thesis project in the Building Energy Design MSc. program at Aalborg University. It investigates the impact of thermal bridges in buildings and evaluates mitigation strategies to improve energy efficiency and sustainability. By integrating numerical simulations, standardized calculations, and life cycle assessment, the study analyzes heat loss and environmental impact, providing insights into optimizing thermal bridge mitigation while balancing energy performance and sustainability.

The project was supervised by Endrit Hoxha and Rasmus Lund Jensen, whose guidance and support have been invaluable. I sincerely appreciate their constructive feedback, which has greatly contributed to this study. Furthermore, I extend my gratitude to Aalborg University for providing the necessary resources and to the HTflux team for granting access to their software under a student license, which was essential for the simulations.

Aalborg University, May 21, 2025

Rojvan Amin
<ramin22@student.aau.dk>

Abbreviation and symbols	**Full Form**	**Unit**
A	Area	m^2
d	Thickness	m
l	Length	m
R	Thermal resistance	$m^2.K/W$
U	Thermal transmittance	$W/(m^2.K)$
θ	Temperature	°C
λ	Design thermal conductivity	W/(m.K)
Φ	Heat flow rate	W
Ψ	Linear thermal transmittance	W/m.K
χ	Point thermal transmittance	W/K
DPM	Damp proof membrane	-
$EPDs$	Environmental Product Declarations	-
SFH	Single Family House	-
kWh	Energy consumption	kWh
GWP	Global Warming Potential	kg CO_2-eq
LCA	Life Cycle Assessment	-
LCC	Life Cycle Costing	-
$HTflux$	Heat Transfer Simulation Software	-
$BE18$	Building Energy Calculation Tool	-
$BR18$	Danish Building Regulation 2018	-
$LCAbyg$	Environmental Impact Assessment Tool	-
ΔT	Temperature difference	K
T_i	Indoor temperature	°C
T_e	Outdoor temperature	°C
E	Total energy demand	kWh/m^2
Φ_{total}	Total heat flux through the analyzed junction	W
A_1-A_3	Raw material extraction, transportation, and manufacturing	-
B_4	Emissions from material replacements	-
C_3	Waste processing before disposal	-
C_4	Final disposal of materials	-
D	Benefits or burdens from material reuse, recycling, or energy recovery	-
XPS	Extruded polystyrene insulation	-
ISO	International Organization for Standardization	-
DS	Danish Standards	-
EN	European Norm (European Standard)	-
SBI	Danish Building Research Institute	-

Table 1: List of Abbreviations and Symbols

Chapter 1

Introduction

1.1 Introduction

Buildings account for approximately 30% of global energy consumption and 26% of energy-related CO_2 emissions, making them a significant contributor to climate change. As energy demands continue to rise, improving building efficiency through sustainable renovation has become crucial for reducing carbon footprints and meeting global climate goals. However, one of the main challenges in achieving energy-efficient buildings is the presence of thermal bridges, which can significantly undermine insulation performance and increase overall energy use [1].

Thermal bridges occur at junctions between walls, floors, roofs, and around windows and doors, where insulation continuity is disrupted. These weak points allow excessive heat transfer, leading to higher heating demands in winter and increased cooling loads in summer. In some cases, thermal bridges can account for up to 30% of total heat loss and increase cooling loads by 20% [2]. This inefficiency not only raises energy consumption but also affects occupant comfort and increases operational costs [16].

In addition to energy inefficiencies, thermal bridges can cause secondary issues such as condensation and mold formation. These problems may compromise the structural integrity of buildings and negatively affect indoor air quality, posing risks to occupant health. Addressing these challenges requires a targeted approach, focusing on insulation strategies that effectively minimize heat transfer at critical junctions in the building envelope [6, 9, 32].

Several methods exist to mitigate thermal bridges, including enhanced insulation, improved construction detailing, and thermally broken materials. However, while these strategies can reduce heat transfer, they often result in increased material usage and embodied carbon emissions. Existing research has primarily focused on the thermal performance benefits of mitigation strategies, yet fewer studies have comprehensively analyzed the trade-offs between operational energy savings and environmental impact using Life Cycle Assessment (LCA). Understanding these trade-offs is essential for developing renovation strategies that are both energy-efficient and environmentally sustainable [1, 5, 28].

This study investigates the impact of thermal bridges on building performance and evaluates the effectiveness of mitigation strategies through energy and environmental analysis. By assessing transmission heat losses using BE18 and HTflux simulations and evaluating sustainability aspects through LCAbyg, this research aims to provide insights into optimizing building envelopes for lower energy consumption and reduced global warming potential (GWP).

1.2 Purpose

This study investigates strategies for mitigating thermal bridges in buildings, with a focus on balancing energy efficiency and environmental sustainability. Thermal bridges contribute to significant heat loss, and while mitigation measures such as improved insulation and advanced construction techniques enhance energy performance, they can also lead to increased material use and embodied carbon emissions.

To address this challenge, the study examines various insulation methods and renovation strategies, assessing their energy savings and environmental trade-offs. By analyzing material production, installation processes, and life cycle impacts, this research provides a comprehensive evaluation of sustainable thermal bridge mitigation. The goal is to identify practical solutions that enhance building thermal performance while minimizing environmental impact, ensuring that mitigation strategies align with sustainable construction practices.

1.3 State of the art

Thermal bridges have been extensively studied due to their impact on building energy efficiency and thermal performance. This section provides an overview of the classification of thermal bridges, their effects on heat loss, and current methodologies for evaluating and mitigating their impact. By reviewing existing research and standards, this section establishes the foundation for assessing thermal bridges in renovation strategies.

1.3.1 Classification of thermal bridges

Thermal bridges are classified based on their geometry, material properties, or location within a building structure. Understanding these classifications is essential for evaluating their impact on energy efficiency and selecting appropriate mitigation strategies.

1. Geometrical Thermal Bridges: These occur due to discontinuities in a building's shape, such as corners, junctions between walls and floors, and roof intersections. Differences in surface area exposure result in increased heat transfer.

2. Constructional (Material-Related) Thermal Bridges: These arise from variations in material properties, where materials with higher thermal conductivity—such as metal fasteners, reinforced concrete, or structural steel—create localized areas of increased heat loss.

3. Repetitive Thermal Bridges: These occur due to repeated interruptions in the insulation layer, such as timber wall studs, wall ties, or balcony supports. While individually small, their cumulative effect can significantly reduce the thermal resistance of the building envelope.

4. Structural Thermal Bridges: These result from design elements that penetrate the insulation layer, such as cantilevered balconies, window frames, and structural connection points. They create direct pathways for heat loss, making them critical targets for mitigation.

Thermal bridges can also be classified based on their **heat transfer behavior**, distinguishing between **linear and point thermal bridges**:

- **Linear Thermal Bridges:** These occur along extended surfaces, such as wall-to-floor or roof junctions, and are quantified using linear thermal transmittance (ψ-value). Examples include window-to-wall connections and slab edges. The heat loss is calculated as:
$$\phi_{\text{linear}} = \psi \cdot l \cdot (\theta_i - \theta_e)$$
where ψ is the linear thermal transmittance ($W/m.K$), l is the length of the thermal bridge (m), θ_i is the indoor temperature, and θ_e is the outdoor temperature. Standard tables in DS418 provide typical ψ-values, though complex junctions may require numerical simulation [20, 21, 23, 31].
- **Point Thermal Bridges:** These occur at discrete points, such as structural penetrations, anchors, or fasteners, and are represented by the point thermal transmittance (χ-value). The heat loss is calculated as:
$$\phi_{\text{point}} = \chi \cdot (\theta_i - \theta_e)$$
where χ is the point thermal transmittance (W/K), and θ_i and θ_e are the indoor and outdoor temperatures, respectively [11, 21].

1.3.2 Importance and consequences

As insulation standards improve, thermal bridges remain one of the most significant sources of heat loss, contributing between 20–30% of total energy losses in well-insulated homes. Their relative impact increases as overall insulation levels improve, making them a growing concern in modern construction. Beyond energy loss, thermal bridges create localized cold spots, increasing the risk of condensation and mold, which can damage materials and negatively affect indoor air quality [20, 24].

1.3.3 Assessment and standards

Accurate assessment of thermal bridges is critical for compliance with energy performance standards such as ISO 10211 [21], ISO 14683 [22], and DS418 [31]. These standards define calculation methods for thermal bridge heat losses and ensure reliable energy performance evaluations. Analytical methods for assessing thermal bridges include:

- **Simplified Calculations:** These rely on tabulated ψ-values for common junctions, as specified in standards such as DS418. While these methods provide a quick estimate of heat loss, they often assume idealized conditions and may underestimate the impact of thermal bridges [31].

- **Numerical Simulations:** More advanced methods use software tools such as THERM (2D analysis), ANSYS (3D finite element analysis), and HTflux to model heat transfer through complex junctions. HTflux, in particular, follows ISO 10211 for calculating linear thermal transmittance (ψ-values) and incorporates surface temperature analysis to assess mold and condensation risks, aligning with ISO 13788. These models account for detailed material properties and geometric configurations, providing more accurate results than simplified methods [11, 18, 24].

Additional tools such as BE18 and LCAbyg are used for broader energy and environmental assessments. These tools are discussed in more detail in the methodology section.

1.3.4 Mitigation strategies

Effective mitigation strategies aim to reduce thermal bridging through design improvements and material selection, ensuring better energy performance and thermal comfort. These strategies can be categorized into insulation continuity, thermal break integration, and enhanced detailing:

- **Ensuring continuity of insulation layers:** Minimizing interruptions in insulation, especially at critical areas such as corners, junctions, roof-wall connections, and floor edges, helps reduce thermal bridging effects [23].
- **Incorporating thermal breaks:** Using insulated balcony connectors, thermally efficient lintels, or other structural break solutions reduces heat transfer at penetrations and connections [20].
- **Applying exterior or interior insulation systems:** Continuous insulation layers, sandwich panels, or interior insulation can effectively minimize heat loss. However, interior insulation requires careful moisture control to prevent condensation issues, particularly in heritage buildings where external insulation is restricted [23, 24].
- **Optimizing construction detailing:** Special attention to windows, doors, balconies, and foundation junctions is essential to mitigate both linear and point thermal bridges. Proper design detailing reduces unintended energy losses [23].

These strategies are particularly crucial in renovation projects, where structural limitations and budget constraints often complicate implementation. Detailed numerical simulations provide precise thermal performance evaluations, helping optimize mitigation measures for both new and existing buildings[17, 23].

1.3.5 Challenges in renovations

Renovation projects often face challenges due to older construction methods, material limitations, and restricted access to critical junctions. Many older buildings feature wooden beam floors or uninsulated masonry walls, limiting the use of external insulation due to structural constraints. In such cases, interior insulation becomes the only viable option, but it increases the risk of condensation and moisture accumulation, particularly at beam ends and masonry interfaces.

For more recent buildings, fewer structural restrictions exist, but economic feasibility and construction detailing remain key factors in selecting cost-effective thermal bridging mitigation measures. Regardless of building age, balancing energy efficiency, cost constraints, and potential structural impacts remains a major challenge in renovations. Numerical simulations and detailed assessments are essential for identifying the most effective and feasible solutions [23, 24].

1.4 Study cases

This study examines three distinct building types selected as reference cases to evaluate the effectiveness of thermal bridge mitigation strategies. These buildings represent a range of construction methods, architectural designs, and energy performance levels, providing a diverse basis for analysis.

For each case, key thermal bridges were identified and analyzed, focusing on those with the most significant impact on heat loss. Figures of the selected buildings illustrate the primary thermal bridges considered in this study, ensuring that the analysis addresses the most critical factors influencing building performance.

1.4.1 Case 1: single–family house

The first case study examines a single-family house in Aalborg, Denmark, built in 2023 to meet BR15 energy requirements. The house has a total floor area of 181 m^2, consisting of a 90.5 m^2 ground floor and a 90,5 m^2 first floor. It is designed as an energy-efficient structure with a specific heat capacity of 80 $Wh/K{\cdot}m^2$, contributing to improved thermal stability.

The building's annual energy consumption is approximately 44.4 kWh/m^2, and an airtightness test confirmed a result of 0.8 l/s per m^2, meeting BR15 standards [14].

The total design heat loss, excluding windows and doors, is 3.8 W/m^2, which is significantly below the threshold of 5.0 W/m^2. The building achieves an estimated annual CO_2 emission of 1.58 tons, aligning with Denmark's climate goals, and holds an A2015 energy label, reinforcing its energy-efficient and low-emission profile [15].

Construction Details and Thermal Performance

- **Total external area: 363 m^2**
- **Lightweight Outer Wall:** Cement-bonded particle boards with a PUR insulation core, U-value: **0.12 $W/m^2.K$** area: 171 m^2.
- **Sloping Roof:** DC elements with PUR insulation, U-value: **0.08 $W/m^2.K$** area: 120 m^2.
- **Terrain Deck:** Polystyrene insulation and reinforced concrete, U-value: **0.08 $W/m^2.K$** area: 72 m^2..

The foundation system integrates concrete slabs with high-performance insulation, significantly reducing thermal losses. The roof construction follows a layered insulation strategy, incorporating PUR insulation, mineral wool, and ventilated battens to enhance thermal efficiency.

This well-insulated envelope ensures compliance with strict energy regulations, minimizing heat loss and improving indoor comfort.

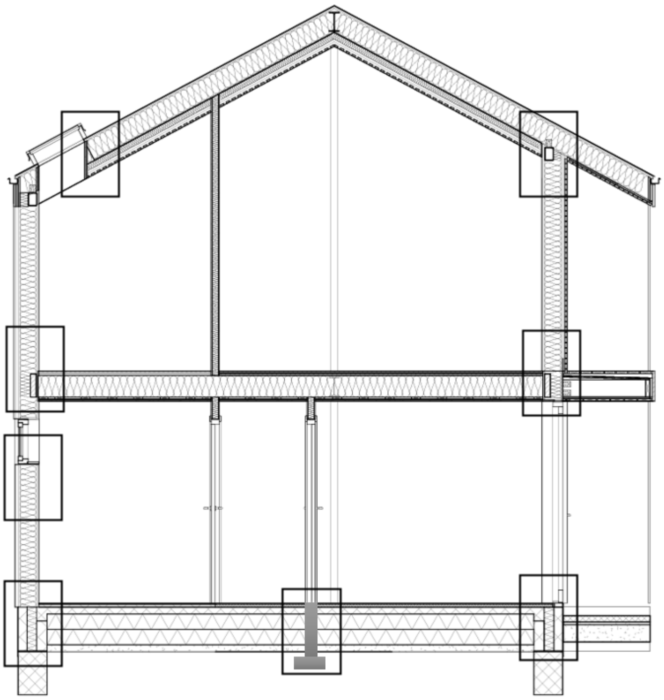


Figure 1.1: Study Case 1 - Single-Family House

1.4.2 Case 2: multi–storey residential building (Magisterparken)

The second case study examines Magisterparken, a large multi-storey residential complex in Aalborg, Denmark, originally constructed in the 1960s and renovated in 2012 to improve energy efficiency. Before renovation, the building experienced significant heat loss due to poor insulation. Following the upgrades, it achieved an energy label C, indicating potential for further improvements.

The renovation measures included adding 250 mm of mineral wool to the roof and 200–225 mm of insulation to the external walls, significantly reducing heat transmission. The building's current energy demand is approximately 75.4 kWh/m^2 per year, with a heat capacity of 120 Wh/K·m^2 [26].

The total heated floor area of the building is **1400 m²**, with no heated basement. The total developed area is **446.8 m²**.

Construction Details and Thermal Performance

- **Total external area: 1755.8 m²**
- **External Walls:** U-value: **0.158 W/m².K**, area: 706.05 m².

- **Roof:** U-value: **0.13 W/m².K**, area: 468.53 m².
- **Ground Floor:** U-value: **0.38 W/m².K**, area: 468.53 m².
- **Staircase Walls:** U-value: **0.38 W/m².K**, area: 112.86 m².

The renovation included improved insulation on all external walls and the roof to enhance thermal efficiency. The roof received additional insulation, reducing heat transfer and ensuring better energy performance. The staircase walls and ground floor have relatively higher U-values; however, they are not included in the heated area. These improvements contribute to an overall reduction in energy demand and carbon emissions, making the building more sustainable while improving indoor comfort.

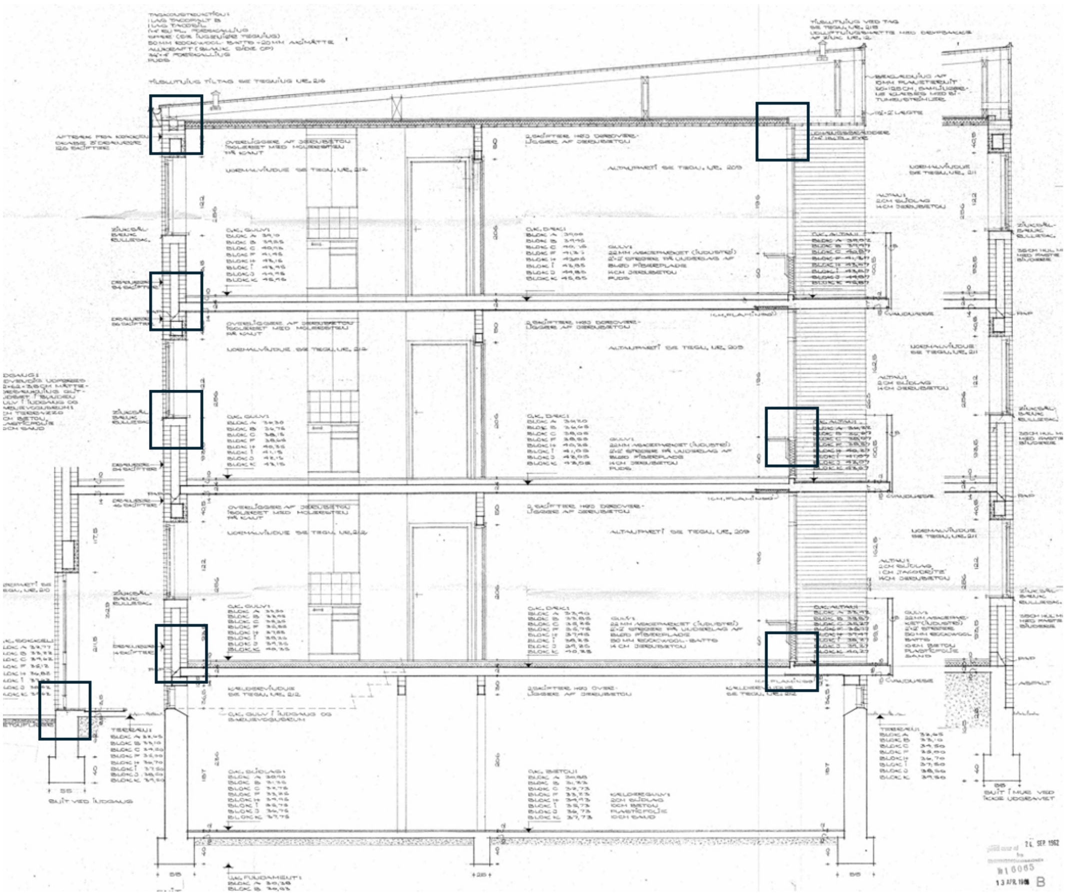


Figure 1.2: Study Case 2 - Multi-Storey Residential Building

1.4.3 Case 3: kindergarten building (Sønderholm Børnehave)

The third case study focuses on Sønderholm Børnehave, a kindergarten located in Nibe, Denmark. The building was constructed in the 1980s and renovated in 2017 to improve energy efficiency. However, no upgrades were made to the construction components.

The kindergarten has a heated floor area of **540 m²** and a heated basement of **60 m²**. The total energy frame is 101 kWh/m^2 per year, meeting the requirements of "Renovation Class 2" in BR18 [13]. The construction consists of bricks and concrete, and the building has a specific heat capacity of 63 Wh/K·m^2 [8].

Construction Details and Thermal Performance

- **Total external area: 1013 m²**
- **Hollow External Wall (35 cm Brick/Layer):** U-value: **0.33 W/m².K**, area: 84 m².
- **Beam of Wood (200 mm Insulation):** U-value: **0.2 W/m².K**, area: 20 m².
- **Facade Element (24 cm Concrete/Concrete):** U-value: **0.69 W/m².K**, area: 17 m².
- **Light Wall Towards Unheated Room (Wood/Timber):** U-value: **0.22 W/m².K**, area: 4 m².
- **Ground Floor (50 mm Mineral Wool):** U-value: **0.26 W/m².K**, area: 235 m².
- **Basement Floor (150 mm LECA):** U-value: **0.41 W/m².K**, area: 145 m².
- **Basement External Wall (0-1m Depth):** U-value: **0.39 W/m².K**, area: 31 m².
- **Basement External Wall (1-2m Depth):** U-value: **0.31 W/m².K**, area: 31 m².
- **Basement External Wall (Over 2m - 300 mm):** U-value: **0.22 W/m².K**, area: 25 m².
- **Basement External Wall Against Soil Unheated Room:** U-value: **0.22 W/m².K**, area: 30 m².
- **Attic Space Roof(100-200 mm Insulation):** U-value: **0.35 W/m².K**, area: 159 m².
- **Attic Space Roof (Alternative, 100-200 mm Insulation):** U-value: **0.18 W/m².K**, area: 232 m².

The construction features a mix of brick, concrete, and insulation elements to ensure thermal performance. Despite meeting energy efficiency standards, the relatively high U-value of some elements indicates potential areas for further improvement.

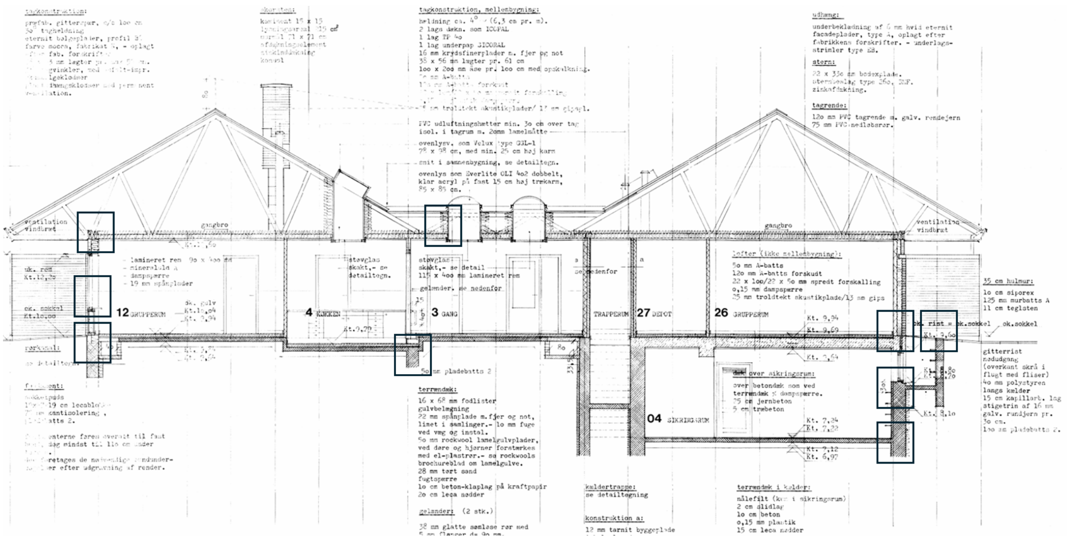


Figure 1.3: Study Case 3 - Kindergarten Building

1.5 Problem statement

This study examines the environmental and energy impacts of thermal bridges in buildings, with a focus on identifying optimal design and insulation strategies to minimize heat loss and reduce global warming potential (GWP). The research evaluates various insulation materials and construction techniques in both renovation and new construction scenarios. Through simulations and real-world case studies, this study aims to address the following key questions:

- **What proportion of total heat loss can be attributed to thermal bridges?**
- **To what extent can energy consumption and environmental impact be reduced through effective insulation?**
- **Which materials are most effective in mitigating thermal bridge effects?**
- **How can the trade-off between reduced heating and cooling energy demand and increased embodied emissions from additional insulation be optimized?**

1.6 Limitations

This study has several limitations:

- **Point thermal losses:** Point thermal losses are excluded due to the extensive computational time required for 3D simulations. Although HTflux supports 3D modeling, a 2D approach was selected to balance accuracy and computational efficiency [18].

- **Wall corners:** Wall corners, including outward and inward connections, are excluded from the thermal bridge analysis. According to DS418, corner connections may be disregarded if their impact on heat loss is negligible. Outward corners with uninterrupted insulation typically exhibit negative linear thermal transmittance, reducing heat loss, while inward corners generally contribute to positive linear losses. These effects tend to balance each other out, simplifying the analysis in compliance with DS418 [31].
- **Moisture analysis:** While thermal bridges can lead to secondary issues such as condensation and mold formation, this study focuses solely on thermal performance.
- **Fire and moisture safety considerations:** Fire protection and moisture control have not been assessed in this study. Any implementation of thermal bridge mitigation strategies should be reviewed by specialists in fire safety and perform building moisture analysis to ensure compliance with regulations.
- **Life Cycle Assessment (LCA):** This study does not compare insulation materials based on their environmental impact. Instead, it evaluates the overall embodied environmental impact of the building after implementing thermal bridge mitigation strategies. Materials are sourced from Danish Environmental Product Declarations (EPDs), ensuring standardized data. However, no material ranking is conducted, as the focus remains on assessing the building's overall sustainability rather than the individual performance of materials.

Chapter 2

Methods

2.1 Methodology

This study follows a structured methodology integrating numerical simulations, standard-based calculations, and life cycle assessment (LCA) to evaluate the impact of thermal bridges on building performance. The methodology consists of six key steps:

1. Define case study buildings and gather their geometric and material specifications.
2. Identify thermal bridges and analyze heat transfer using HTflux.
3. Perform BE18 calculations to estimate total energy demand, transmission losses, and regulatory compliance.
4. Compare standardized DS418 linear loss values with simulation-based results.
5. Optimize thermal bridge mitigation strategies and assess improvements.
6. Evaluate environmental impact using LCAbyg to quantify embodied and operational carbon emissions.

This integrated approach ensures a comprehensive assessment of both energy efficiency and environmental trade-offs.

2.1.1 Tools and standards used

To evaluate thermal bridge effects and the environmental impact of mitigation strategies, this study employs three primary tools: HTflux, BE18, and LCAbyg. Table 2.1 summarizes their functions and compliance with relevant standards.

Table 2.1: Overview of Tools and Standards Used in This Study.

Tool	**Function**	**Standard Used**
HTflux	Thermal bridge simulations	ISO 10211
BE18	Total energy demand, transmission loss, and compliance verification	DS418
LCAbyg	Life cycle environmental impact assessment	EN 15804

Each of these tools plays a distinct role in the study, contributing to different aspects of the thermal and environmental assessment.

2.1.2 HTflux: thermal bridge simulations

HTflux was used to refine the calculation of linear thermal transmittance (Ψ-values), which quantify the heat loss due to thermal bridges. These calculations comply with ISO 10211, ensuring standardized heat transfer modeling. The simulation process follows these steps:

1. Define the geometric and material properties of each junction.
2. Assign boundary conditions based on indoor and outdoor temperatures as per DS418.
3. Conduct steady-state heat flow simulations to determine the thermal bridge effect.
4. Extract refined Ψ-values and compare them to standard DS418 tabulated values.

Although HTflux supports 3D modeling, this study adopts a 2D approach to balance computational efficiency with accuracy. Point thermal bridges are excluded due to the extensive computational effort required for 3D simulations.

2.1.3 BE18: total energy demand, transmission loss, and regulatory compliance

BE18 was used to estimate the total energy demand of the selected buildings, ensuring compliance with Danish energy regulations. The software evaluates multiple energy-related parameters, including:

1. Total energy demand, including heating, ventilation, and domestic hot water consumption.
2. Transmission heat loss through walls, floors, roofs, and windows, calculated using U-values and heat transfer coefficients determined according to methods outlined in DS418.
3. Ventilation and infiltration losses, considering mechanical ventilation efficiency and air-tightness levels.
4. Internal heat gains from occupants, lighting, and appliances, influencing the net heating demand.
5. Compliance with Danish building energy performance regulations, verifying whether the building meets BR18 or BR15 energy requirements.

BE18 provides a comprehensive energy analysis, serving as a baseline before incorporating refined Ψ-values from HTflux.

2.1.4 LCAbyg: environmental impact assessment

To quantify the environmental footprint of different thermal bridge mitigation strategies, LCAbyg was used. The tool evaluates both embodied and operational carbon emissions, following the EN 15804 standard. The LCA analysis considers:

1. Embodied carbon emissions from insulation materials, structural components, and other construction materials.
2. Operational energy savings due to reduced thermal bridge effects.
3. End-of-life impacts, including recyclability, disposal, and potential reuse of materials.

The amount of thermal bridges considered in the LCA is calculated based on the total length of such junctions in the building design, in accordance with ISO 10211, EN ISO 14683, and DS418. To determine the material quantities associated with these thermal bridges, the total length of each junction type is multiplied by the thicknesses of the involved building elements (e.g., floor slabs, balcony slabs, and walls). This provides the volume of materials contributing to the thermal bridge, which is then used to assess embodied carbon impacts in LCAbyg.

As illustrated in Figure 2.1, the balcony detail in a multi-storey junction represents a typical thermal bridge. The structural elements each have a length of 1000 mm, including the floor, balcony slab, light wall, and brick wall. These dimensions are used to define the global warming potential (GWP) of the thermal bridge as an individual component in the case study.

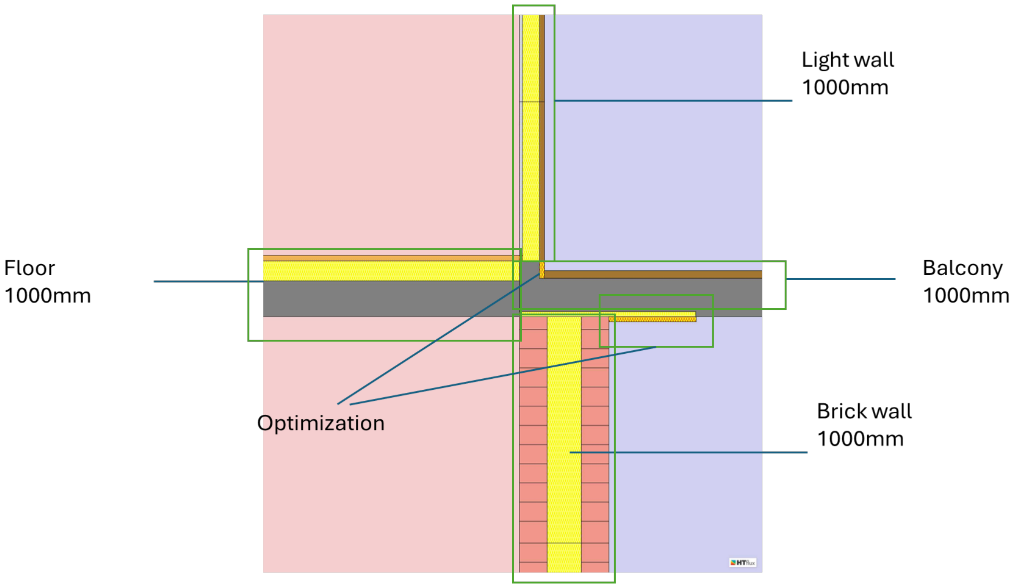


Figure 2.1: LCA – Thermal Bridge Calculation Method – Multi-Storey Building

2.2 Summary of methodology

This study integrates BE18 for total energy requirement calculations, HTflux for thermal bridge simulations, and LCAbyg for environmental assessments. The combined methodology ensures a comprehensive evaluation of both energy performance and environmental sustainability.

1. BE18 provides total energy demand calculations, including heating, ventilation, and transmission losses.
2. HTflux refines thermal bridge calculations in compliance with ISO 10211.
3. LCAbyg evaluates embodied carbon and environmental trade-offs.

This structured approach ensures that thermal bridge mitigation strategies are optimized for both energy efficiency and environmental sustainability.

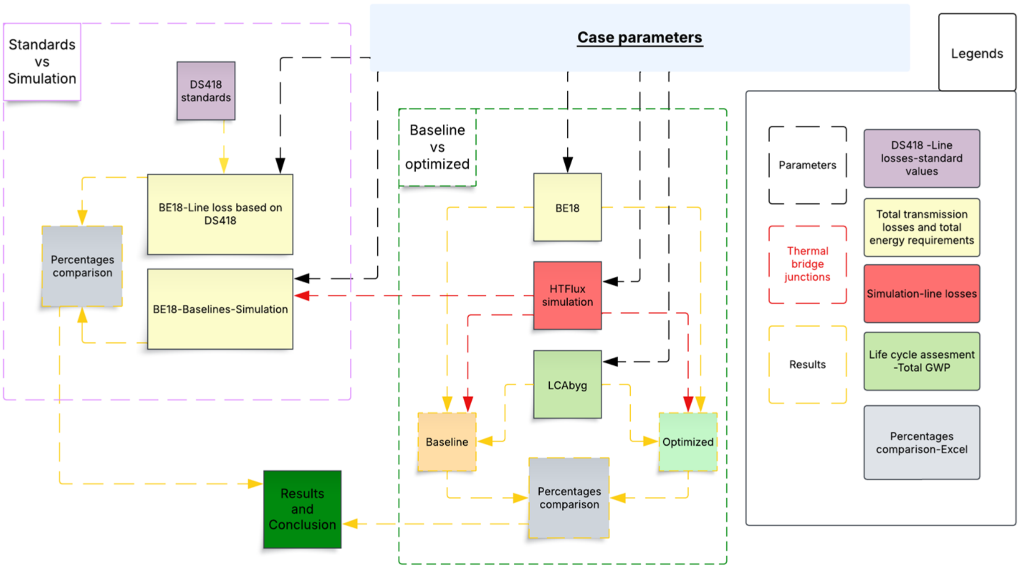


Figure 2.2: Overview of the Methodological Workflow.

Chapter 3

Findings

3.1 Design transmission losses

Total transmission loss for the building cases is calculated using the methods outlined in DS418 and the BE18 tool, which is based on the SBI213 standard, depending on the type of construction. Initially, transmission losses are calculated both with and without windows and doors to determine their influence on overall thermal performance and to allow a focused evaluation of structural thermal bridges. Excluding windows and doors provides a clearer understanding of the relative contribution of thermal bridges to total transmission losses (see Appendix 6) [27, 31].

Baseline scenarios are then established using linear thermal transmittance (values) provided in DS418 tables to represent ideal Transmission loss conditions. Subsequently, thermal bridge simulations are performed using HTflux to evaluate their impact on transmission loss. The results of these simulations, which incorporate material properties, geometric complexities, and junction-specific heat transfer behaviors, are compared to the baseline values to quantify the additional transmission loss identified through the detailed simulation process. This comparison highlights critical areas where improved insulation strategies can be implemented to reduce the overall transmission loss of the building (see Appendix 7) [18].

3.1.1 Design transmission losses based on standards

Figure 3.1 highlights the contribution of design linear losses to total transmission losses in building envelopes, based on DS418 standard table values. The percentages represent the proportion of design linear losses relative to the total transmission losses, excluding doors and windows, as these elements typically dominate overall losses. Transmission losses are presented per square meter, where the total transmission losses are divided by the total external areas.

The data illustrates that design linear losses, even when calculated using standardized values, constitute a significant share of transmission losses. In the single-family house, design linear losses account for 25% of the total losses, while in the multi-storey building, they contribute 32%. In the kindergarten, the percentage is lower but still notable at 10%.

The highest observed percentage among the cases is 32%, demonstrating that design linear losses account for approximately 10–32% of the total transmission losses (7).

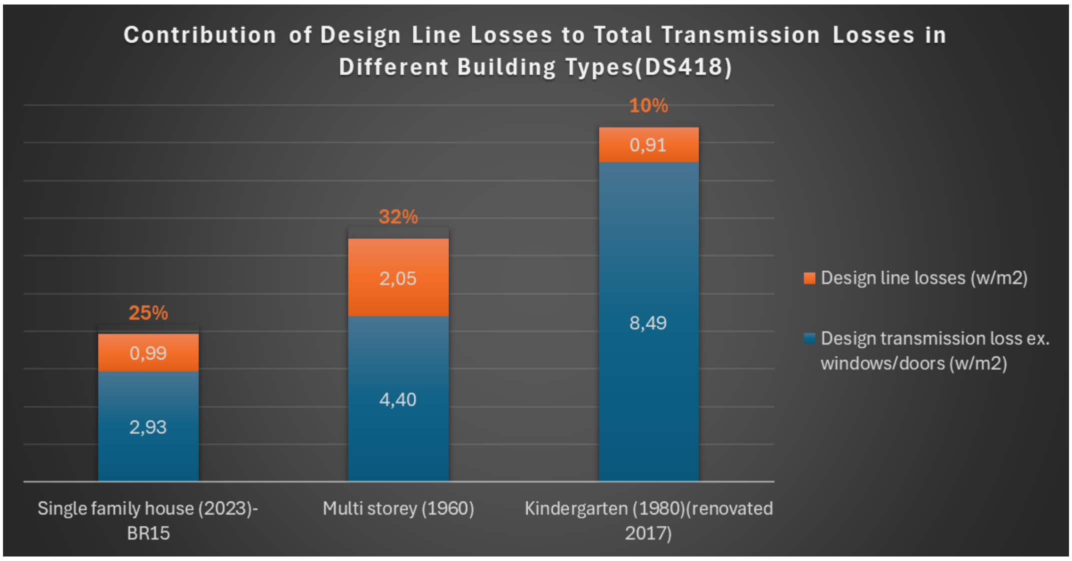


Figure 3.1: Contribution of Line Losses to Total Transmission Losses in Different Building Types (DS418)

3.1.2 Design transmission losses based on simulations(baseline)

Thermal bridges with relative length: Figure 3.2 highlights the percentage of transmission losses caused by thermal bridges, calculated using simulation methods. The results reveal a significantly higher contribution of thermal bridges compared to the values derived from DS418 standards, as illustrated in Figure 3.1.

According to the simulations, the impact of thermal bridges is far more substantial than what is indicated by standardized values. In the single-family house, thermal bridges account for 51% of the total transmission losses, compared to 20% under the DS418 methodology. For the multi-storey building, the contribution reaches 52% in simulations, while the standardized approach estimates only 24%, showing a 2.2-fold increase. Similarly, in the kindergarten case, thermal bridges represent 30% of transmission losses in the simulation results, compared to 9% in the standardized calculations.

The findings reveal that standardized methods often underestimate the role of thermal bridges. Simulations provide more precise results by incorporating factors such as material properties, geometric configurations, and junction-specific heat flow. This enhanced accuracy highlights the importance of simulations in improving energy performance assessments and guiding strategies to effectively reduce heat loss. Details of the simulations and methods used can be found in Appendix (8).

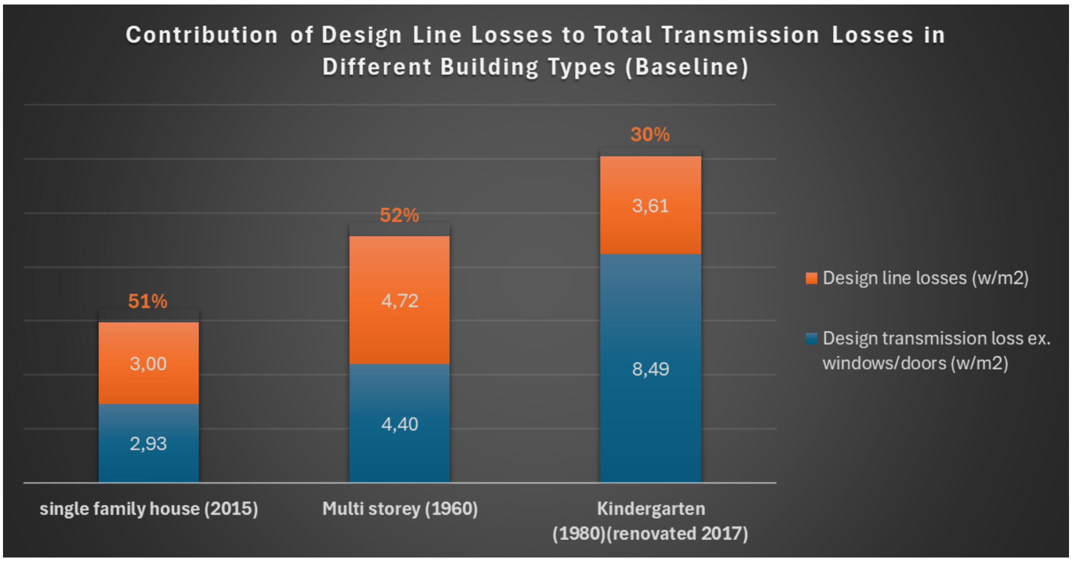


Figure 3.2: Contribution of Line Losses to Total Transmission Losses in Different Building Types (Baseline-Simulations)

3.2 Solutions for thermal bridges

Based on the analysis of 2D simulations that quantified the precise impact of thermal bridges on total transmission heat losses (as detailed in the previous chapter), several targeted solutions were developed and applied to three distinct cases. The primary objective of these interventions was to minimize linear thermal transmittance (Ψ-values) and evaluate the extent to which thermal bridge optimization could improve the energy performance of buildings.

The analysis highlighted the critical role of thermal bridges in overall transmission heat loss, particularly at junctions such as wall-to-roof connections, floor-to-wall interfaces, window and doors installations, and foundation details. Addressing these areas, the proposed solutions were designed to reduce thermal losses while ensuring compatibility with current construction practices. These solutions were informed by an in-depth review of existing literature, including modeling-based studies and practical examples from the field [2],[11],[12],[17],[20],[23],[24],[25],[31].

3.3 Thermal bridges – single–family house

This case represents a newly constructed building. The solutions implemented in this scenario were more straightforward to apply, as the project was assumed to be in the design phase. Unlike renovation projects, no significant challenges related to structural stability or accessibility were encountered. Renovation cases often require addressing thermal bridge connections while overcoming structural constraints and limited access to critical junctions.

Figures (3.3, 3.4) depict cross-sectional simulation results for the single-family house. This method was employed as a strategy to identify the coldest spots within the construction, either by analyzing the temperature distribution throughout the building elements or by assessing the heat flux direction and intensity. These analyses facilitate the optimization of thermal bridge mitigation strategies to enhance overall energy performance.

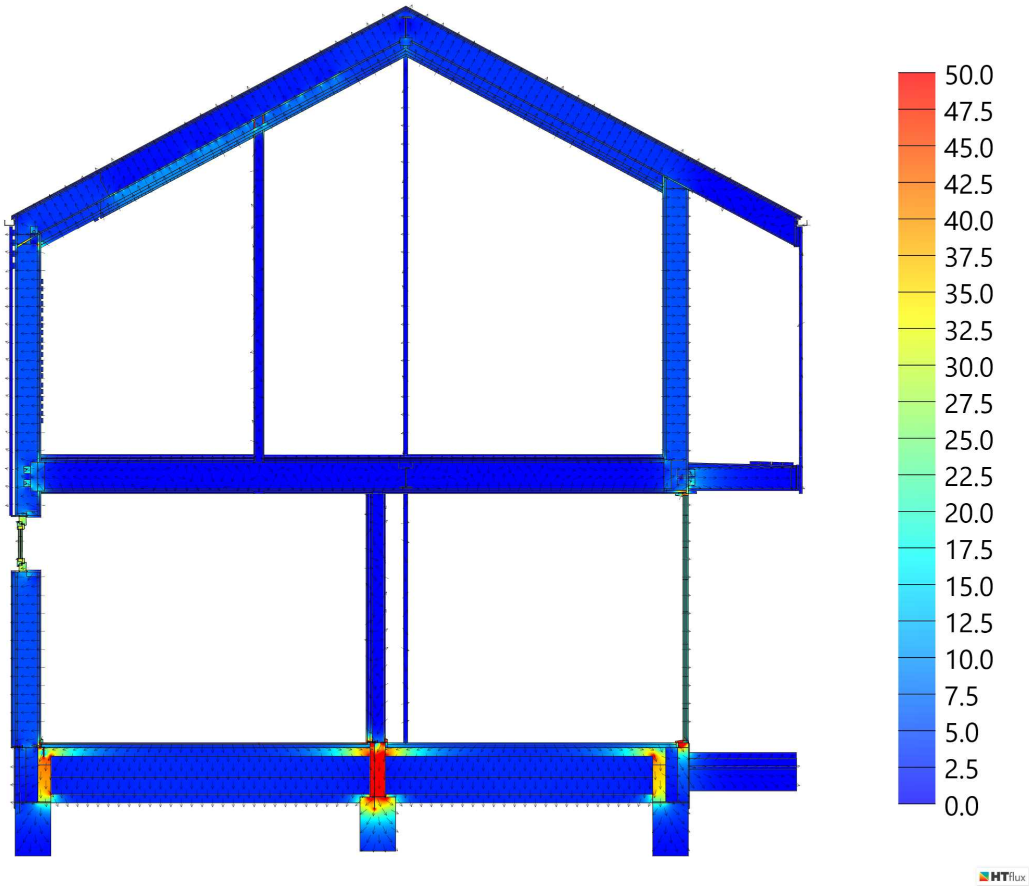


Figure 3.3: Heat Flux Distribution in The Single-Family House Section (W/m²)

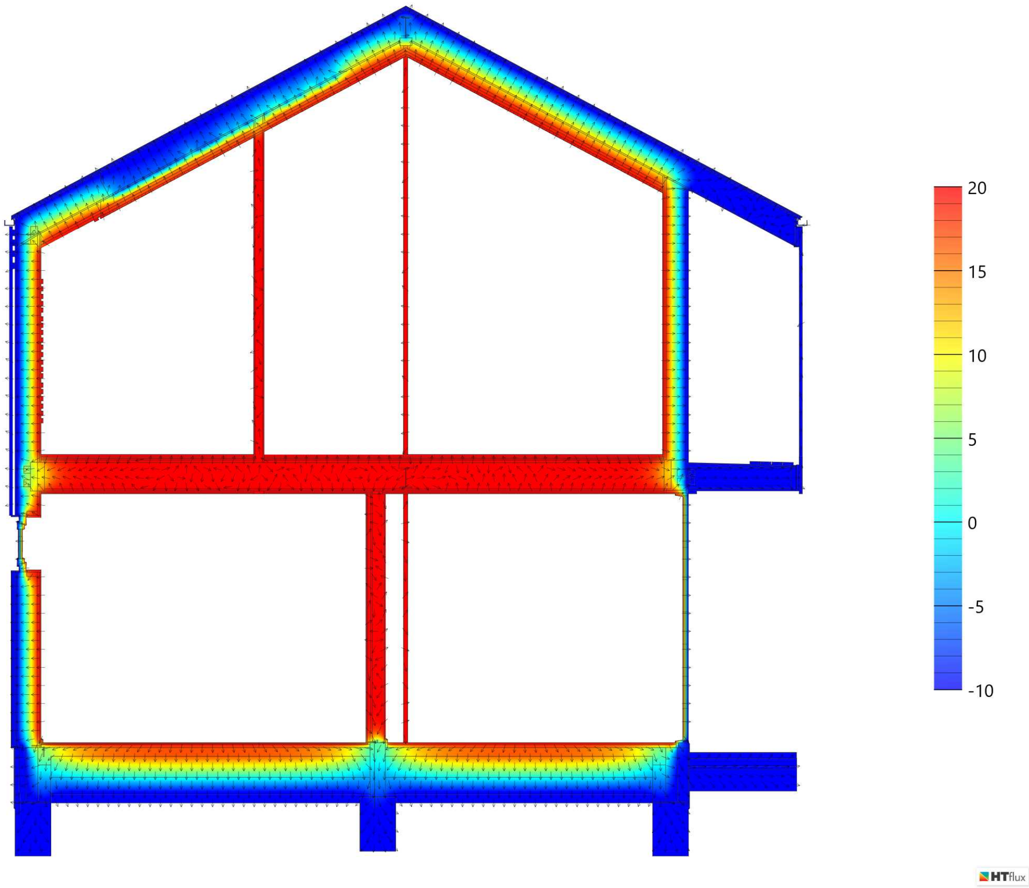
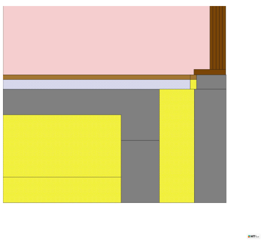
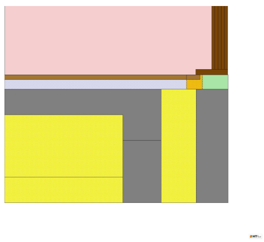
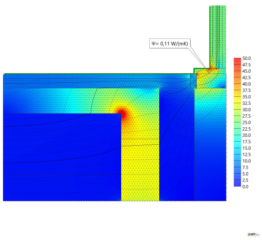
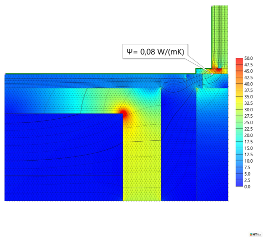
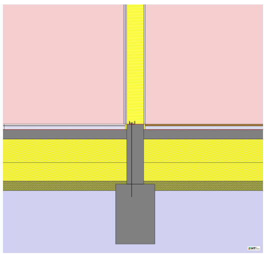
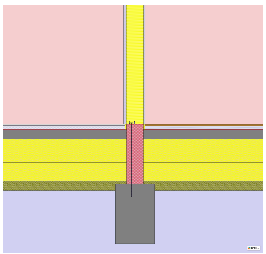
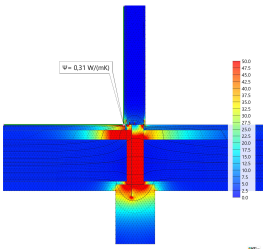
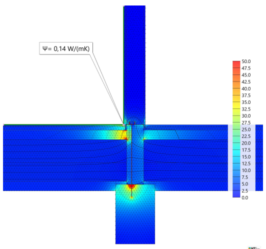
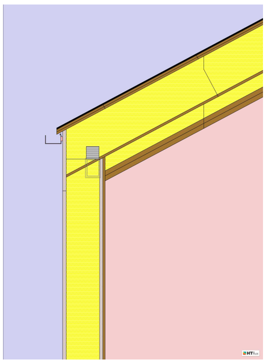
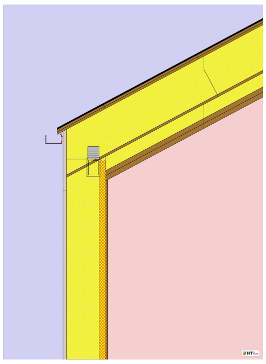
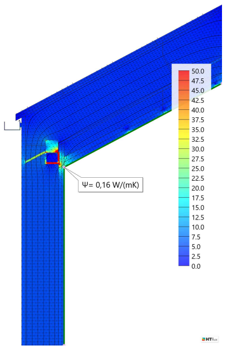
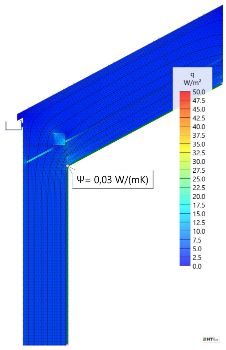
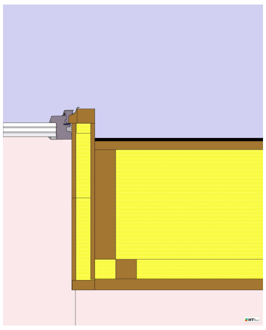
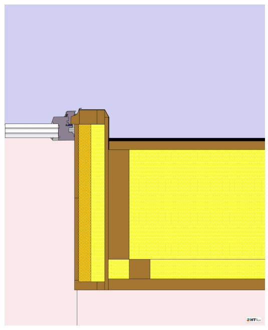
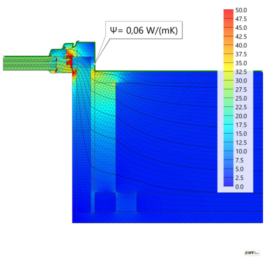
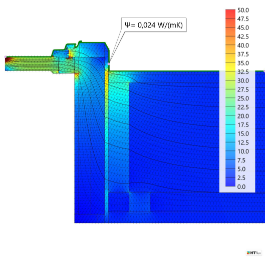


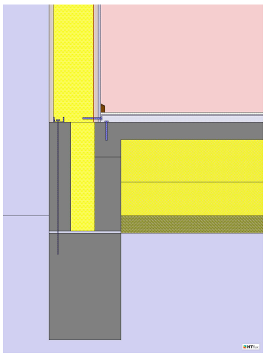
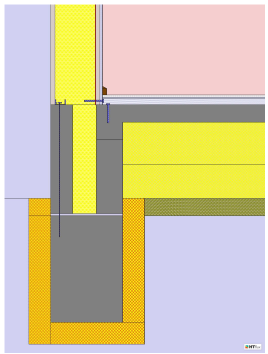
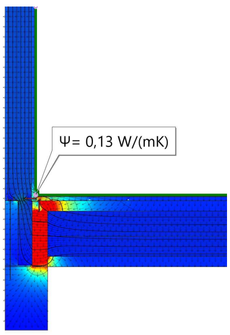
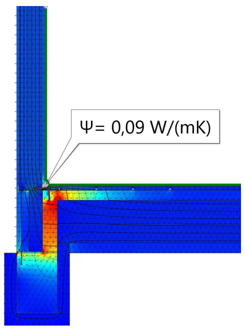
Figure 3.4: Temperature Distribution in The Single-Family House Section (°C)

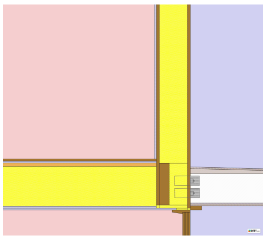
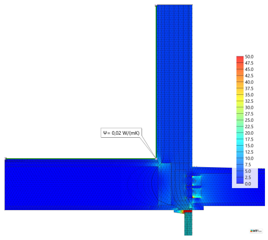
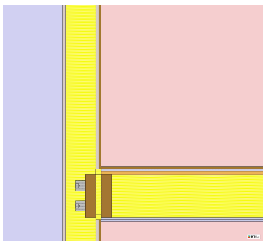
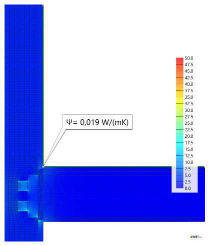
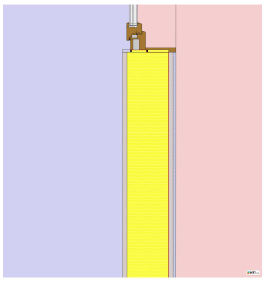
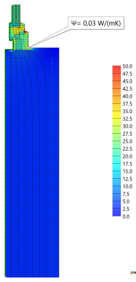
Description	**Baseline**	**Optimized**
Door-foundation-floor junction	In a new construction, there is a small linear thermal transmittance at this junction due to the door frame's contact with the leveling layer, which consists of XPS groove panels.	Increasing the perimeter insulation thickness from 25 mm to 50 mm can enhance the thermal performance of the ground floor. Additionally, incorporating a thermal break, such as ClimaSpec or Armatherm FRR, beneath the door frame can further reduce thermal bridging [10].
Detail **- Insulation** **- Concrete** **- Wood** **- XPS** **- Thermal Break** **- Optimized**		
Heat Flow		
Linear Loss, Ψ: Baseline = 0.11 W/m.K, Optimized = 0.08 W/m.K		

Description	**Baseline**	**Optimized**
Int. foundation	The linear thermal transmittance in this detail is relatively high for a new building, that is due to the direct placement of the partition wall on the partition foundation.	Replacing the partition material with lightweight concrete, which has lower thermal conductivity, can significantly reduce the linear transmittance. However, this may not always be feasible due to structural requirements. In this case, it is considered feasible since the project involves a single-family house, which is considered to be in the design phase [4].
Detail - Insulation - Concrete - Wood - XPS - Optimized		
Heat Flow		
Linear Loss, Ψ: Baseline = 0.31 W/m.K, Optimized = 0.14 W/m.K		

Description	Baseline	Optimized
Roof-wall	The roof anchor has direct contact with the wooden boards, which contributes to a significant thermal bridge.	Increasing the wall insulation thickness and adding insulated plasterboard to the interior frame significantly reduce thermal loss, lowering the linear thermal bridge by over 80%.
Detail **- Insulation** **- Concrete** **- Wood** **- Optimized**		
Heat Flow		
Linear Loss, Ψ: Baseline = 0.16 W/m.K, Optimized = 0.03 W/m.K		

Description	Baseline	Optimized
Skylight	The skylight detail is based on assumptions due to limited material information; however, it is sourced from a manufacturer [3].	The optimized skylight line loss is achieved by increasing the skylight frame joint size and incorporating a 25 mm thick insulation layer to enhance thermal performance and reduce linear thermal losses, as specified in Table 6.12.4 of DS418 [31].
Detail **- Insulation** **- Concrete** **- Wood** **- XPS** **- Optimized**		
Heat Flow		
Linear Loss, Ψ: Baseline = 0.06 W/m.K, Optimized = 0.024 W/m.K		

Description	Baseline	Optimized
Wall-floor-foundation	The foundation exhibits a significant thermal bridge, presenting opportunities for improvement through the application of effective solutions.	Adding 100 mm insulation around the foundation block, extending up to the lightweight plinth render above the foundation, helps to minimize linear thermal losses.
Detail **- Insulation** **- Concrete** **- Wood** **- XPS** **- Optimized**		
Heat Flow		
Linear Loss, Ψ: Baseline = 0.13 W/m.K, Optimized = 0.09 W/m.K		

The thermal junctions that no enhancement needed.		
Wall-balcony junction The frame is insulated, which significantly reduces linear thermal loss in this connection. This insulation effectively prevents heat transfer through the junction, making further improvements unnecessary for this detail.A Ψ value of 0.02 W/m.K can be neglected according to DS418[31].		
Wall-storey partition Similar to the previous junction with the balcony, the wooden frame is insulated, resulting in low linear thermal loss in this connection, resulting a Ψ value of 0.019 W/m.K.		
Wall-window The window performs well, with a U-value of 0.9 W/m²K and minimal linear thermal loss with a Ψ value of 0.03 W/m.K.		

3.3.1 Thermal bridge analysis results – single–family house

Figure 3.5 shows the results of the linear thermal transmittance for the SFH case, Among the analyzed details, the **internal foundation junction** exhibited the highest linear thermal transmittance in the baseline scenario, with a Ψ-value of 0.31 W/m.K. This was primarily due to direct contact between high-conductivity materials, such as concrete, and insufficient insulation. However, after optimization, this value was reduced to 0.14 W/m.K, achieving a **55% reduction** in heat loss.

The **roof-wall junction** showed a baseline Ψ-value of 0.16 W/m.K, where the roof anchor in direct contact with wooden boards contributed to significant thermal bridging. Optimized solutions reduced this to 0.03 W/m.K, marking the highest reduction of **81%**.

Similarly, the **wall-floor-foundation junction**, with a baseline Ψ-value of 0.13 W/m.K, demonstrated notable heat loss due to limited insulation around the foundation block. After applying improved insulation, this was reduced to 0.09 W/m.K, corresponding to a **31% reduction**.

Additional improvements were observed in the **walls and doors junction**, which initially had a Ψ-value of 0.11 W/m.K. Optimizations resulted in a reduction to 0.08 W/m.K, corresponding to a **27% decrease**. The **roof windows junction** experienced a substantial **56% reduction**, from 0.054 W/m.K to 0.024 W/m.K.

The applied optimization strategies included replacing high-conductivity materials with alternatives of lower thermal conductivity and increasing insulation thickness. These modifications significantly reduced heat loss across all critical junctions, demonstrating the effectiveness of targeted improvements.

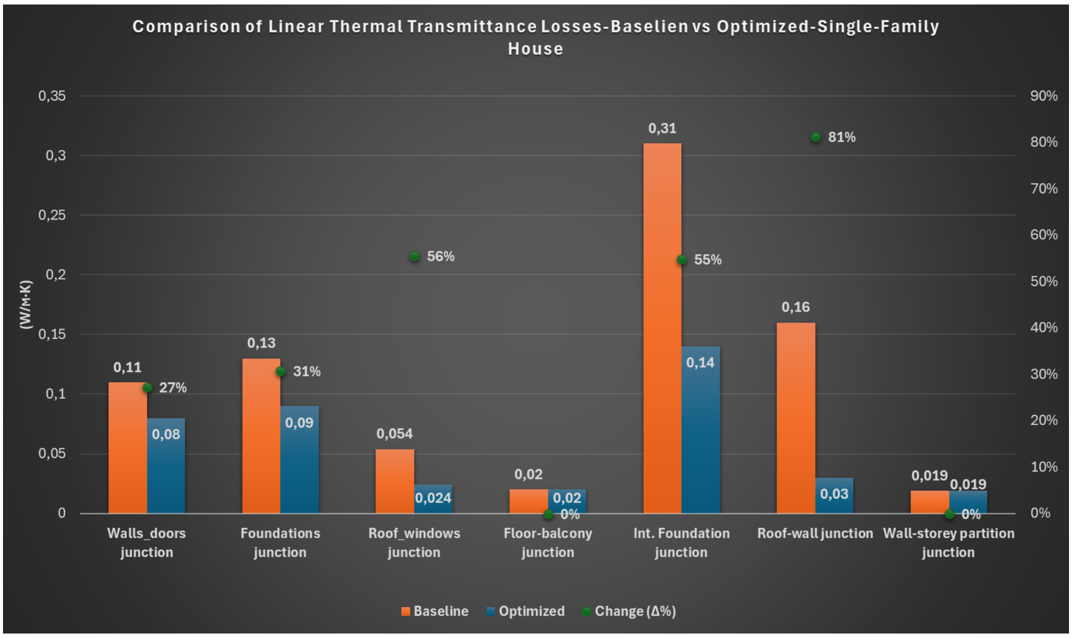


Figure 3.5: Comparison of Linear Thermal Transmittance Losses-Baseline vs Optimized-Single Family House

3.4 Thermal bridges – multi–storey building

A multi-storey building undergoing renovation involves the application of energy performance improvements to existing structures. Unlike new constructions, renovation projects often encounter challenges such as addressing thermal bridge connections while maintaining structural stability and ensuring accessibility. These solutions require meticulous planning and precision to minimize energy losses. Moreover, renovations must balance technical enhancements with the limitations imposed by the existing building [23, 24].

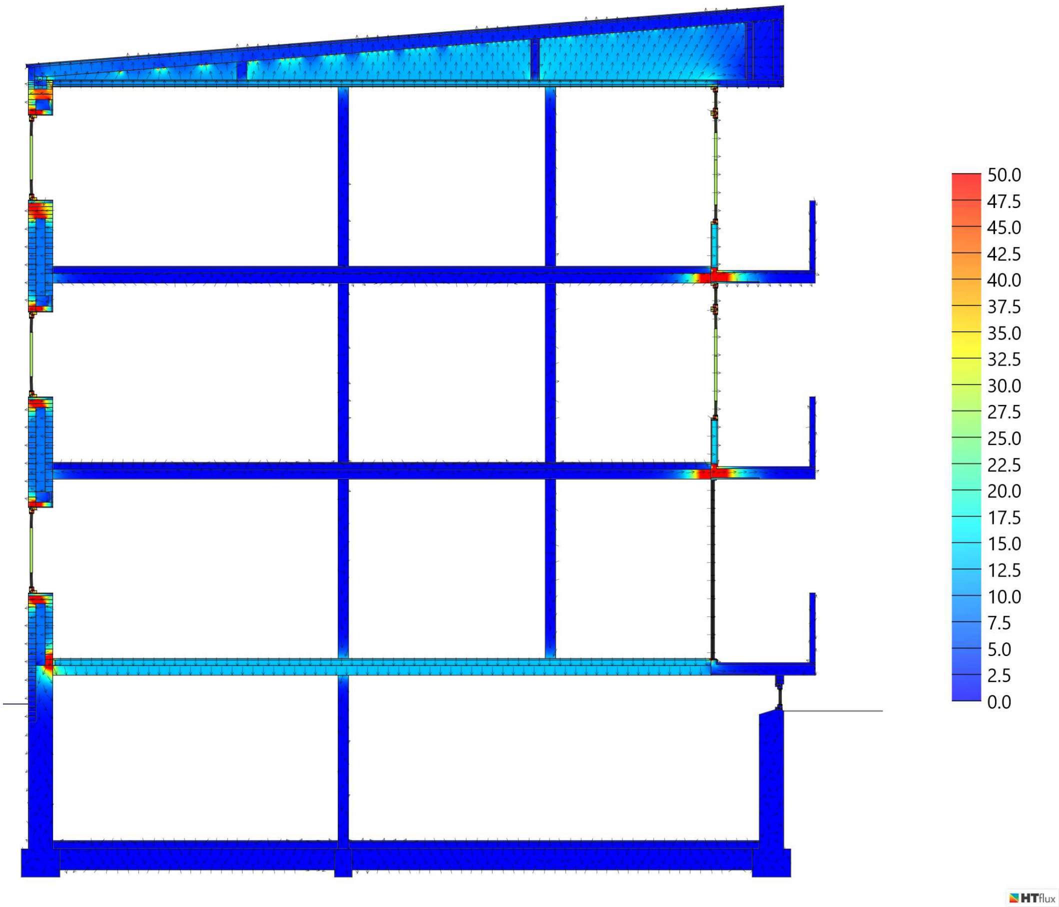


Figure 3.6: Heat Flux Distribution in The Multi-Storey Building Section (W/m²)

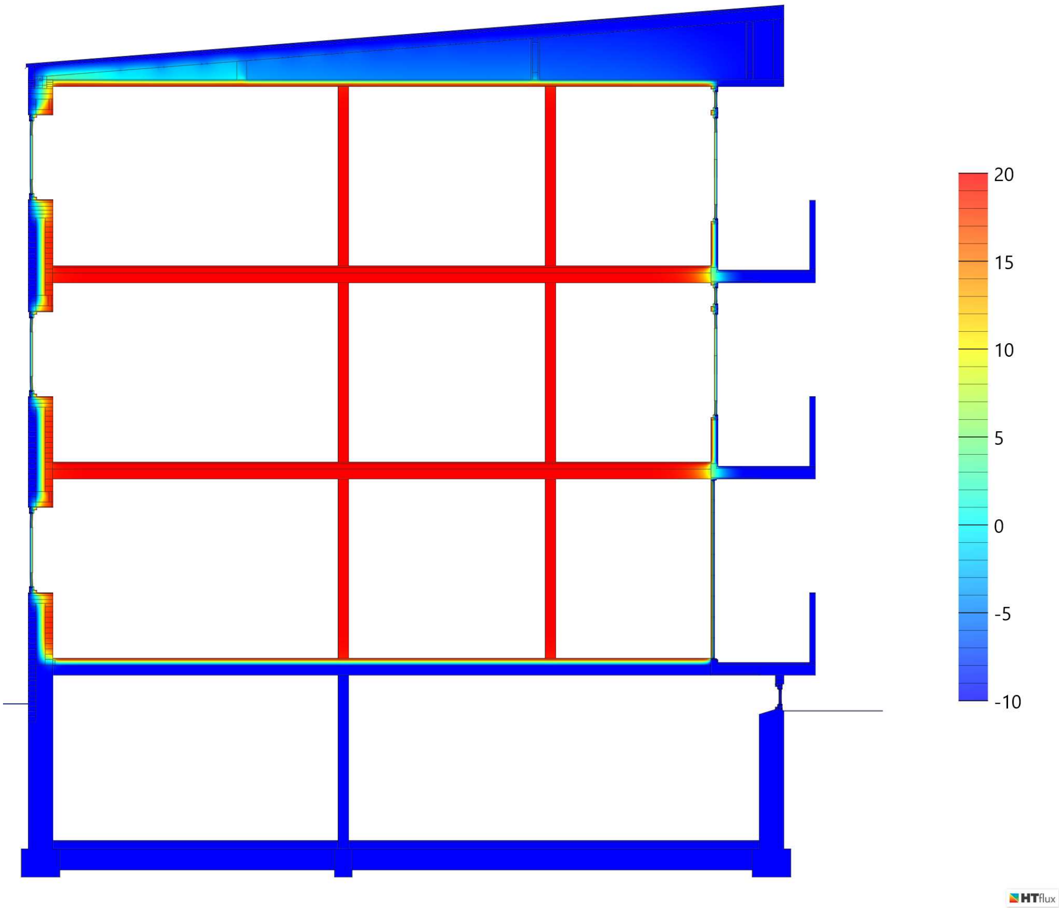
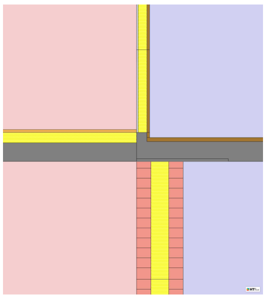
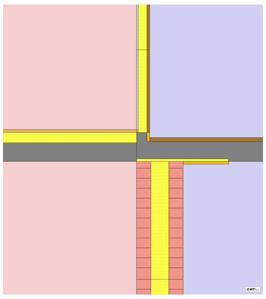
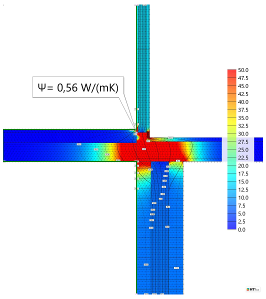
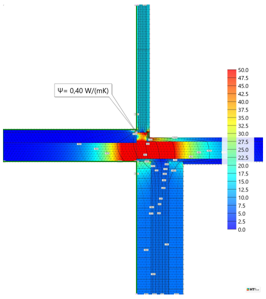
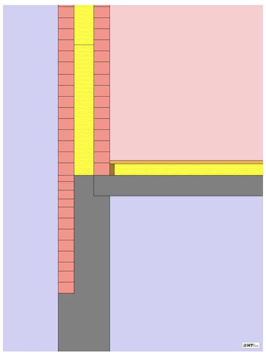
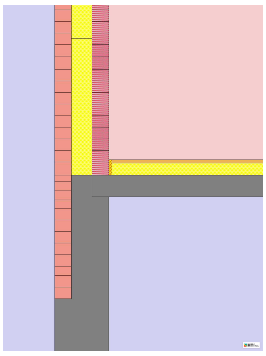
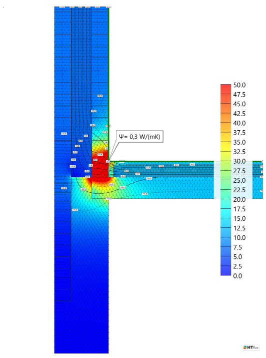
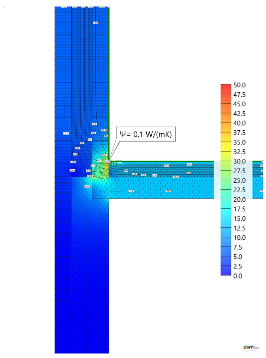
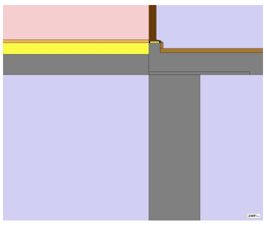
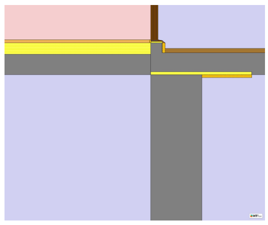
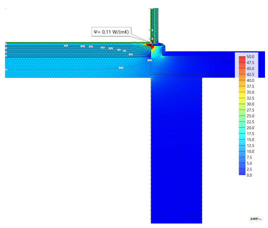
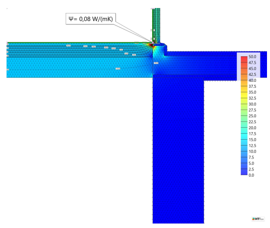
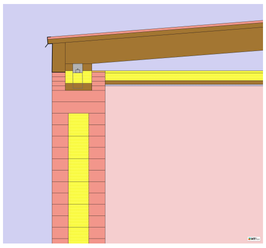
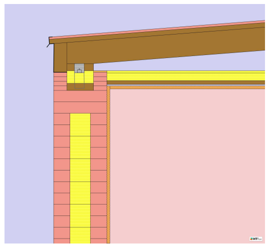
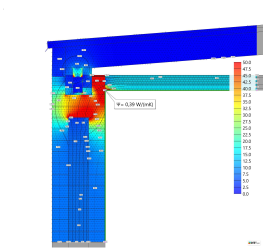
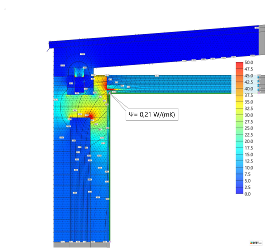


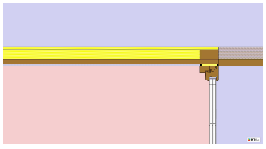
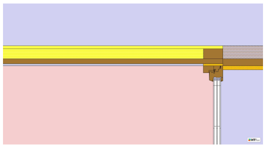
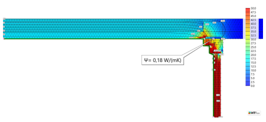
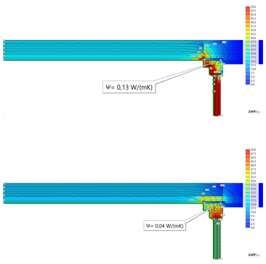
Figure 3.7: Temperature Distribution in The Multi-Storey Building Section (°C)

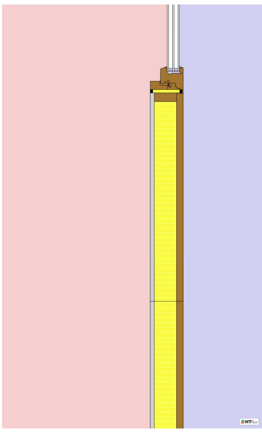
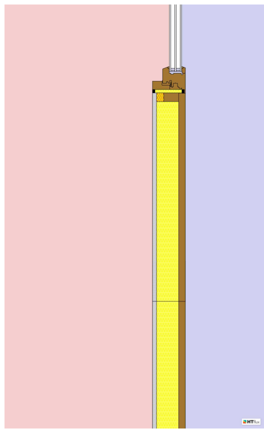
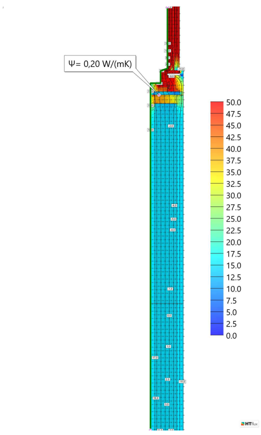
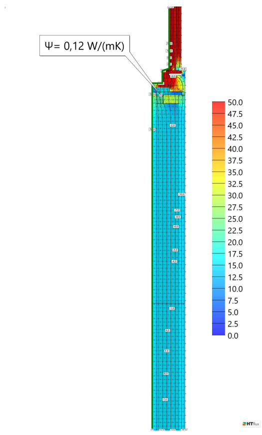
Description	**Baseline**	**Optimized**
Balcony	The connection between the balcony, the external wall, the storey partition, and the window board exhibits significant linear thermal loss due to the continuous slab, which creates a clear path for heat to escape.	Adding external insulation to the balcony slab can mitigate these losses by reducing the surface area through which heat escapes. Alternatively, internal insulation could also lower the linear thermal losses; however, it may increase the risk of condensation. Additionally, small insulation sections are applied at the points where the wooden and gypsum boards contact the concrete slab.
Detail **- Insulation** **- Concrete** **- Wood** **- Bricks** **- Optimized**		
Heat Flow		
Linear Loss, Ψ: Baseline = 0.56 W/m.K, Optimized = 0.4 W/m.K		

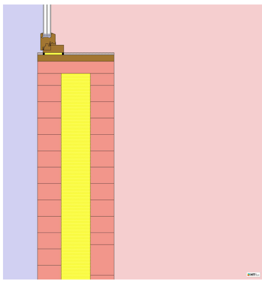
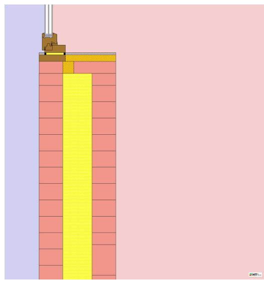
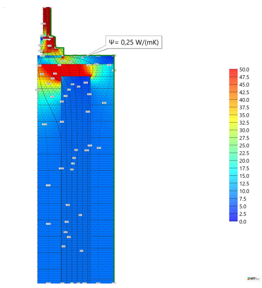
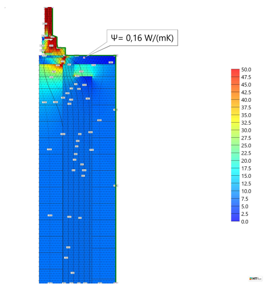
<table>
<tr><th>Description</th><th>Baseline</th><th>Optimized</th></tr>
<tr><td>External wall - groundfloor Partition</td><td>The inner layer of the external wall is in direct contact with the floor slab, which allows heat to escape into the unheated basement.</td><td>To minimize this linear thermal loss, the inner materials of the external wall could be replaced with materials that have lower thermal conductivity. For example, using lightweight aggregate blockwork for the inner leaf can enhance the thermal performance of the external wall by reducing heat transfer through the junction.</td></tr>
<tr><td>Detail
- Insulation
- Concrete
- Wood
- Bricks
- Optimized</td><td></td><td></td></tr>
<tr><td>Heat Flow</td><td>
</td><td>
</td></tr>
<tr><td colspan="3">Linear Loss, Ψ: Baseline = 0.3 W/m.K, Optimized = 0.1 W/m.K</td></tr>
</table>

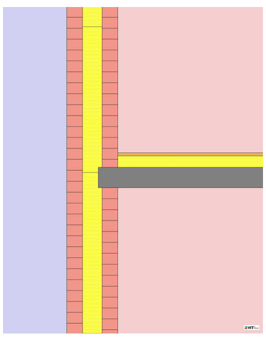
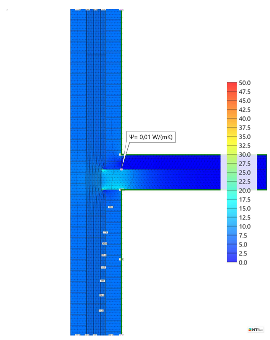
Description	**Baseline**	**Optimized**
Door - groundfloor	This junction is quite similar to the balcony case; however, the door is included in the linear loss calculation, resulting in lower heat loss.	Therefore, the solution could involve a combination of enhancing the door's thermal performance, adding perimeter insulation, and applying external insulation similar to that used for the balcony slab.
Detail - **Insulation** - **Concrete** - **Wood** - **Bricks** - **Optimized**		
Heat Flow		
Linear Loss, Ψ: Baseline = 0.11 W/m.K, Optimized = 0.08 W/m.K		

Description	Baseline	Optimized
Roof-wall	This connection exhibits significant linear thermal loss due to the brickwork lintel.	The solution for this junction involves adding insulated plasterboard to the inner side of the external wall, as well as to the roof, to reduce heat transfer.
Detail **- Insulation** **- Concrete** **- Wood** **- Bricks** **- Optimized**		
Heat Flow		
Linear Loss, Ψ: Baseline = 0.39 W/m.K, Optimized = 0.21 W/m.K		

Description	Baseline	Optimized
Roof-window	The windows have not been replaced, which is the primary reason for the high linear thermal loss.	Similar to the balcony junction, applying external insulation can enhance the thermal performance of the window frame, though its impact is limited. However, replacing the window with a lower U-value can significantly reduce linear thermal loss.
Detail **- Insulation** **- Wood** **- Optimized**		
Heat Flow		
Linear Loss, Ψ: Baseline = 0.18 W/m.K, Optimized = 0.13 / 0,04 W/m.K		

Description	Baseline	Optimized
Window 1	This is a cross-section of a window with its board.	To reduce the thermal bridge, insulation has been added to the frame of the window board to prevent line loss through the frame.
Detail - **Insulation** - **Wood** - **Optimized**		
Heat Flow		
Linear Loss, Ψ: Baseline = 0.20 W/m.K, Optimized = 0.12 W/m.K		

Description	Baseline	Optimized
Window 2	In this case, the connection is between the window and the external wall, which is a common external wall-window connection from the 1960s.	To improve the thermal performance of the frame, a PU/PIR insulation core can be added to the brickwork below the frame. Additionally, applying an insulated plasterboard reveal can further enhance the thermal performance of the window frame.
Detail **- Insulation** **- Concrete** **- Wood** **- Bricks** **- Optimized**		
Heat Flow		
Linear Loss, Ψ: Baseline = 0.25 W/m.K, Optimized = 0.16 W/m.K		

The thermal junctions that no enhancement needed.		
External wall-storey Partition: This construction detail does not offer opportunities for thermal performance enhancements, as the floor slab terminates before intersecting with the insulation layer, resulting in a linear thermal transmittance (Ψ = 0.01 W/m.K), which can be considered negligible.		

3.4.1 Thermal bridge analysis results – multi–storey building

The **floor-balcony connection** exhibited the highest linear thermal transmittance in the baseline scenario, with a Ψ-value of 0.56 W/m.K as shown in figure 3.8 This was primarily due to the direct contact between the balcony slab, storey partition, and external wall, facilitating significant heat loss. After optimization, this was reduced to 0.40 W/m.K, achieving a **29% reduction**.

Similarly, the **roof-wall junction** had a baseline Ψ-value of 0.39 W/m.K, where the presence of brickwork created a thermal bridge. After optimization, the value was reduced to 0.21 W/m.K, achieving a **46% reduction**.

The **external wall-ground floor partition** also presented a significant Ψ-value of 0.30 W/m.K due to the uninsulated contact between the floor slab and inner wall layers, allowing heat transfer into the unheated basement. Optimized solutions reduced this value to 0.10 W/m.K, marking the highest improvement of **67%**.

Additional improvements were observed in **joints at windows**, which initially had a Ψ-value of 0.20 W/m.K. Optimization resulted in a reduction to 0.12 W/m.K, corresponding to a **40% decrease**. The **window 2 junction** experienced a **36% reduction**, from 0.25 W/m.K to 0.16 W/m.K. The **door junction** also showed a **27% decrease**, improving from 0.11 W/m.K to 0.08 W/m.K.

Conversely, the **wall-storey partition** remained unchanged at **0.01 W/m.K**, indicating that further modifications may be needed. The **roof-window junction** demonstrated a **28% reduction**, lowering from 0.18 W/m.K to 0.13 W/m.K.

The applied optimization strategies involved increasing insulation thickness, utilizing materials with lower thermal conductivity, and enhancing construction detailing, such as reducing frame height to minimize thermal bridging. These measures effectively lowered heat loss across the most critical junctions in the multi-storey building.

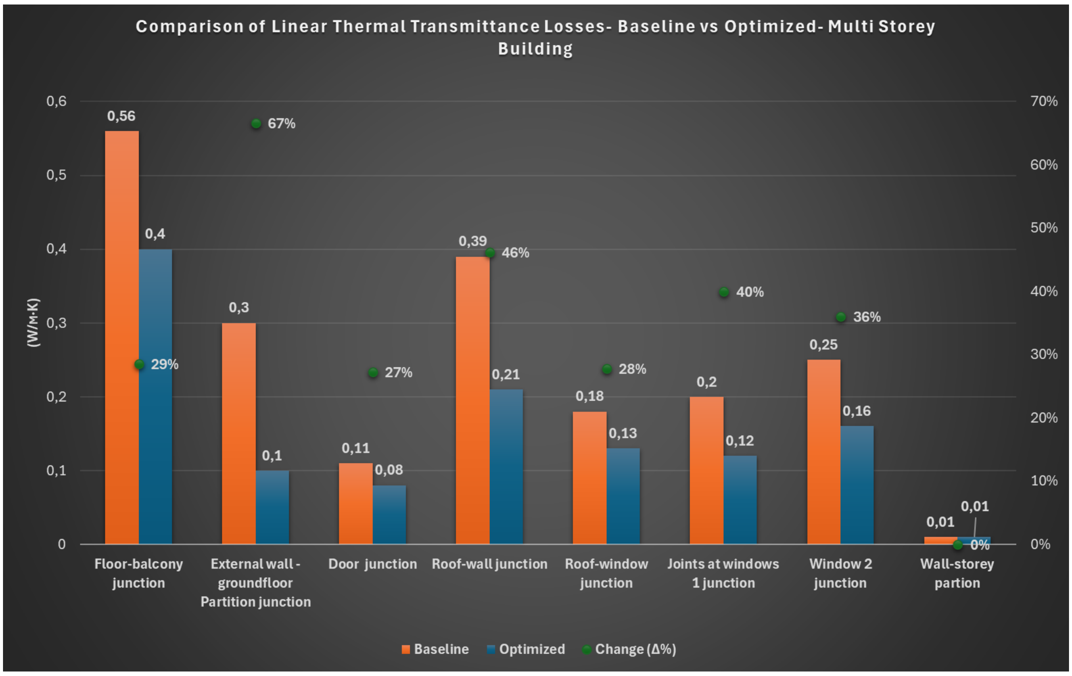


Figure 3.8: Comparison of Linear Thermal Transmittance Losses-Baseline vs Optimized-Multi Storey Building

3.5 Thermal bridges – kindergarten building

Previous studies, including a blower door test, revealed significant air leakage in the kindergarten, primarily due to its large windows and doors. The building's poor air-tightness has resulted in reduced thermal performance and higher energy consumption. With the help of simulations, it's now possible to closely examine the thermal bridge performance and identify areas for improvement. Renovating the kindergarten will involve tackling these thermal bridges and air leakage issues while adhering to modern building standards and preserving the building's usability.

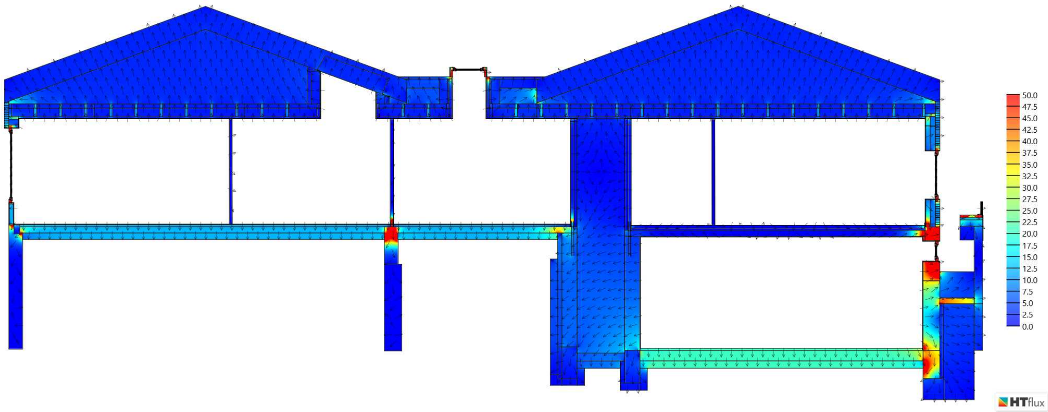


Figure 3.9: Heat Flux Distribution in The Kindergarten Building Section (W/m²)

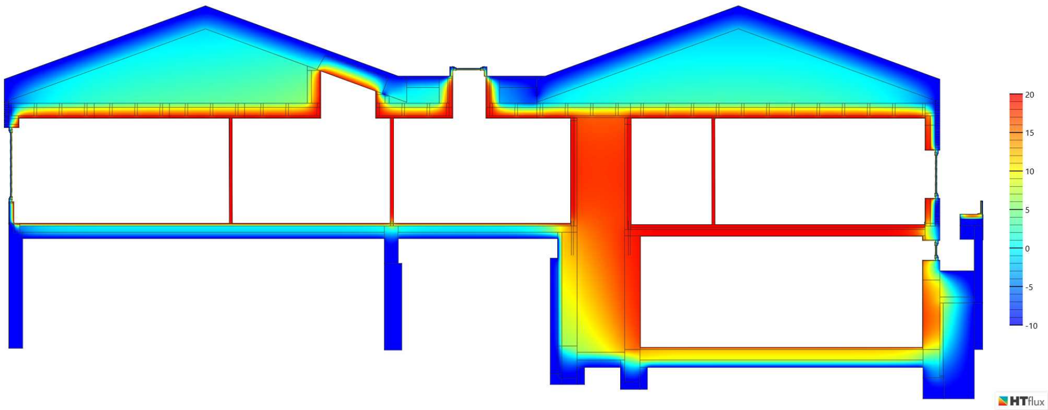
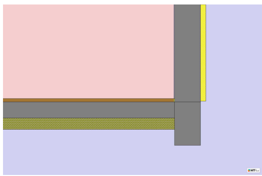
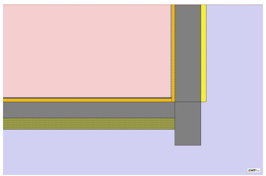
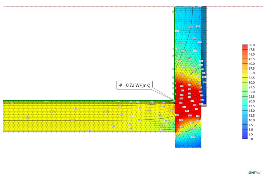
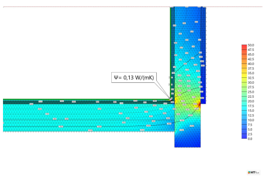
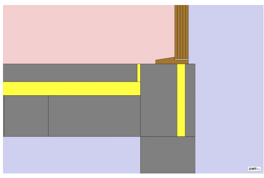
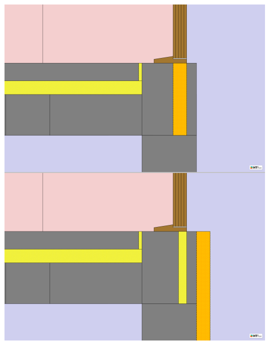
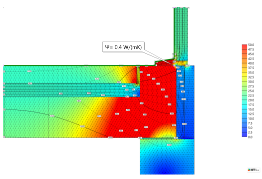
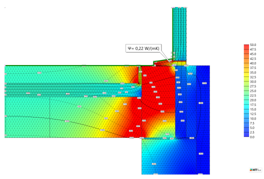
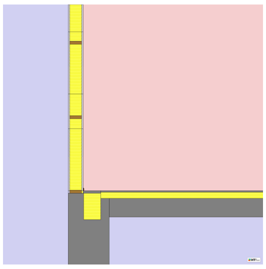
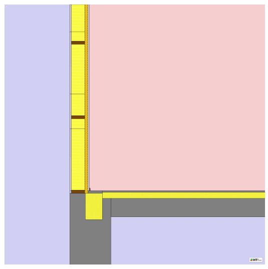
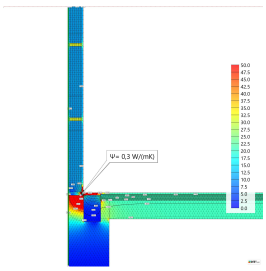
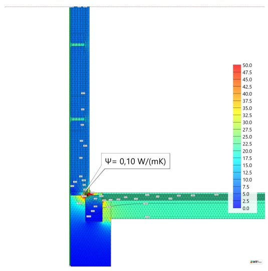
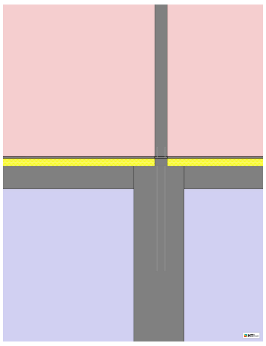
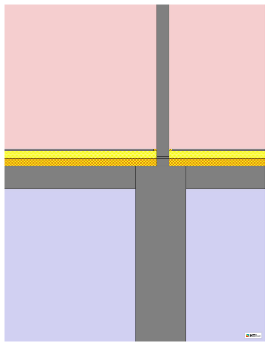
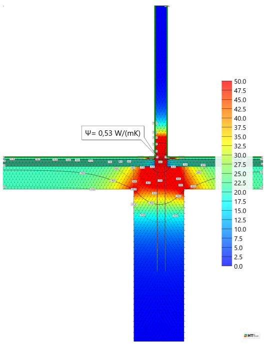
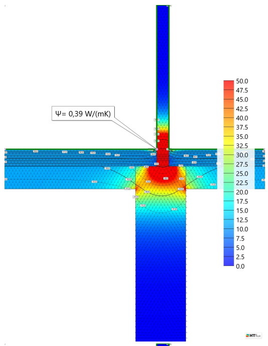
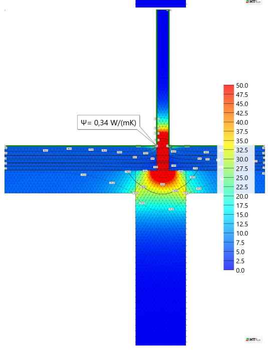


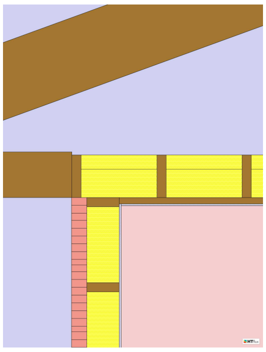
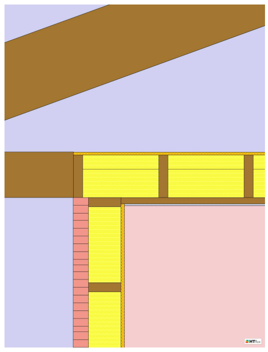
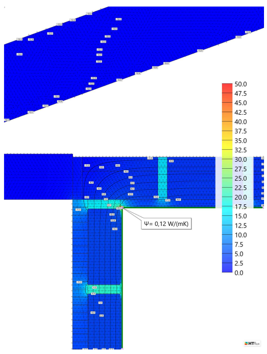
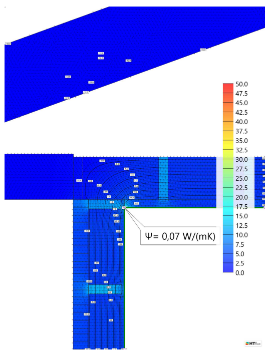
Figure 3.10: Temperature Distribution in The Kindergarten Building Section (°C)

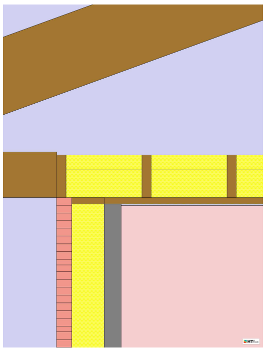
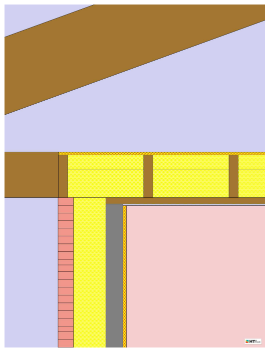
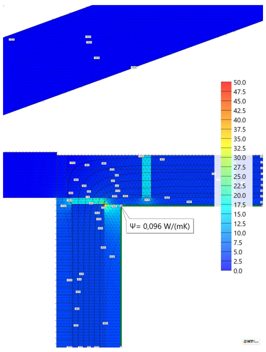
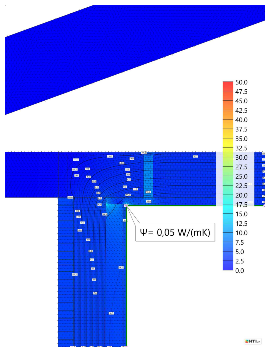
Description	Baseline	Optimized
Basement wall-floor	The basement in the kindergarten is heated; however, the floor is not insulated, leading to a high U-value and significant linear thermal bridging.	Adding internal post-insulation to both the basement wall and floor can significantly reduce these linear thermal losses. To minimize the risk of condensation, diffusion-closed insulation materials, such as XPS, can be used [25].
Detail **- Insulation** **- Concrete** **- Wood** **- Bricks** **- Optimized**		
Heat Flow		
Linear Loss, Ψ: Baseline = 0.72 W/m.K, Optimized = 0.13 W/m.K		

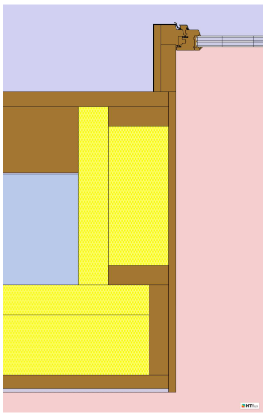
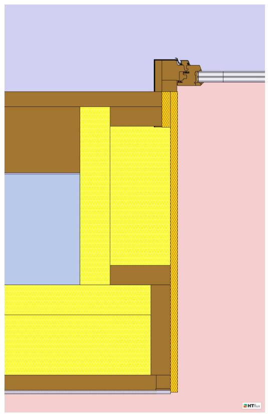
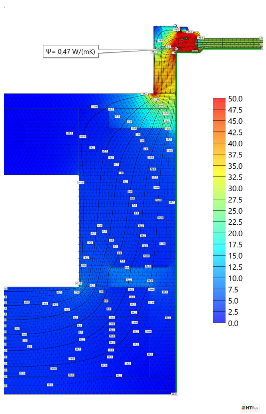
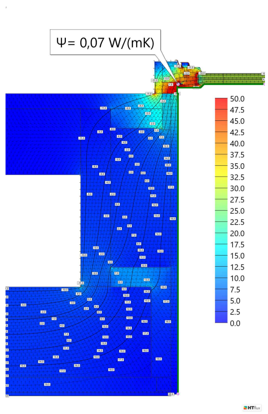
Description	**Baseline**	**Optimized**
Door	The door frame is positioned above the foundation block. The insulation within the block is relatively thin due to the lower thermal requirements of the 1980s. The inner part of the foundation serves as a primary pathway for heat loss, allowing heat to escape through the floor slab and into the ground. Implementing modifications to the inner section of the foundation can be extremely challenging and costly.	This solution involves either changing the foundation block insulation or adding additional insulation to the foundation. Both approaches result in approximately the same linear thermal transmittance. The best choice depends on feasibility and cost.
Detail - **Insulation** - **Concrete** - **Wood** - **Bricks** - **Optimized**		
Heat Flow		
Linear Loss, Ψ: Baseline = 0.4 W/m.K, Optimized = 0.22 W/m.K		

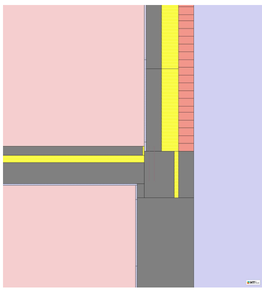
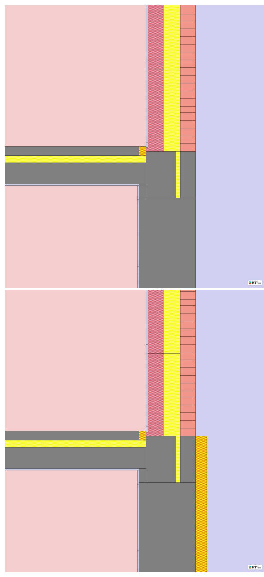
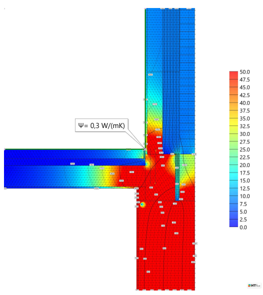
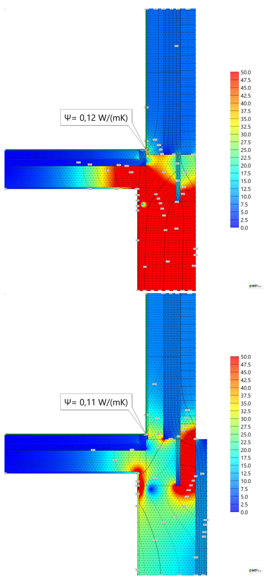
Description	**Baseline**	**Optimized**
Foundation-Floor	This building has multiple window-curtain walls where the window board has a low U-value, leading to high linear thermal transmittance.	Adding insulation to the window board or replacing it with a thicker, better-insulated alternative can reduce heat loss at this junction.
Detail **- Insulation** **- Concrete** **- Wood** **- Bricks** **- Optimized**		
Heat Flow		
Linear Loss, Ψ: Baseline = 0.3 W/m.K, Optimized = 0.1 W/m.K		

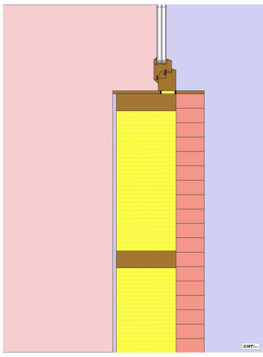
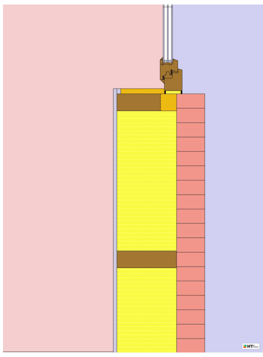
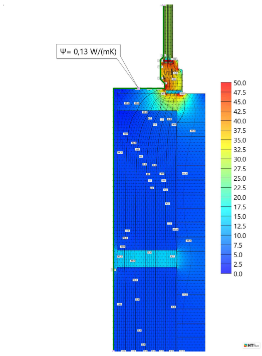
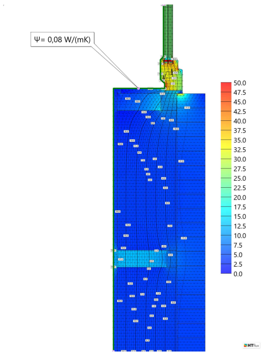
Description	**Baseline**	**Optimized**
Int. foundation	The linear thermal transmittance in this detail is relatively high, making it a critical issue to address in the renovation.	Increasing the insulation thickness by both 50 mm and 100 mm is proposed to assess the extent to which heat loss can be reduced. Additionally, adding 20 mm of edge insulation is recommended to prevent direct contact with the floorboards.
Detail **- Insulation** **- Concrete** **- Wood** **- Bricks** **- Optimized**		
Heat Flow		 
Linear Loss, Ψ: Baseline = 0.53 W/m.K, Optimized = 0.39-0.34 W/m.K		

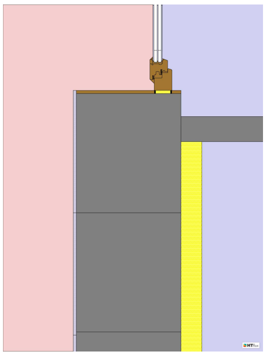
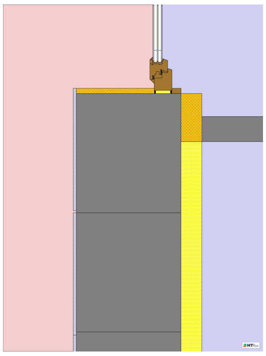
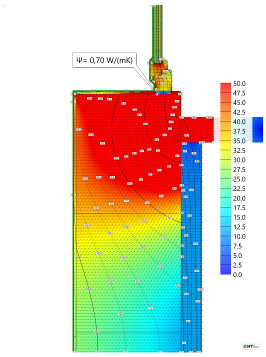
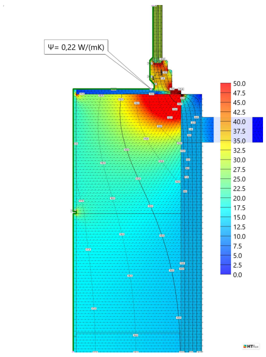
Description	Baseline	Optimized
Roof-Wall	The roof-wall connection exhibits linear thermal transmittance.	To mitigate heat loss, adding 20 mm of insulated plasterboard can enhance the thermal performance of the wall. Additionally, applying 20 mm of insulation above the roof framework can further reduce heat loss.
Detail **- Insulation** **- Concrete** **- Wood** **- Bricks** **- Optimized**		
Heat Flow		
Linear Loss, Ψ: Baseline = 0.12 W/m.K, Optimized = 0.07 W/m.K		

Description	**Baseline**	**Optimized**
Roof-Wall 2	The linear thermal transmittance in this roof-wall connection is relatively low. However, the simulation indicates that the wooden framework provides a direct path for heat loss, as observed in the previous detail.	Similar to the previous solution, adding 20 mm of insulated plasterboard can enhance thermal performance. Additionally, the wooden board can be terminated at the inner concrete leaf of the wall, as the concrete functions as the load-bearing element.
Detail **- Insulation** **- Concrete** **- Wood** **- Bricks** **- Optimized**		
Heat Flow		
Linear Loss, Ψ: Baseline = 0.096 W/m.K, Optimized = 0.05 W/m.K		

<table>
<tr><th>Description</th><th>Baseline</th><th>Optimized</th></tr>
<tr><td>Skylight</td><td>This skylight has not been renovated since its construction, as confirmed by thermal imaging from a previous site study assessing the building envelope, indicating a high linear thermal loss.</td><td>The frame joint is 300 mm thick, making improvements challenging. However, according to DS418 Table 6.12.4 [31], a shorter frame joint reduces linear thermal transmittance. Additionally, adding a small amount of insulation in the joint and using insulated plasterboards to prevent direct contact between the wooden frames can further improve the skylight's thermal performance.</td></tr>
<tr><td>Detail
- Insulation
- Concrete
- Wood
- Bricks
- Optimized</td><td></td><td></td></tr>
<tr><td>Heat Flow</td><td></td><td>
</td></tr>
<tr><td colspan="3">Linear Loss, Ψ: Baseline = 0.47 W/m.K, Optimized = 0.07 W/m.K</td></tr>
</table>

Description	Baseline	Optimized
Wall-Floor	According to the detailed section of the building, some parts of the basement walls are not insulated. In this case, for instance, this results in a high U-value and, consequently, a high linear thermal loss.	Two solutions are proposed for this junction. The first involves replacing the inner leaf of the wall with a material of lower thermal conductivity, such as lightweight concrete or light weight aggregate blocks. The second solution is adding external insulation to the foundation. In both scenarios, the total linear loss is nearly the same. A combination of these solutions results in a lower linear loss, approximately 0.06 W/m.K [4].
Detail **- Insulation** **- Concrete** **- Wood** **- Bricks** **- Optimized**		
Heat Flow		
Linear Loss, Ψ: Baseline = 0.3 W/m.K, Optimized = 0.12 W/m.K		

Description	**Baseline**	**Optimized**
Window 1	The window connection exhibits a low linear thermal transmittance but still has potential for improvement.	Simulations indicate heat loss through the wooden framework. Therefore, incorporating PU core insulation between the frame and brickwork can help block the heat escape path. Additionally, adding insulated plasterboard to the window sill can further reduce linear thermal transmittance and enhance the overall thermal performance of the window.
Detail - **Insulation** - **Concrete** - **Wood** - **Bricks** - **Optimized**		
Heat Flow		
Linear Loss, Ψ: Baseline = 0.13 W/m.K, Optimized = 0.08 W/m.K		

Description	Baseline	Optimized
Window 2	This window exhibits a significantly higher linear thermal transmittance compared to the previous window. It is placed on a concrete basement wall, allowing heat to escape more easily due to the high thermal conductivity of the material.	To improve thermal performance, adding insulated plasterboard to the window sill and applying external insulation to uninsulated sections of the basement wall can significantly reduce heat loss. These optimizations reduce the linear thermal transmittance by approximately 70%.
Detail - **Insulation** - **Concrete** - **Wood** - **Bricks** - **Optimized**		
Heat Flow		
Linear Loss, Ψ: Baseline = 0.7 W/m.K, Optimized = 0.22 W/m.K		

3.5.1 Thermal bridge analysis results – kindergarten

According to the analysis and the figure 3.11, the most critical thermal bridging was identified at the **basement wall-floor junction** and **window 2**, both with a Ψ-value of approximately 0.72 W/m.K and 0.7 W/m.K, respectively. These high values were due to the absence of insulation, allowing substantial heat transfer. After optimization, these were reduced to 0.13 W/m.K and 0.22 W/m.K, achieving a **82% and 69% reduction**, respectively.

The **internal foundation** exhibited a Ψ-value of 0.53 W/m.K, highlighting a major heat loss pathway due to direct thermal contact with structural elements. Optimization brought this down to 0.34 W/m.K, resulting in a **36% reduction**. Similarly, the **skylight frame** had a Ψ-value of 0.47 W/m.K, attributed to the height of the joint/frame and the lack of insulation. This was reduced to 0.07 W/m.K, achieving an **85% reduction**.

The **door connection to the foundation block** displayed a very high thermal loss, with a Ψ-value of 0.4 W/m.K, primarily caused by insufficient insulation in the foundation material. Optimized solutions reduced this to 0.22 W/m.K, achieving a **45% reduction**.

Additionally, the **foundation-floor junction** and the **wall-floor junction** both recorded a Ψ-value of 0.3 W/m.K, contributing significantly to heat loss. After optimization, these were reduced to 0.10 W/m.K and 0.12 W/m.K, achieving **67% and 60% reductions**, respectively.

Other improvements were observed in **roof-wall junctions**, with the first instance reducing from 0.12 W/m.K to 0.07 W/m.K (**42% reduction**) and the second from 0.096 W/m.K to 0.05 W/m.K (**48% reduction**). The **window 1 junction** also demonstrated a **38% reduction**, lowering from 0.13 W/m.K to 0.08 W/m.K.

The applied optimization strategies included increasing insulation thickness, optimizing window and door seals, and integrating thermal breaks at key junctions. These measures effectively reduced both conductive and convective heat losses, enhancing the overall energy performance of the kindergarten building.

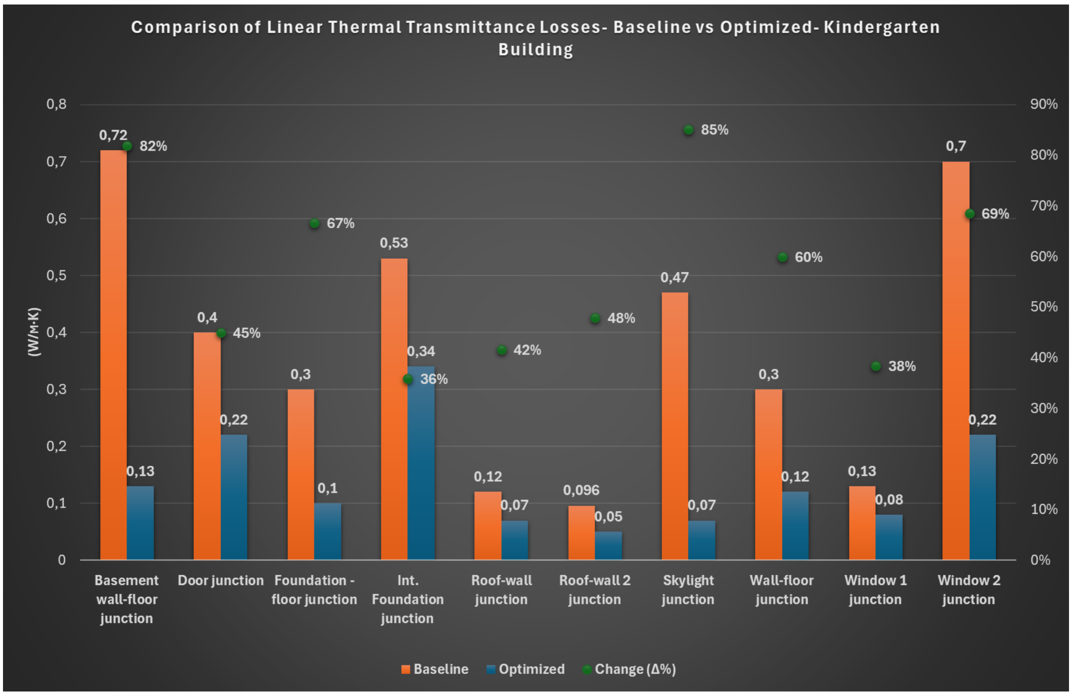


Figure 3.11: Comparison of Linear Thermal Transmittance Losses- Baseline vs Optimized- Kindergarten Building

3.6 Impact of optimizations on thermal bridges and transmission losses across building cases

The implementation of thermal bridge optimizations significantly reduced transmission heat losses across all analyzed buildings, as illustrated in Figure 3.12. The graph presents the results following the application of optimization measures, highlighting the overall reduction in both design transmission losses and linear thermal transmittance (thermal bridge) losses.

In the **single-family house**, linear thermal transmittance losses were reduced by **46.8%**, contributing to an overall **23.7%** reduction in total design transmission losses. The optimization process in this case was more straightforward, as the building was considered a new construction in the design phase, where modifications to thermal bridge strategies could be easily implemented.

For the **multi-storey building**, thermal bridge losses saw a **41.7%** reduction, while total transmission losses decreased by **21.6%**. The graph captures the post-optimization state, demonstrating the effectiveness of additional insulation in mitigating severe thermal bridging, particularly at the **balcony, roof-wall, and external wall-groundfloor junctions**.

The **kindergarten** exhibited the most significant reduction in thermal bridge losses, achieving a **75.1%** decrease, while total transmission losses were reduced by **22.4%**. As illustrated in the graph, this reduction is primarily due to the **building's initially high U-values**, which minimized the proportional impact of thermal bridge optimizations on overall transmission heat loss. Appendix 7 presents the calculations and methodology. The reduction in design transmission losses lowers the building's energy demand, which will be analyzed in the upcoming LCA sections.

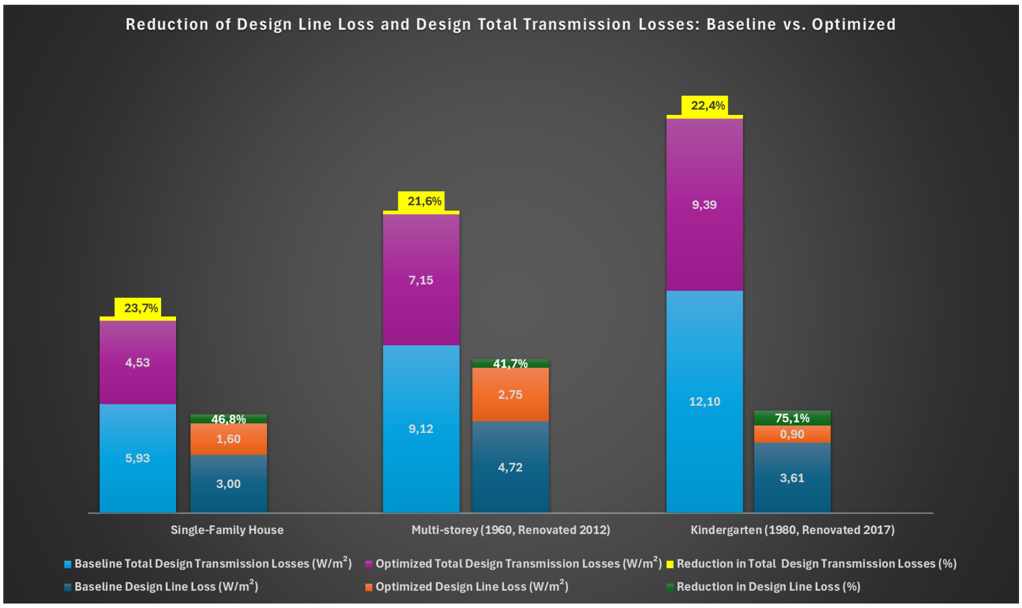


Figure 3.12: Reduction of Design (Thermal Bridge and Total Transmission Losses): Baseline vs Optimized

3.7 Life cycle assessment

The life cycle assessment focuses on comparing the baseline and optimized cases to quantify the changes in Global Warming Potential (GWP). The analysis includes the thermal bridge junctions where optimizations were applied, assessing the environmental impact of the additional materials and reduced heating demand. The calculations are provided in Appendix 9.

3.8 LCA – Single–family house

The single-family house is considered to be in the design phase for thermal bridge mitigation. In the LCA analysis, it is treated as a newly built case to enable a comparison between the baseline and the optimized scenarios. **The stages and materials** analysis is conducted for the optimized scenario, as it provides the final and total GWP of the building after thermal bridge mitigation.

3.8.1 Stages and components

The stage analysis shows that the ground floor slabs and foundations have the highest GWP contributions in the **A1–A3** stage, with approximately 0.57 and 0.54 kg CO_2-eq/m^2/year, respectively. In contrast, roofs exhibit a significant negative GWP in **A1–A3** (around –1.2), and external walls also show minor negative values in this stage. This is due to the use of timber-based construction, where the biogenic carbon stored in the wood during tree growth is accounted for as negative emissions in the production stage. As a result, timber elements such as the roof reduce the overall GWP due to their role as temporary carbon sinks.

Significant contributions from **C3** (waste processing) are visible across most components—especially roofs, floor slabs, and external walls. The **C4** (disposal) stage is present but remains minimal throughout. **B4** (replacements) plays a notable role in roofs and windows/doors, while **Stage D** (benefits beyond the system boundary) indicates strong environmental offsets in roofs, floor slabs, and floor decks.

Looking at the overall results (yellow dots), the highest total GWP contributions come from the floor slabs (0.824), followed by roofs (0.635), foundations (0.589), and external walls (0.139). Components like windows/doors (0.082), balconies (0.108), and floor decks (0.012) have relatively minor impacts. Thermal bridges, included as a distinct component, contribute approximately **2.8%** of the total GWP from building elements, confirming their relevance in the overall climate impact assessment.

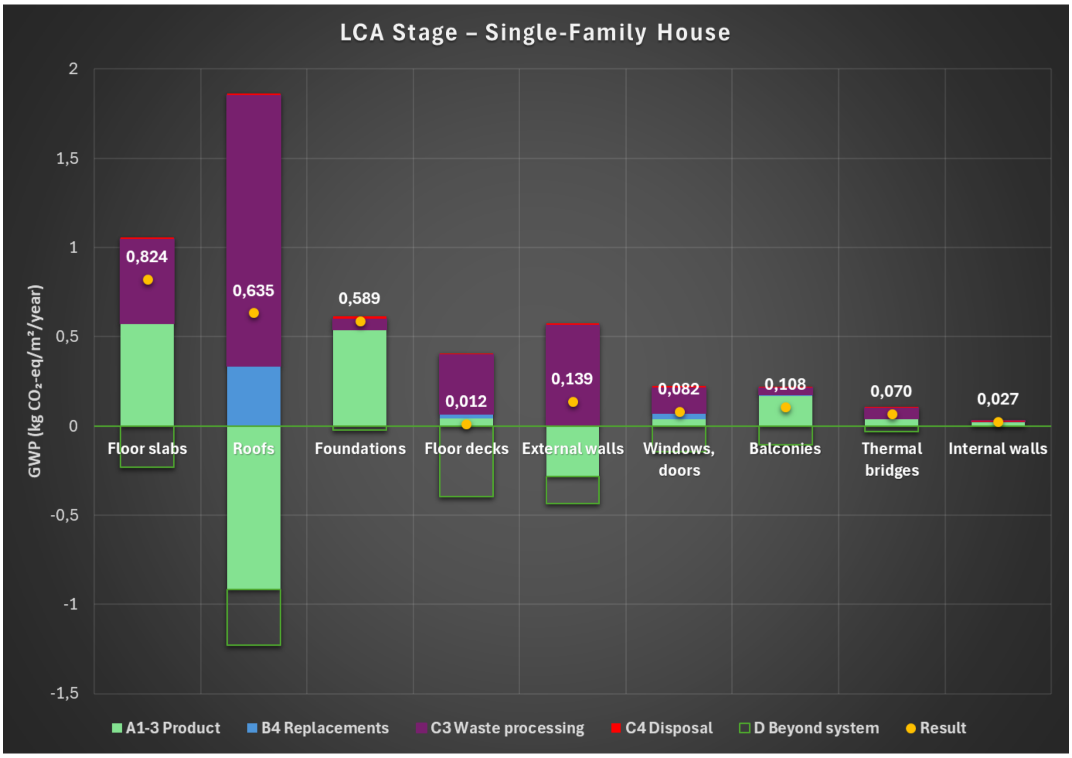


Figure 3.13: LCA-Stages-Single-Family House

Materials analysis:

In the case of the single-family house, the materials analysis reveals that the largest contribution to the Global Warming Potential (GWP) comes from **insulation materials**, followed by **mineral building products** such as concrete. **Wood** also accounts for a significant share of the total impact. Other notable contributors include **components for windows and curtain walls**, **metals**, and **plastics**, which have smaller but still relevant impacts. These results highlight that the environmental impact is highly influenced by material choices—particularly insulation and structural elements. Therefore, selecting insulation materials with a low environmental impact is crucial for minimizing the overall footprint of the single-family house.

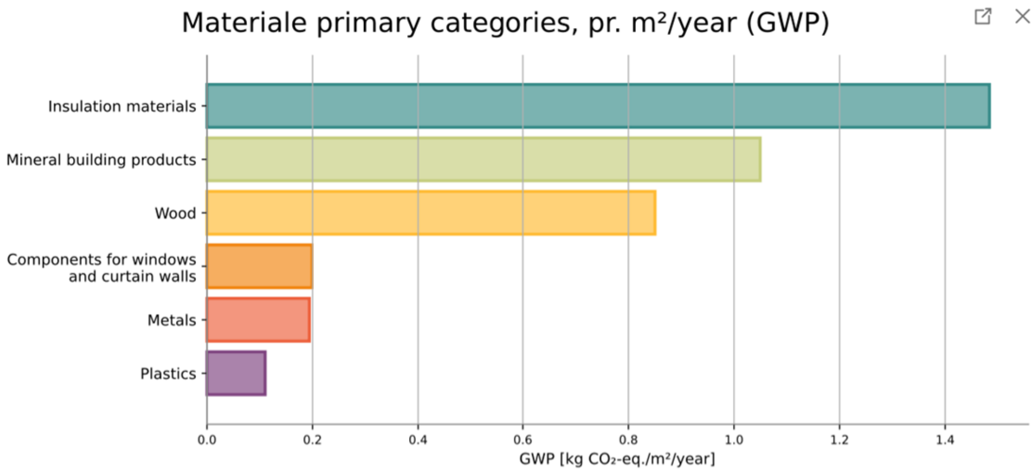
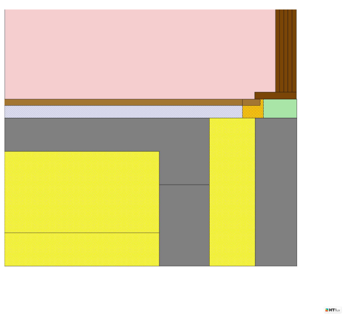
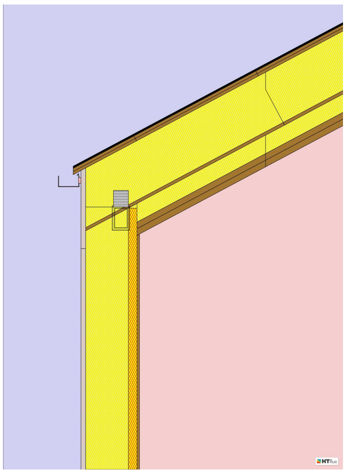
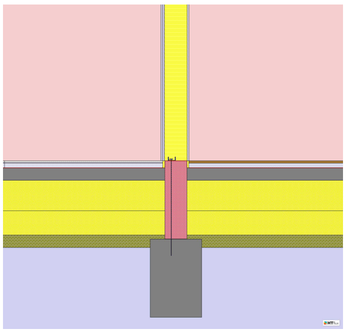
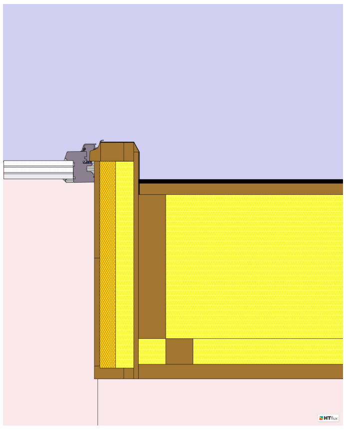
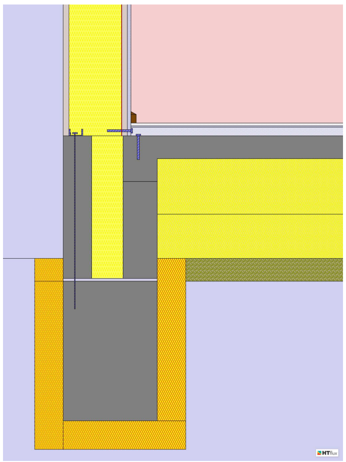


Figure 3.14: LCA-Materials-Single-Family House

3.8.2 Single–family house – overview of thermal bridge optimized materials

Component	Description of added materials in optimized version
	**Door thermal bridge:** 50×45 mm perimeter insulation added and a thermal break placed beneath the door frame.

Component	Description of added materials in optimized version
	**Roof-wall thermal bridge:** 35 mm mineral wool added.
	**Int. foundation thermal bridge:** 140 mm of lightweight concrete block added.
	**Skylight thermal bridge:** 75 mm of mineral wool insulation added at the skylight joint.

Component	Description of added materials in optimized version
	**Wall–floor–foundation thermal bridge:** 100 mm of XPS insulation added around the foundation block

3.8.3 Single–family house – LCA for thermal bridges

Figure 3.15 presents the Global Warming Potential (GWP) of each thermal junction in the single-family house before and after implementing optimized thermal bridge solutions. The results show that some thermal bridges exhibit minimal changes in GWP, while others experience notable increases due to material adjustments.

The **Door-Thermal Bridge**, **Wall-Floor**, **Wall-Floor-Balcony**, and **Window Thermal Bridges** show negligible or no variation in GWP, indicating that the optimization strategy had little impact on their environmental footprint or was not applied.

The **Roof-Wall Thermal Bridge** experiences a 2.50% increase, while the **Skylight Thermal Bridge** shows a 4.07% increase, suggesting that material changes or insulation modifications slightly affected their embodied emissions. The **Wall-Floor-Foundation Thermal Bridge** sees a 1.16% increase, indicating that adjustments to this junction moderately affect the building's total environmental impact.

The most significant GWP increase occurs in the **Internal Wall-Floor-Foundation Thermal Bridge**, with a 10.08% rise, primarily due to the substitution of partition materials with lower thermal conductivity.

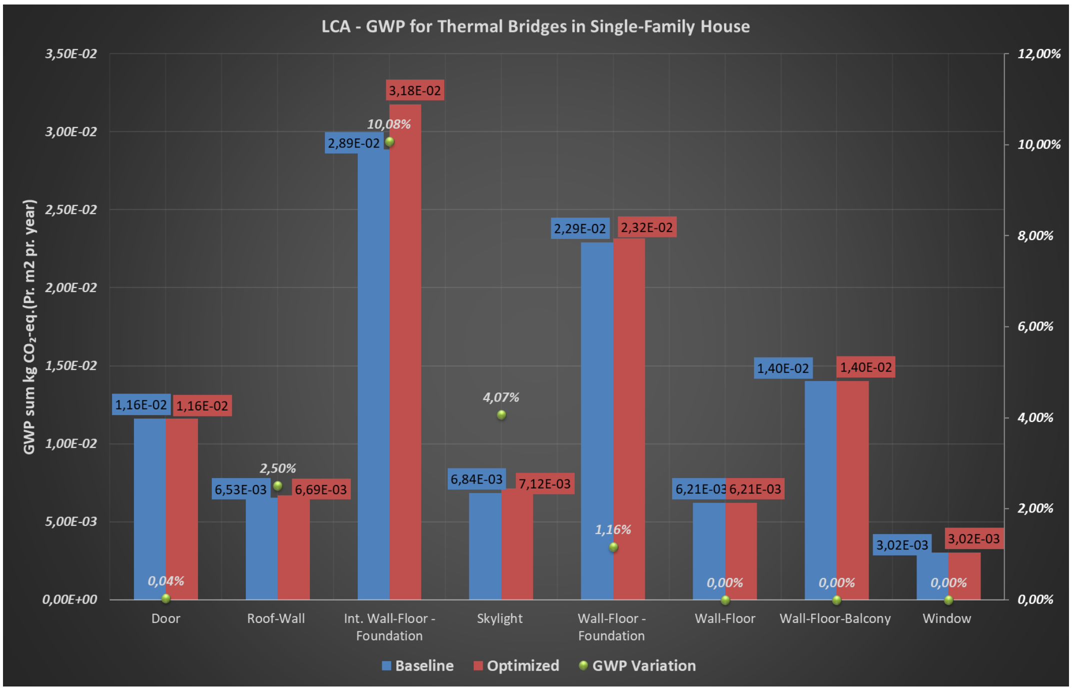


Figure 3.15: LCA - GWP for Thermal Bridges in The Single-Family House

3.9 LCA – Multi–storey building

Stages and components:

The stage analysis shows that the external walls and ground floor slabs are the main contributors to the GWP in **A1–A3**, primarily due to the use of mineral-based materials such as bricks and concrete. In contrast, the roof presents a negative GWP in this stage, which is attributed to its timber-based construction.

C3 contributes significantly to the GWP of the roof, with smaller contributions seen in the external walls and other elements. **C4** also adds to the total GWP, although its impact remains relatively minor across components. **B4** has a modest influence, with the most noticeable contributions appearing in the roof and windows and doors. **D** introduces environmental savings across multiple components, especially for the roof, which benefits from material reuse or recycling at end-of-life.

Looking at the overall results, the highest total GWP contributions are found in the external walls (1.540 kg CO_2-eq/m^2/year), followed by ground floor slabs (0.735), foundations (0.273), and windows and doors (0.142). Other components, such as internal walls (0.092), thermal bridges (0.018), and balconies (0.012), contribute to a lesser extent. The roof, despite its large role in several stages, ends up with a total GWP of –0.183.

Thermal bridges, treated as a separate component, account for approximately **0.7%** of the total GWP from building elements.

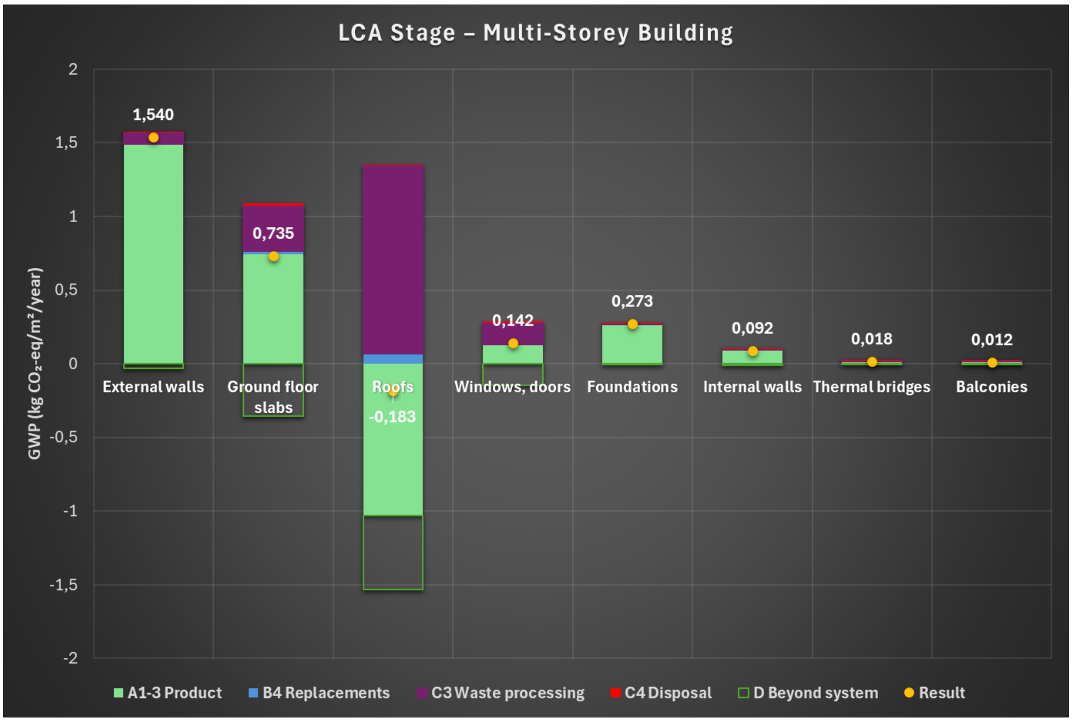


Figure 3.16: LCA-Stages-Multi-Storey Building

Materials analysis:

The materials analysis shows that the highest GWP contribution comes from **mineral building products**, which include materials such as concrete and masonry. This is expected, as the building is primarily constructed using these materials, resulting in a high environmental impact from the structural elements. **Wood** also contributes noticeably, reflecting its use in selected building components. **Insulation materials** and **components for windows and curtain walls** account for smaller, yet still relevant, shares of the total emissions. These results suggest that enhancements to the insulation may not significantly impact the embodied emissions. However, the enhancements in this case also included some mineral materials, such as the inner leaf of the external walls (bricks).

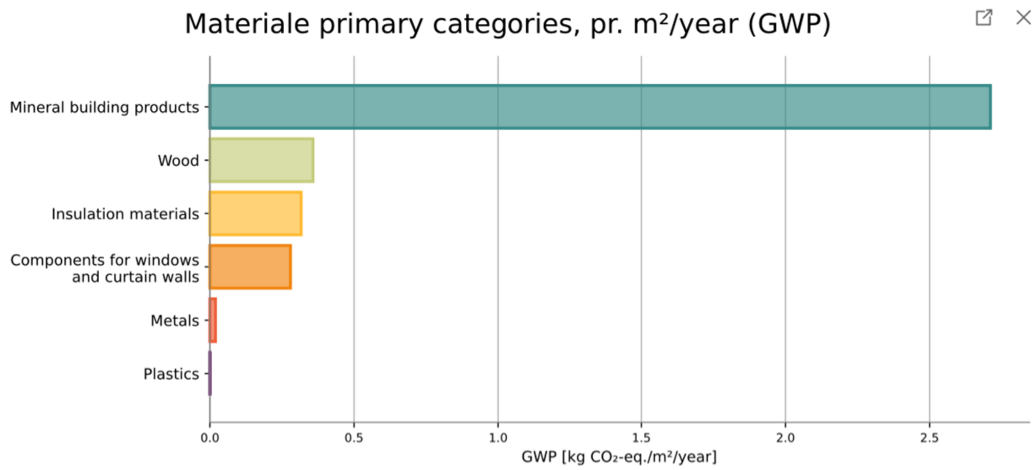
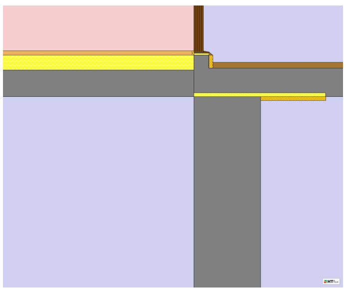
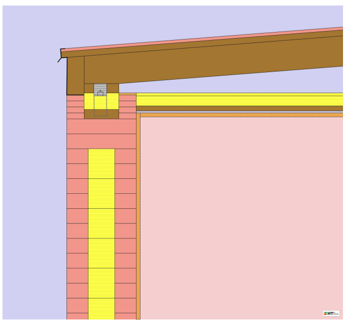
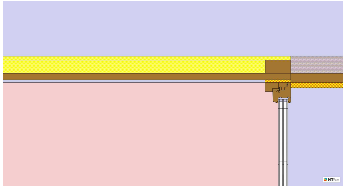
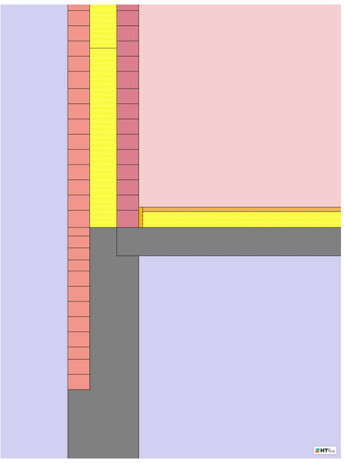
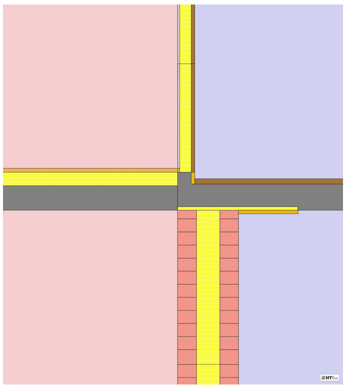
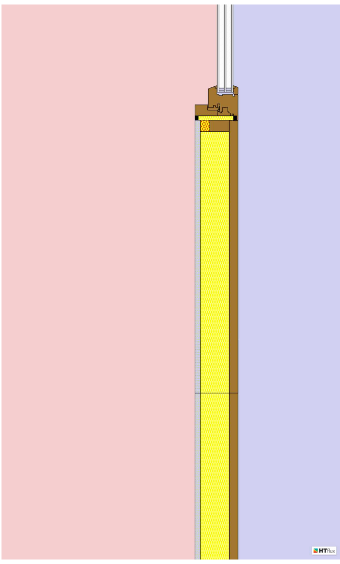
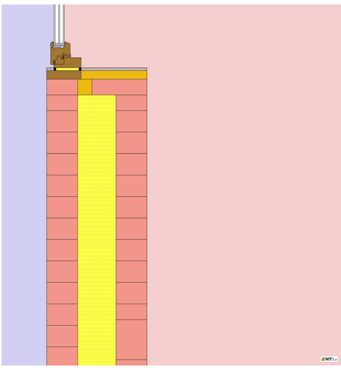


Figure 3.17: LCA-Materials-Multi-Storey Building

3.9.1 Multi–storey building – overview of thermal bridge optimized materials

Component	Description of added materials in optimized version
	**Door thermal bridge:** Several insulation layers applied to separate high-conductivity materials; total insulation volume of 0.00838 m^3/m equals approximately 8 mm thickness per meter along the thermal bridge.
	**Roof-wall thermal bridge:** 20 mm of mineral wool insulation added at the roof and wall.

Component	Description of added materials in optimized version
	**Roof-window thermal bridge:** 20 mm of external mineral wool insulation applied over a 240 mm wide area at the roof–window junction.
	**Ex. wall-Groundfloor thermal bridge:** Lightweight aggregate blockwork with graphite core added to replace the inner layer of the external wall at the ground floor junction, totaling 0.108 m^3/m.
	**Wall-floor-balcony thermal bridge:** Several insulation layers applied to separate high-conductivity materials; total insulation volume of 0.00838 m^3/m equals approximately 8 mm thickness per meter along the thermal bridge.

Component	Description of added materials in optimized version
	**Window 1 thermal bridge:** 25×20 mm mineral wool insulation added around the window frame
	**Window 2 thermal bridge:** 230×30 mm mineral wool insulation added to the window sill and 50×55 mm insulation placed below the window frame to reduce thermal bridging, totaling 0.009 m^3/m.

3.9.2 Multi–storey building – LCA for thermal bridges

Figure 3.18 illustrates the GWP impact of various thermal junctions.

The **door-thermal bridge**, **ex. wall-storey partition thermal bridge**, **wall-floor-balcony thermal bridge**, and **window thermal bridges** exhibit minimal or no variation in GWP. This suggests that either no optimization measures were applied or their impact was negligible due to the structural and design constraints of multi-storey buildings. For instance, the mitigation of the **door-thermal bridge** involved applying 20 mm of external insulation to the balcony slab and adding perimeter insulation to the door frame joint.

Conversely, the **roof-wall thermal bridge** shows a 0.98% increase, while the **roof-window thermal bridge** increases by 0.34%, indicating modifications in insulation or material composition. Similarly, the **wall-floor-foundation thermal bridge** exhibits a 0.08% increase, reflecting a limited influence of optimization strategies on embodied emissions.

The most significant change is observed in the **ex. wall-groundfloor thermal bridge**, where GWP increases by 6.64%. This rise is attributed to the substitution of conventional bricks with low thermal conductivity blocks (lightweight aggregate blocks), which enhance thermal performance but result in higher embodied carbon emissions due to the additional material use.

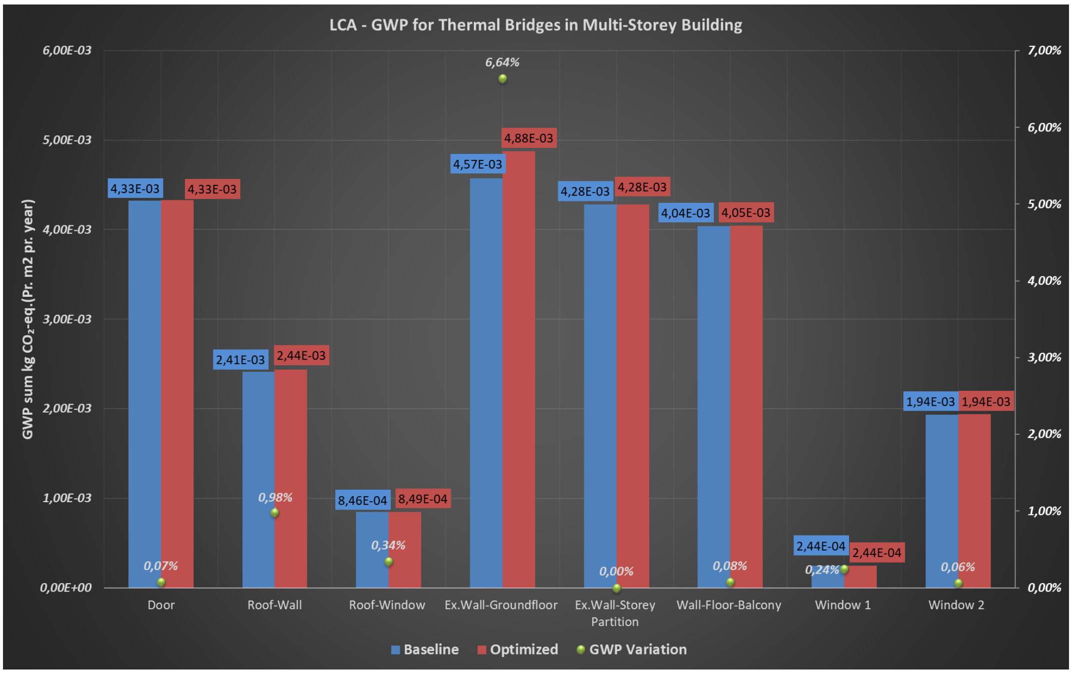


Figure 3.18: LCA - GWP for Thermal Bridges in The Multi-Storey Building

3.10 LCA – kindergarten building

Stages and components:

The GWP distribution in the kindergarten building reflects a structure shaped largely by its material load. Floor decks and external walls stand out as the most emission-intensive components, with contributions of approximately 1.00 and 0.67 in **A1–A3**, respectively. This is primarily due to their high material demands during production. Foundations also contribute significantly (0.52), reinforcing the trend observed in major structural elements. Ground floor slabs contribute around 0.25, while windows and doors show a lower value of roughly 0.10. The roof shows a negative value of around –0.20 in **A1–A3**.

C3 has a noticeable impact, particularly on the roof, where it dominates the total GWP (0.045), followed by moderate contributions in external walls, windows and doors, and floor decks. **B4** remains modest overall but is visible in windows and doors (0.137). **C4** is present across components but has a minor influence overall. The roof contributes less than other major components overall, largely due to lower material intensity and the environmental benefits from **D**, which partly offset its emissions.

The total GWP results, the highest contributors are the floor decks (1.096), followed by external walls (0.729), foundations (0.552), and ground floor slabs (0.289). Components such as windows and doors (0.137), roofs (0.045), internal walls (0.034), and thermal bridges (0.077) show comparatively lower impacts.

Thermal bridges account for approximately **2.6%** of the total GWP from building elements. This value highlights their relevance and suggests that design improvements should take their embodied impact into account.

All values are expressed in kg CO_2-eq/m^2/year.

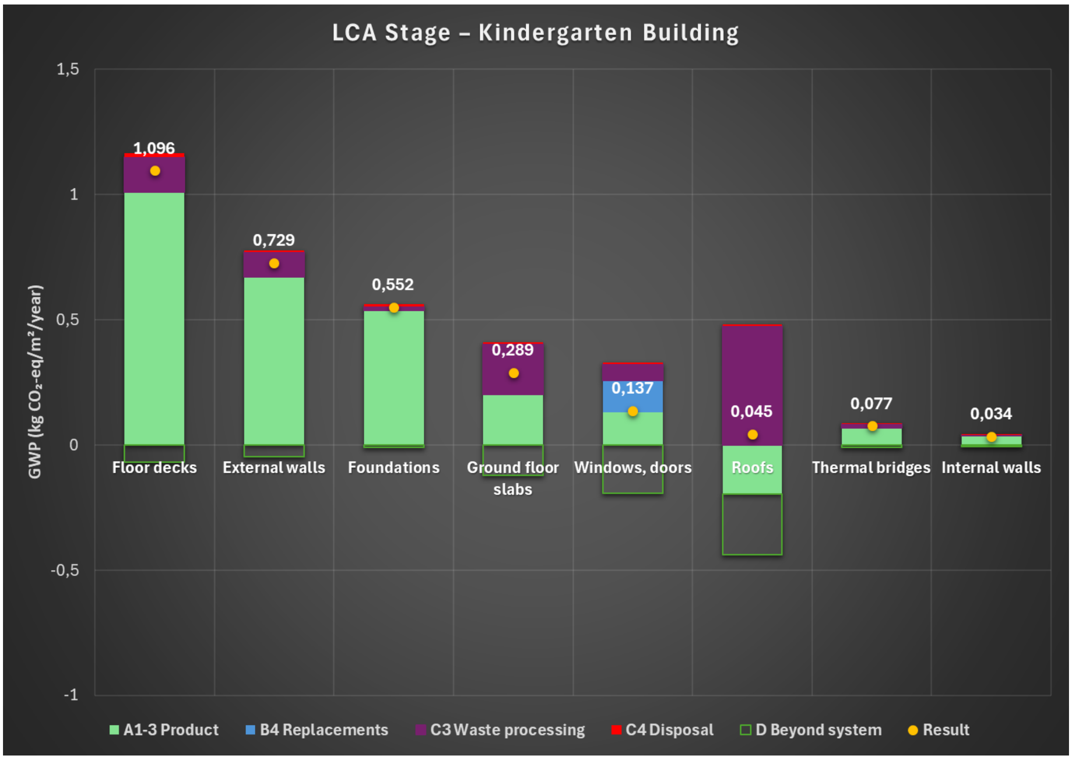


Figure 3.19: LCA-Stages-Kindergarten Building

Materials analysis:

The material breakdown for the kindergarten building clearly shows that the largest share of GWP comes from **mineral building products**, which include concrete and masonry elements commonly used in the structure. **Insulation materials** also contribute significantly, likely due to additional thermal improvements. **Components for windows and curtain walls** and **wood** follow, though with a smaller share of the total impact. Other categories such as **plastics** and **metals** play only a minor role. These results reflect a construction profile where structural mass and insulation requirements dominate the environmental footprint.

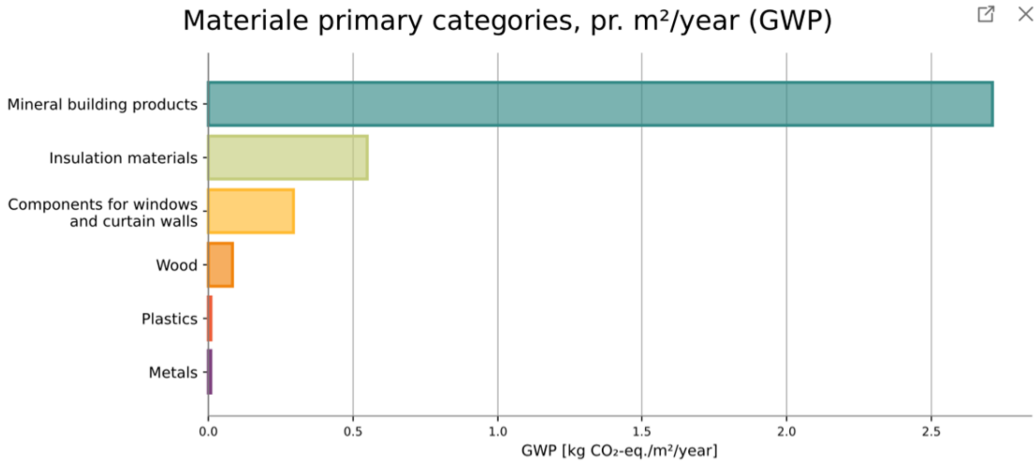
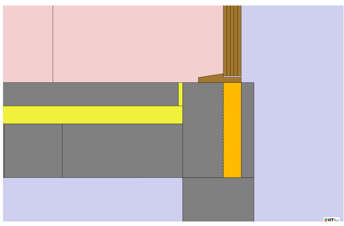
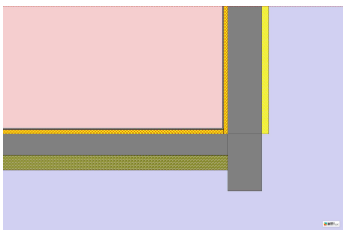
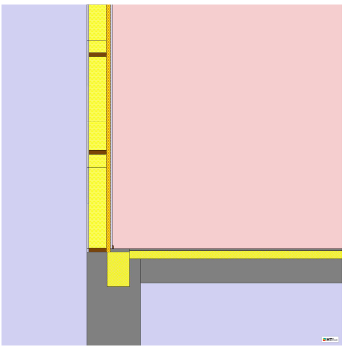
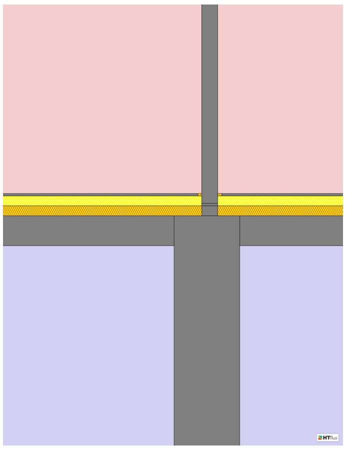
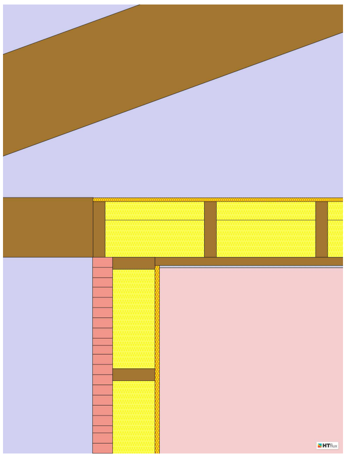
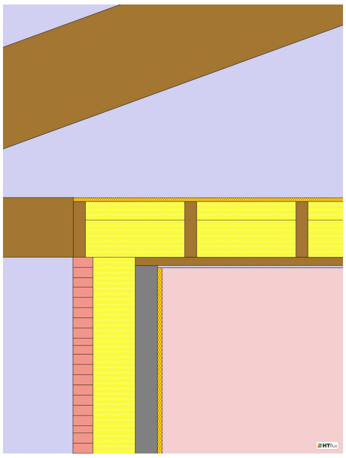
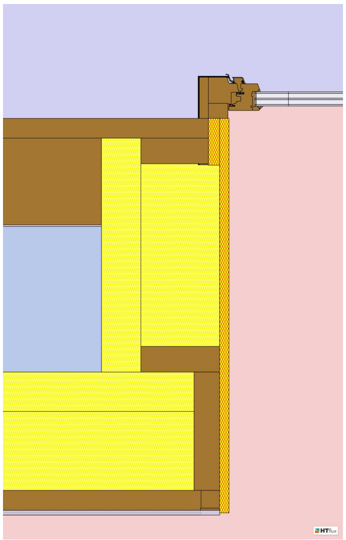
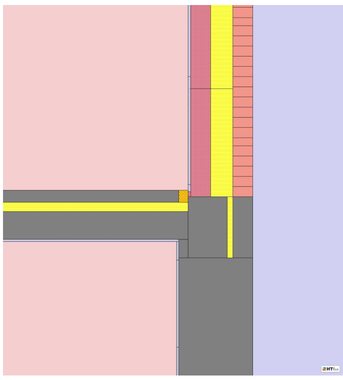


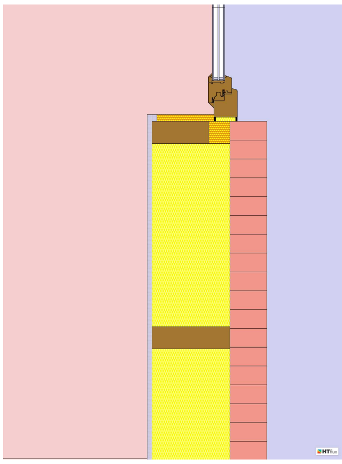
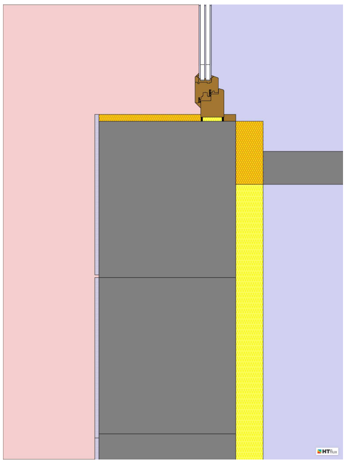
Figure 3.20: LCA-Materials-Kindergarten Building

3.10.1 Kindergarten building building – overview of thermal bridge optimized materials

Component	Description of added materials in optimized version
	**Door thermal bridge:** 50×265 mm (0.01325 m^3/m) of extruded polystyrene (XPS) added beneath the door frame inside the foundation block.
	**Basement wall-floor thermal bridges:** 50 mm (0.05 m^3/m) of mineral wool and extruded polystyrene (XPS) were added along the wall and floor, respectively.

Component	Description of added materials in optimized version
	**Foundation-floor thermal bridge:** 25 mm (0.025 m^3/m) of mineral wool added at the window board.
	**Int. foundation thermal bridge:** 50 mm (0.05 m^3/m) of XPS added between the internal foundation and the optimized floor deck.
	**Roof-wall thermal bridge:** 25 mm (0.025 m^3/m) of mineral wool (or insulated plaster board) added to both the roof and the wall.

Component	Description of added materials in optimized version
	**Roof-wall 2 thermal bridge:** 25 mm (0.025 m^3/m) of mineral wool added to both the roof and the wall.
	**Skylight thermal bridge:** The frame height was reduced, and insulated plasterboards were added to the skylight sill.
	**wall-floor thermal bridge:** 120 mm (0.12 m^3/m) of lightweight concrete blocks and 0.00325 m^3/m of XPS were added at the base of the external wall and floor slab connection.

Component	Description of added materials in optimized version
	**Window 1 thermal bridge:** 0.0072 m^3/m of mineral wool was added around the window frame to improve insulation and reduce thermal bridging.
	**Window 2 thermal bridge:** 0.006 m^3/m of mineral wool was added around the window frame.

3.10.2 kindergarten building – LCA for thermal bridges

Figure 3.21 illustrates the GWP impact of various thermal bridges in the kindergarten building. Unlike multi-storey structures, where structural constraints limit mitigation strategies, single-storey buildings offer greater flexibility in applying insulation and optimizing materials. As a result, thermal bridge mitigation is often more effectively implemented in kindergartens compared to multi-storey buildings, where load-bearing requirements and design limitations restrict interventions.

The **door-thermal bridge**, **foundation-floor thermal bridge**, **roof-wall thermal bridge**, and **window thermal bridges** show negligible changes in GWP, suggesting that either optimization measures were minimal or had little impact due to existing design constraints. For instance, perimeter insulation was applied to the **door-thermal bridge** and **foundation-floor thermal bridge**, while post-insulation of the **roof-wall thermal bridge** with 20 mm thickness resulted in a low GWP increase.

In contrast, the **roof-wall thermal bridge** recorded a 1.22% increase, indicating that material adjustments played a small yet measurable role in embodied emissions. Similarly, the **roof-wall 2 thermal bridge** saw a 0.88% rise, underscoring the limited effectiveness of optimization efforts in these areas.

The most substantial change was observed in the **wall-floor thermal bridge**, which experienced a 9.38% increase, while the **internal foundation thermal bridge** recorded a 5.28% increase in GWP. This rise is attributed to the use of low thermal conductivity materials that enhance insulation but simultaneously increase embodied carbon emissions due to the additional material required for improved thermal performance, including 100 mm of insulation added to the floor below the internal foundation and low thermal conductivity concrete used in the wall-floor junction.

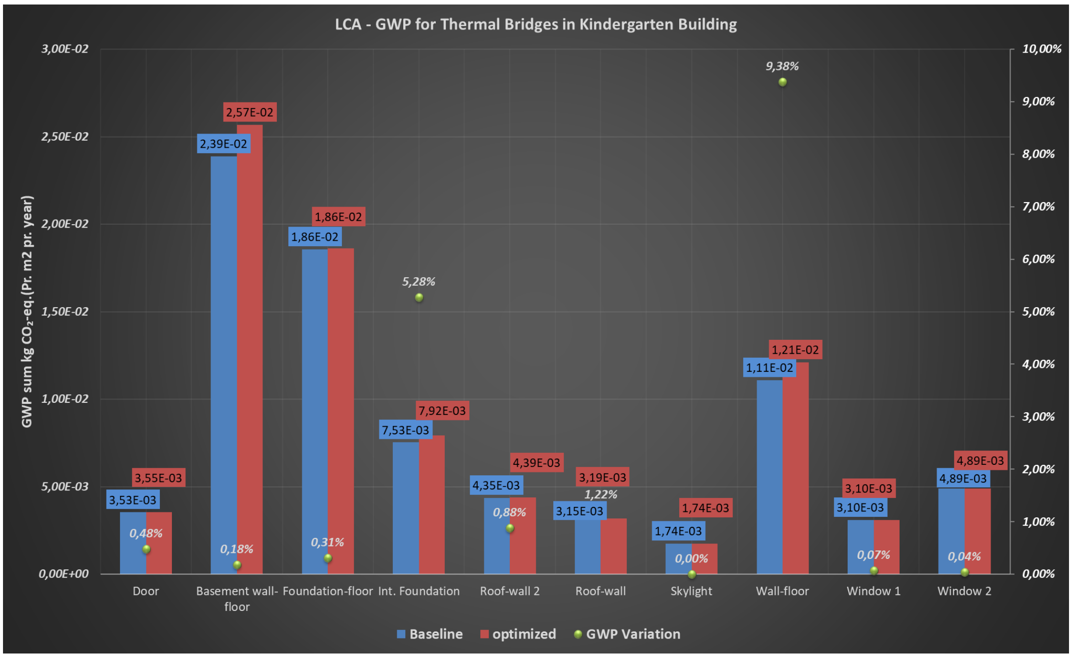


Figure 3.21: LCA - GWP for Thermal Bridges in The Kindergarten Building

3.11 GWP variation across building cases

The final step of the LCA analysis is to compare the embodied GWP and operational energy use across the cases over a 50-year span. Figure 3.22 illustrates the total GWP for each case in both baseline and optimized versions, along with the variations observed after optimization.

In the single-family house case, the embodied GWP increased by 0.55% due to the additional materials used for construction optimizations. However, the operational GWP decreased by 4.51%, attributed to an improved energy performance following enhancements to the building envelope.

For the multi-storey building, a significant reduction in operational GWP was achieved, decreasing by 14.76%. Meanwhile, the embodied GWP increased by only 3.81%, leading to an overall improvement of 10.95% in the total GWP of the building.

The kindergarten case also demonstrated a notable reduction in total GWP, achieving a 6.14% decrease, highlighting the effectiveness of optimization strategies in reducing the building's environmental impact.

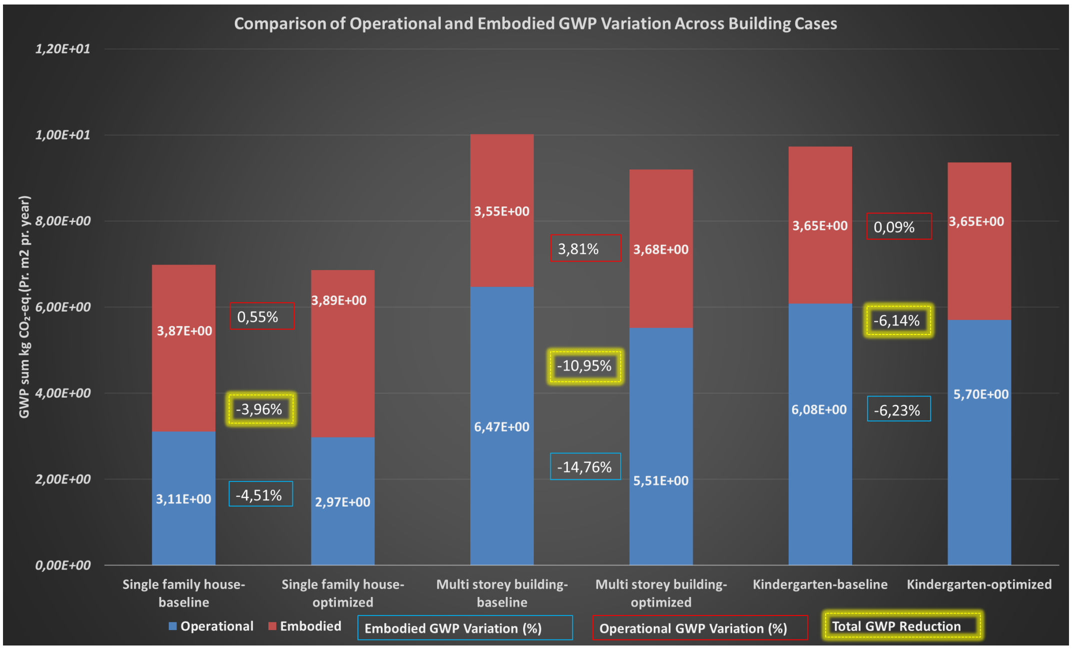


Figure 3.22: Comparison of Operational and Embodied GWP Variation Across Building Cases

Chapter 4

Discussion

This chapter presents a critical discussion of the findings from this study, focusing on heat loss mitigation strategies and their environmental impact. The analysis highlights key considerations related to thermal bridge solutions, addressing challenges associated with moisture control, fire safety, structural durability, and the environmental impact of materials. The discussion further examines the life cycle assessment (LCA) results, emphasizing the implications of material choices on the overall sustainability of the building.

4.1 Heat loss

The mitigation of thermal bridges is a complex process that requires a holistic approach to ensure both energy efficiency and the long-term integrity of the building. The optimizations applied in this study specifically targeted the reduction of linear thermal transmittance, thereby minimizing the overall transmission losses. However, several additional factors must be considered when implementing thermal bridge solutions:

- **Moisture management:** While reducing thermal losses, it is critical to assess moisture-related risks. Implementing additional insulation or modifying construction elements may alter the vapor diffusion and condensation behavior within the structure. This necessitates a thorough evaluation of moisture barriers, such as damp-proof membranes (DPM), to prevent mold growth and structural deterioration. The correct placement of these barriers is essential to avoid unintended moisture accumulation.
- **Fire safety considerations:** Modern fire safety regulations are becoming increasingly stringent, requiring careful assessment of materials used in thermal bridge mitigation. Some insulation materials with favorable thermal conductivity properties may not meet fire resistance standards. Collaboration with fire safety specialists is essential to ensure that the selected materials balance thermal performance with compliance to fire safety codes. In some cases, alternative fire-resistant materials with similar thermal conductivity may be required.
- **Structural durability and load-bearing capacity:** Optimizing thermal bridges in load-bearing elements presents additional structural challenges. The choice of mate-

rials must align with both thermal performance and mechanical durability requirements. Certain insulation materials may affect the load-bearing strength of structural elements, necessitating careful selection to ensure long-term stability. Additionally, optimizing thermal bridges in reinforced concrete or steel structures may require adjustments in design to maintain the building's structural integrity over time.

4.2 Life cycle assessment (LCA)

The materials selected for the LCA analysis in this study are conventional construction materials based on Danish Environmental Product Declarations (EPDs). While these materials comply with industry standards, recent research highlights the potential of bio-based and carbon-negative materials in improving both thermal performance and environmental impact.

Studies indicate that bio-based insulation materials, such as hempcrete, wood fiber, and straw, offer superior environmental performance compared to synthetic alternatives, primarily due to their carbon sequestration potential and lower embodied emissions [29]. Additionally, cork-based insulation and mineral wool have been identified as highly effective materials that balance thermal efficiency with a low environmental footprint [28]. These materials not only reduce operational energy demand but also minimize end-of-life environmental burdens, making them strong candidates for sustainable renovations [29].

Furthermore, carbon-infused concrete and other carbon-negative materials present an opportunity to sequester CO_2 while simultaneously mitigating thermal bridges, leading to a net-positive environmental impact [29]. However, despite their promise, challenges related to scalability, cost-effectiveness, and long-term durability must be addressed before widespread adoption.

Future research should expand LCA comparisons to a broader range of materials, considering factors such as resource availability, recyclability, end-of-life impact, and carbon sequestration potential [28, 29]. A holistic approach integrating thermal simulations, embodied carbon analysis, and economic feasibility (LCC) assessments will be essential in defining optimal solutions for climate-resilient and energy-efficient buildings.

Chapter 5

Conclusion

This chapter presents the conclusions of the study and addresses the problem statement.

Effective thermal bridge strategies: Thermal bridge mitigation starts with their identification. In existing buildings, thermographic cameras detect the coldest areas, while simulations assist in the design and renovation phase. By analyzing heat flow direction and magnitude, the primary pathways of heat loss are mapped. This process enables the optimal placement of thermal breakers, enhancing energy efficiency and reducing environmental impact. Additionally, selecting appropriate insulation materials and construction techniques further minimizes thermal losses while maintaining structural integrity and regulatory compliance.

The choice of strategy depends on the magnitude and nature of the thermal bridge. For instance, in a single-family house, the most significant thermal bridge impact was observed at the internal foundation, where the partition wall's steel frame is placed on the partition foundation. In the design phase, this issue can be addressed by selecting a low-conductivity material for the foundation. However, in a renovation scenario, applying a thermal breaker beneath the partition wall is the most viable approach, although it may be less efficient.

In renovation projects, replacing materials can be challenging, making thermal bridge mitigation more complex. The most effective strategies involve adding materials to disrupt the thermal bridge and reduce heat loss. Additionally, repositioning elements such as windows, doors, and skylights can improve thermal performance. This was demonstrated in the kindergarten case, where repositioning the skylight reduced the linear thermal loss. Internal post-insulation and insulated plasterboards are also viable solutions for renovations, provided that fire safety and moisture control are carefully considered.

Research questions and results

- **What proportion of total heat loss can be attributed to thermal bridges?** The contribution of thermal bridges to total heat loss varies depending on the calculation method. Standardized values from DS418 estimate that thermal bridges account for **10–32%** of total transmission losses. However, simulation-based calculations indicate a higher contribution, ranging from **30–52%** or more when point losses are also included. This difference highlights the importance of detailed simulation methods, which better capture the geometric complexity and material behavior of building components.

- **To what extent can energy consumption and environmental impact be reduced through effective insulation?** The results show that mitigating thermal bridges leads to significant reductions in both energy consumption and environmental impact. Individual thermal bridge optimizations resulted in reductions of up to **85%** as shown in Figure 3.11, and the total linear thermal losses were reduced by approximately **40–75%**, depending on the building type and construction details, as shown in Figure 3.12. The total transmission losses were reduced by **23.7%** in the single-family house, **22.4%** in the kindergarten, and **21.6%** in the multi-storey building.

  In terms of environmental impact, optimization resulted in a **14.76%** decrease in operational energy-related GWP for the multi-storey building, with only a **3.81%** increase in embodied GWP, leading to an overall net reduction of **10.95%** in total GWP. The kindergarten case demonstrated a total GWP reduction of **6.14%**, highlighting the effectiveness of thermal bridge mitigation strategies as shown in Figure 3.22. These findings indicate that the reduction in operational energy demand outweighs the embodied emissions from additional insulation, making thermal bridge optimization a viable approach for improving building sustainability.

- **Which materials are most effective in mitigating thermal bridge effects?** A range of materials can be used to mitigate thermal bridge effects. **Thermal breakers** are particularly effective when a frame, structural element, or door is placed directly against a highly conductive conventional material. **Insulated plasterboards** are suitable in cases where elements cannot be altered, such as the inner leaf of a load-bearing wall; they can also be used as window sills. **Low-thermal-conductivity blocks** are effective in areas where parts of the wall or foundation can be replaced.

  Increasing the insulation thickness in building components can also help reduce thermal bridging by minimizing direct contact between highly conductive materials.

  As also discussed in the materials analysis, **bio-based insulation materials** such as hempcrete, wood fiber, and straw offer sustainable alternatives with the added benefit of carbon sequestration. Additionally, **carbon-infused concrete** and other carbon-negative materials can further reduce a building's embodied emissions while enhancing thermal performance.

- **How can the trade-off between reduced heating and cooling energy demand and increased embodied emissions from additional insulation be optimized?** Achieving an optimal balance between energy efficiency and embodied emissions requires careful material selection and long-term planning. The findings reveal that insulation upgrades result in substantial operational GWP reductions with relatively modest increases in embodied emissions. Over a 50-year lifespan analysis, the net environmental benefit becomes evident—illustrated by a **10.95%** total GWP reduction in the multi-storey building case. This highlights the importance of life cycle thinking in sustainable building design.

Bibliography

[1] International Energy Agency. *Global Status Report for Buildings and Construction 2021*. Available online: https://globalabc.org/sites/default/files/2021-10/GABC_Buildings-GSR-2021_BOOK.pdf. 2021. URL: https://globalabc.org/sites/default/files/2021-10/GABC_Buildings-GSR-2021_BOOK.pdf.

[2] Anonymous. "Methods for Improving the Thermal Performance of Thermal Bridges of Lightweight Steel-Framed Buildings". In: *PLOS ONE* 12.8 (2017). Accessed January 2025, e0182345. DOI: 10.1371/journal.pone.0314634.

[3] ARCAT. *Roof Windows and Skylights CAD Drawings*. Accessed: 2025-01-23. n.d. URL: https://www.arcat.com/content-type/cad/openings-08/roof-windows-and-skylights-086000.

[4] Thomas Armstrong. *Ultralite Concrete Blocks - Lightweight Dense Concrete Blocks*. Accessed: 2025-01-20. n.d. URL: https://www.thomasarmstrongconcreteblocks.co.uk/lightweight-dense-concrete-blocks/ultralite.

[5] Author(s). "Life Cycle Assessment of Embodied Carbon and Strategies for Decarbonization of a High-Rise Residential Building". In: *Journal Name* (Year). URL: https://www.mdpi.com/2075-5309/12/8/1203.

[6] Fox Blocks. "Thermal Bridging and Its Effects on Building Performance". In: (2023). Accessed: February 14, 2025. URL: https://www.foxblocks.com/blog/thermal-bridging.

[7] BUILD, Aalborg University. *LCAbyg: Life Cycle Assessment Tool for Buildings*. Accessed: 2025-02-05. 2025. URL: https://www.lcabyg.dk/en/.

[8] *Børnehaven Sønderholm Documentation*. Retrieved from AAU Moodle. Document detailing the building specifications and performance of Børnehaven Sønderholm in Nibe, Aalborg.

[9] ClimaSpec. "Condensation Risks | How Structural Thermal Breaks Mitigate". In: (2023). Accessed: February 14, 2025. URL: https://climaspec.com/blog/how-structural-thermal-breaks-mitigate-condensation-risks/.

[10] ClimaSpec. *Windows and Doors Thermal Bridging Solution*. Accessed January 29, 2025. 2024. URL: https://climaspec.com/thermal-bridging-solutions/windows-and-doors-thermal-bridging-solution/.

[11] Jay H. Crandell. *Fundamentals of Thermal Bridging: Small Details with a Large Impact*. Tech. rep. Includes research on foam sheathing and mitigation strategies. Applied Building Technology Group (ABTG), 2023. URL: https://www.continuousinsulation.org.

[12] Jay H. Crandell. "Fundamentals of Thermal Bridging: Small Details with a Large Impact Getting Ready for New Codes". In: *Applied Building Technology Group (ABTG)*. Applied Building Technology Group (ABTG). 2023. URL: https://www.appliedbuildingtech.com/system/files/modules/node/136/thermalbridging2023.pdf.

[13] Danish Transport, Construction and Housing Authority. *Executive Order on Building Regulations 2018*. Accessed: 2024-11-08. 2018. URL: file:///mnt/data/BR18_Executive_order_on_building_regulations_2018.pdf.

[14] *Dokumentation af tæthedskrav 0.8 l/s en m²*. Building leakage test report for Elektravej 22, Aalborg SØ. Prepared by Dansk Infrarød Inspektion A/S, in compliance with ISO 9972 standards. Dansk Infrarød Inspektion A/S, 2020. URL: http://www.energivision.dk.

[15] *Energimærke A2015: Energy Labeling Report for Elektravej 22, 9210 Aalborg SØ*. Prepared by Danish Infrared Inspection A/S, CVR no.: 26225027. Validity: April 3, 2024 - April 3, 2034. 2023. URL: https://www.infrared.dk.

[16] H2X Engineering. *Understanding Thermal Bridging + Its Impact on Building Heat Loss*. Accessed January 2025. n.d. URL: https://www.h2xengineering.com/blogs/understanding-thermal-bridging-impact-building-heat-loss.

[17] ROCKWOOL Group. *Commercial Retrofit Solutions Guide*. Tech. rep. Focuses on energy retrofits and thermal efficiency improvements. ROCKWOOL Group, n.d.

[18] HTflux. *HTflux — Heat Transfer Simulation Software*. [Online; accessed 15-January-2025]. 2025. URL: https://www.htflux.com.

[19] HTflux. *Tutorial: Psi-value Thermal Bridging*. Accessed: February 2025. 2024. URL: https://www.htflux.com/en/documentation/tutorial-psi-value-thermal-bridging/.

[20] Zero Carbon Hub and Luke Whale. *Thermal Bridging Guide: An Introductory Guide to Thermal Bridging in Homes*. Available as PDF download from LABC website. Zero Carbon Hub. n.d. URL: https://www.labc.co.uk/sites/default/files/resource_files/zch-thermalbridgingguide-screen.pdf.

[21] International Organization for Standardization. *ISO 10211:2017 Thermal Bridges in Building Construction — Heat Flows and Surface Temperatures — Detailed Calculations*. IDT with EN ISO 10211:2017 and DS/EN ISO 10211:2017. ISO. Geneva, Switzerland, 2017.

[22] International Organization for Standardization. *ISO 14683:2017 Thermal Bridges in Building Construction — Linear Thermal Transmittance — Simplified Methods and Default Values*. IDT with EN ISO 14683:2017 and DS/EN ISO 14683:2017. ISO. Geneva, Switzerland, 2017.

[23] Amdi Schjødt Worm et al. Mads Hulmose Wagner Steffen E. Maagaard. *Kuldebroer og deres indflydelse på klimaskærmens varmetab*. Tech. rep. Supported by the Landowners Investment Fund. MOE A/S, Arkitema Architects, NCC Danmark A/S, VIA Construction, Energy & Environment, 2018. URL: https://gi.dk/media/q2pnnzd2/kuldebroer_og_deres_indflydelse_p-_klimask-rmens_varmetab.pdf.

[24] Amrish K. Patel and Kyle M. Nay. "Optimizing Renovation: Unveiling Thermal Bridging in Existing Buildings Through Modeling". In: *Building Enclosure Science and Technology*. Building Enclosure Science and Technology Conference. 2024. URL: https://www.buildinginnovation.org/sites/default/files/best/presentations/Optimizing-Renovation-Unveiling-Thermal-Bridging-in-Existing-Buildings-through-Modeling.pdf.

[25] RIBuild Project. *Types of Insulation Systems: Condensate Limiting Solutions*. Accessed January 27, 2025. 2020. URL: https://www.ribuild.eu/types-of-insulation-systems/#condensate-limiting.

[26] *Referat omkring Magisterparken*. Comprehensive documentation detailing the renovation plans, including architectural and structural updates for Magisterparken. Prepared by Himmerland Boligforening in collaboration with C.F. Møller Architects and MOE Consulting Engineers. Himmerland Boligforening, 2023. URL: https://www.himmerlandsboligforening.dk.

[27] Danish Building Research Institute (SBi). *SBI 213: Thermal Insulation of Buildings – Calculation Rules*. SBI 213 provides guidelines for thermal insulation and heat loss calculations. SBi. Copenhagen, Denmark, 2009. URL: https://www.build.aau.dk/til-byggebranchen/software/be18.

[28] José Dinis Silvestre, Jorge de Brito, and Manuel Duarte Pinheiro. "Life-Cycle Assessment of Thermal Insulation Materials for External Walls of Buildings". In: *Conference on Sustainable Construction*. Technical University of Lisbon (UTL) - IST, Department of Civil Engineering and Architecture. 2011. DOI: 10.13140/RG.2.1.1756.7768. URL: https://www.researchgate.net/publication/283326066_Life-Cycle_Assessment_of_Thermal_Insulation_Materials_for_External_Walls_of_Buildings.

[29] Andreas Stephan and Robert H. Crawford. "Comparative life cycle assessment of bio-based insulation materials". In: *Global Change Biology Bioenergy* 11.4 (2019), pp. 848–868. DOI: 10.1111/gcbb.12825. URL: https://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.12825.

[30] *Sustainability of Construction Works – Environmental Product Declarations – Core Rules for the Product Category of Construction Products*. Brussels, Belgium. Available at: https://webshop.ds.dk/standard/M335258/ds-en-15804-2012-a2-2019. 2012.

[31] VIA University College, Jens Peder Pedersen. *DS418 Calculation of Heat Loss from Buildings*. 7th Edition. Danish Standard. Copenhagen, Denmark, 2011.

[32] Build Meets World. *Thermal Bridging: What Are the Effects?* Accessed: 2025-02-16. 2025. URL: https://blog.buildmeetsworld.com/thermal-bridging-what-are-the-effects.

Chapter 6

Appendix-A-

6.1 Design transmission loss calculation

The design transmission heat loss of the building is calculated using two primary equations: one for surface elements and another for linear thermal bridges. These equations are based on DS 418 standards.

6.1.1 Design transmission loss for surface elements

The total design transmission loss (Φ_t) through building elements such as walls, floors, and roofs is determined using the equation:

$$\Phi_t = A \cdot U \cdot (\theta_i - \theta_u) \tag{6.1}$$

where:

- A = Transmission area of the building element (m^2)
- U = Thermal transmittance (U-value) of the building element (W/m^{2}K)
- θ_i = Indoor design temperature (°C)
- θ_u = Outdoor design temperature (°C)

6.1.2 Design transmission loss for linear thermal bridges

To account for additional design heat loss at junctions, the transmission loss due to linear thermal bridges is calculated as:

$$\Phi_t = l \cdot \Psi \cdot (\theta_i - \theta_u) \tag{6.2}$$

where:

- l = Length of the thermal bridge (m)
- Ψ = Linear thermal transmittance (W/mK)

6.2 Line losses in this section based on standard values - DS418

6.2.1 Analysis Scope: Inclusion of Windows and Doors

The first step in the transmission analysis is to evaluate whether windows and doors should be included in the heat loss assessment. By comparing scenarios with and without these elements, the impact of their presence on the overall thermal performance is assessed. This approach helps determine the most effective insulation strategies and identify critical areas for improvement. Understanding the contribution of windows and doors to heat transfer is essential for optimizing building envelope performance and minimizing thermal bridging effects.

6.2.2 Single family house

Heat Loss Distribution: Including Windows and Doors: When including all components, the windows are identified as the largest contributor to the building's total heat loss, accounting for 31% or 910 W. This is followed by doors, contributing 22% of the heat loss at 648 W. Together, windows and doors represent more than half of the total heat losses, underscoring the importance of addressing these elements in any renovation or insulation strategy.

The walls also contribute a significant portion of the heat loss, amounting to 21% or 641 W. Roofs contribute 10% (307 W), while floors account for 4% (115 W). These components indicate further opportunities for improvement through enhanced insulation.

In addition to these main elements, linear thermal losses—which represent heat loss along joints, edges, and interfaces between building elements—make up a combined 12% of the total heat loss. These linear losses can be broken down as follows:

- Line loss between the outer wall and windows/doors: 105 W (3%)
- Line losses at foundations with underfloor heating (UFH): 171 W (6%)
- Line loss between the roof structure and windows: 83 W (3%)

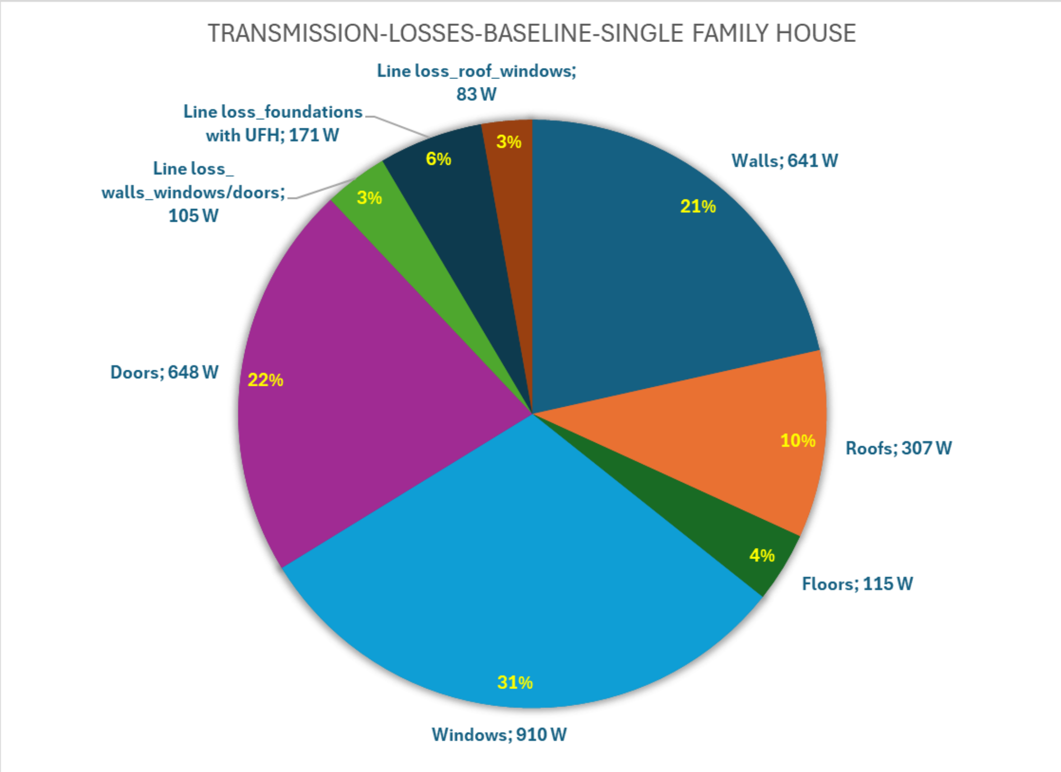


Figure 6.1: Transmission-losses-Percentage-Baseline-single family house

Heat Loss Distribution: Excluding Windows and Doors

The chart 6.2 illustrates the distribution of heat losses across various building components in a single-family house, excluding windows and doors from the analysis, in contrast to Appendix A, where they are included. Walls contribute the largest proportion of heat loss at 45% (641 W), marking them as a primary focus for insulation improvement. Roofs account for 22% (307 W), while floors represent 8% (115 W).

In this scenario, linear thermal losses become more significant, making up 25% of the total heat loss. These are detailed as follows:

- Line losses at foundations with underfloor heating (UFH): 12% or 171 W
- Line losses between walls and windows/doors: 7% or 105 W
- Line losses between the roof structure and windows: 6% or 83 W

This distribution highlights significant thermal bridges within the building structure, particularly at foundations, wall joints, and roof interfaces. Targeting these areas, along with walls and roofs, presents substantial opportunities for improving the building's overall energy efficiency.

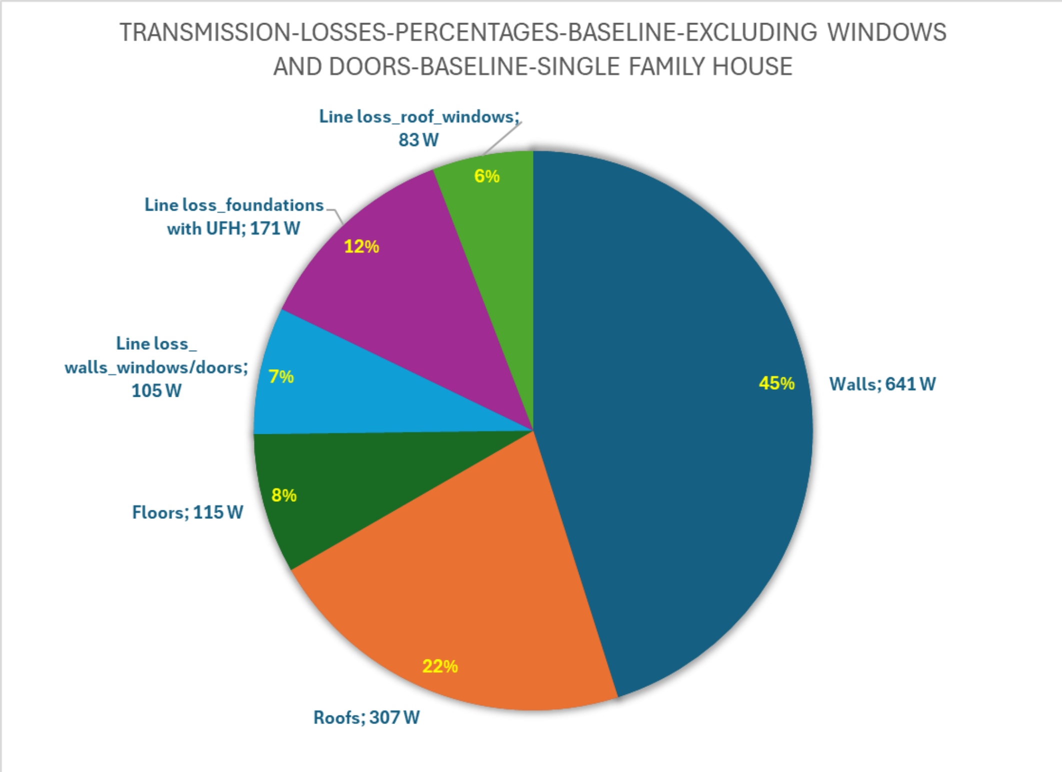


Figure 6.2: Transmission-losses-Percentages-Baseline-excluding windows and doors-single family house

6.2.3 Multi-storey

Heat Loss Distribution: Including Windows and Doors: In Case 2, when all components, including windows and doors, are considered, the windows and doors contribute the most to heat losses, accounting for 56% or 14,470 W. This is followed by the walls, which represent 15% or 3,994 W of the total heat loss. The roofs and floors contribute 8% and 7%, with losses of 1,949 W and 1,780 W, respectively.

Furthermore, line losses are broken down as follows:

- Line loss at foundations contributes 5% (1,393 W)
- Line loss at walls/windows/doors contributes 9% (2,198 W)

The dominance of windows and doors highlights the need for effective insulation strategies for these elements to improve energy efficiency.

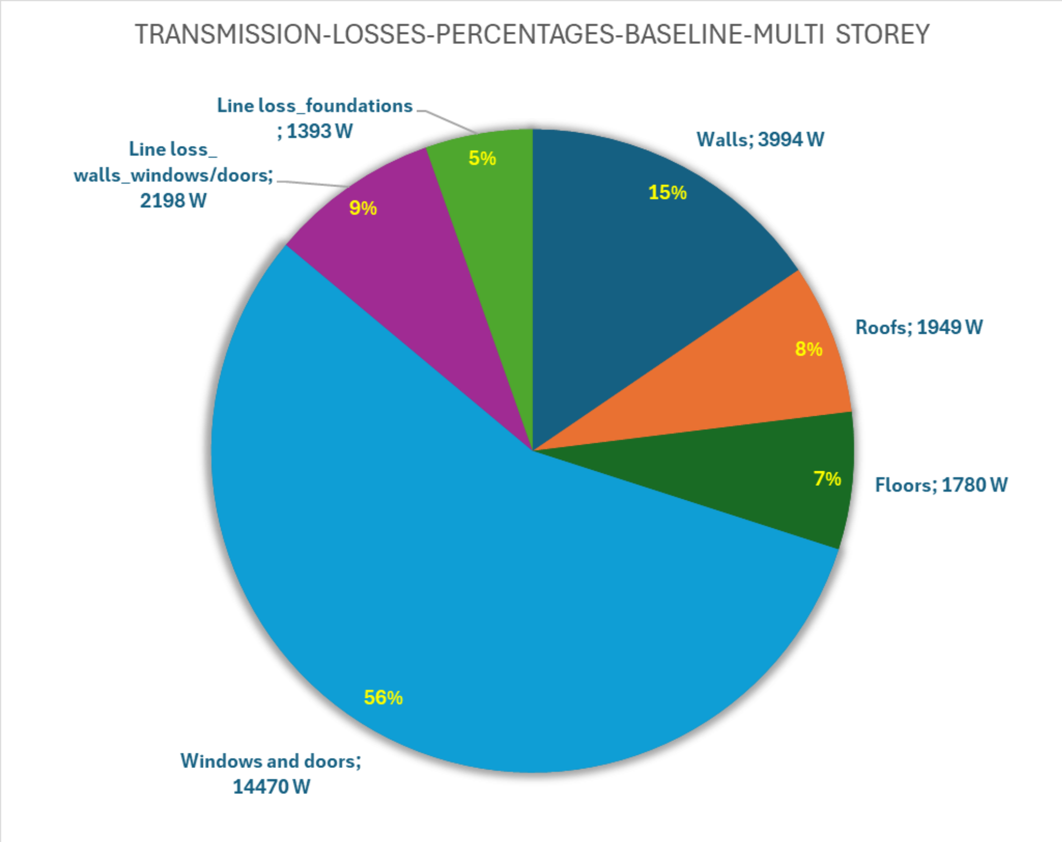


Figure 6.3: Transmission-losses-Percentages-Baseline-multi storey

Heat Loss Distribution: Excluding Windows and Doors

The chart 6.4 illustrates the distribution of heat loss across various components in a multi-storey building, excluding windows and doors, in contrast to Appendix A, where these elements are included. With windows and doors excluded, walls emerge as the largest source of heat loss, contributing 35% or 3,994 W. Roofs account for 17% (1,949 W), while floors represent 16% (1,780 W).

Line losses are also significant in this analysis, with the following contributions:

- Line loss at foundations: 12% or 1,393 W
- Line loss at wall/window/door interfaces: 20% or 2,198 W

This distribution underscores the need for improved wall insulation and highlights that line losses, particularly at foundations and wall/window interfaces, are substantial contributors to overall heat loss. Addressing these thermal bridges could yield significant energy savings.

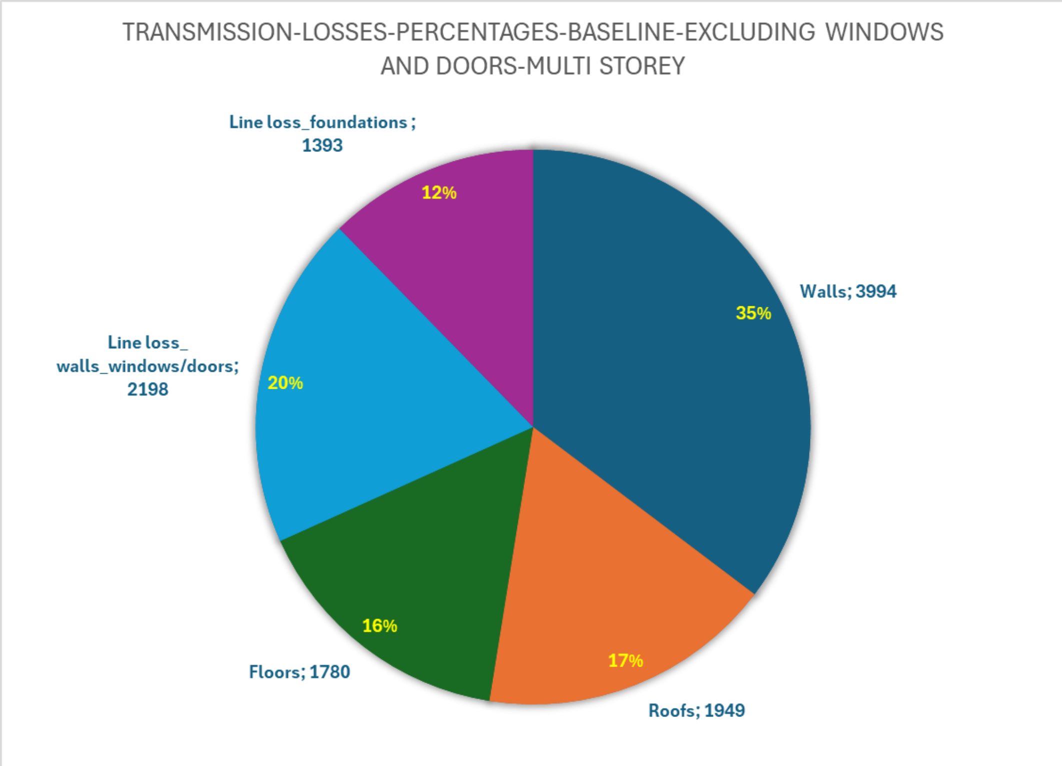


Figure 6.4: Transmission-losses-Percentages-Baseline-excluding windows and doors-multi storey

6.2.4 Case 3: Kindergarten

Heat Loss Distribution: Including Windows and Doors:

In this baseline scenario, when considering all components, **windows and doors** contribute the most to heat losses, representing **36%** or **5,450 W**. This is followed by the **walls**, which account for **17%** or **2,504 W** of the total heat loss. The **roofs** and **floors** contribute **21%** and **20%**, with losses of **3,121 W** and **2,976 W**, respectively.

Furthermore, line losses are broken down as follows:

- **Line loss at foundations** contributes **5%** (790 W).
- **Line loss at walls/windows/doors** contributes a minor **1%** (135 W).

The significant heat loss through windows and doors highlights the need for effective insulation strategies in these elements to improve the overall energy efficiency of the building.

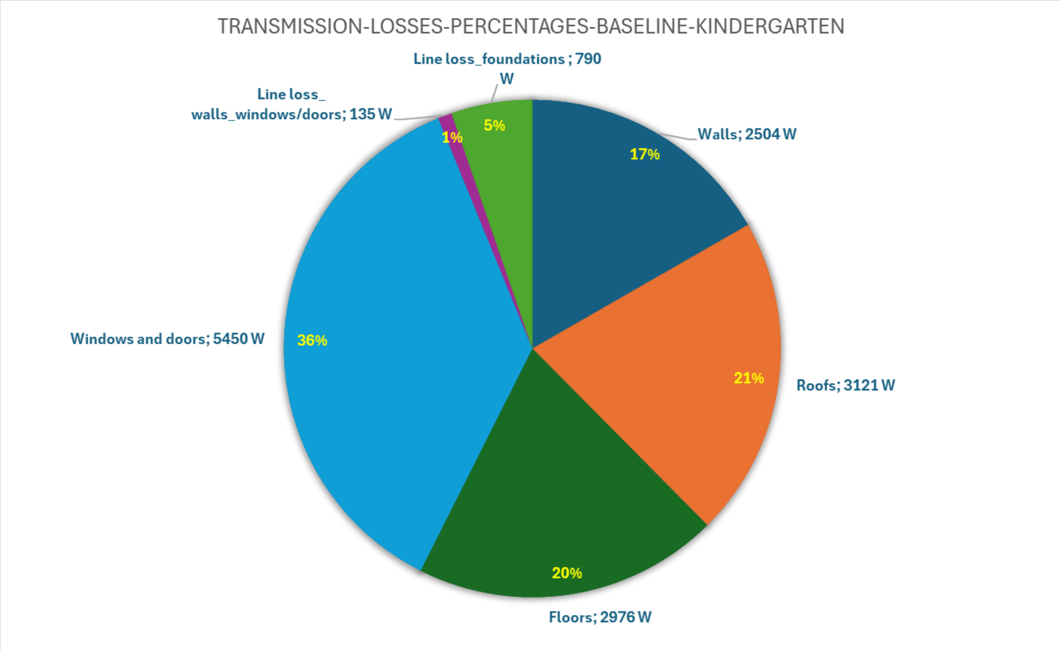


Figure 6.5: Transmission-losses-Percentage-Baseline-kindergarten

Heat Loss Distribution: Excluding Windows and Doors

The chart 6.6 shows the distribution of heat loss across various components in a kindergarten building, excluding windows and doors. Roofs contribute the largest share of heat loss at 33% (3,121 W), followed by floors at 31% (2,976 W) and walls at 26% (2,504 W).

Line losses are also notable, with the following contributions:

- Line loss at foundations: 8% or 790 W
- Line loss at wall/window interfaces: 2% or 135 W

This distribution highlights the importance of enhancing insulation in roofs, floors, and walls, as well as addressing linear thermal bridges at foundations and wall/window interfaces to improve the building's overall energy performance.

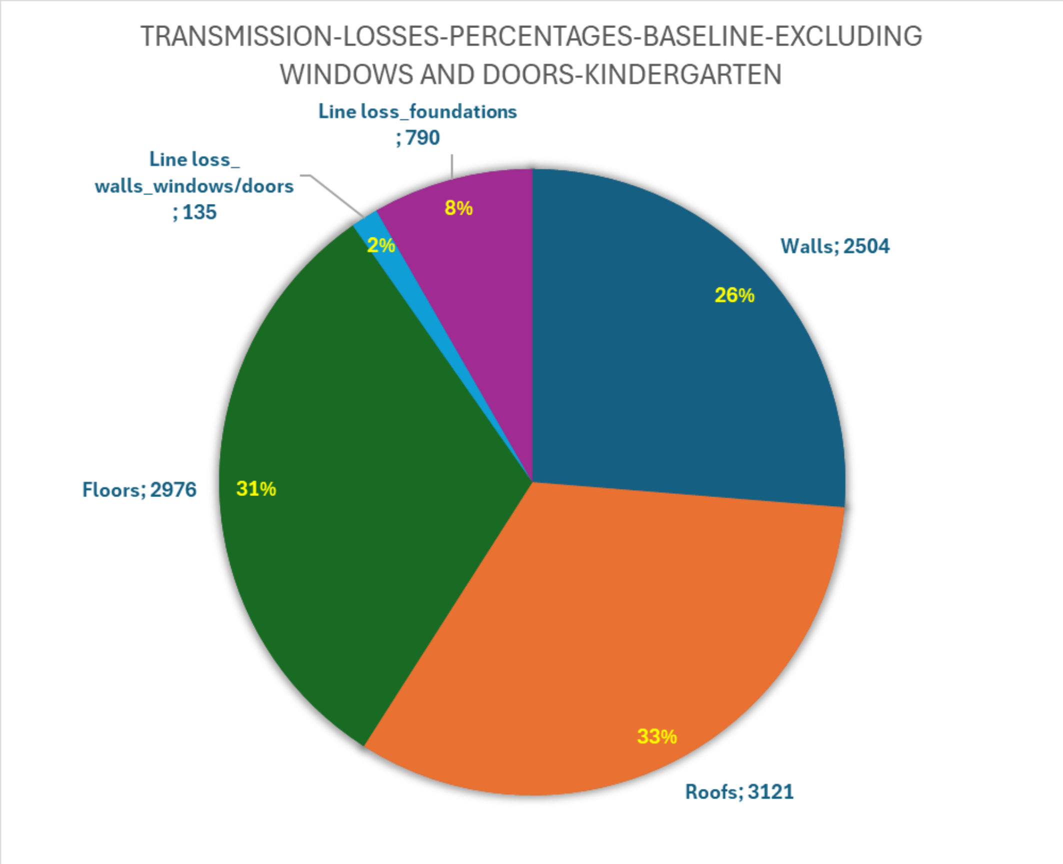


Figure 6.6: Transmission-losses-Percentages-Baseline-excluding windows and doors-Kindergarten

6.2.5 Conclusion: Impact of Excluding Windows and Doors

Excluding windows and doors from heat loss analysis enhances the readability of results by focusing on the structural thermal performance of walls, roofs, floors, and linear thermal bridges. This approach highlights critical areas like foundation interfaces and wall joints, making it easier to prioritize insulation strategies and address thermal bridges effectively, without the overshadowing effect of windows and doors.

Chapter 7

Appendix-B-Transmissions loss analysis

7.1 Calculation methodology

Figures (7.3, 7.4, 7.7) present the main results from BE18 calculations.

The methodology used in this study calculates transmission losses and the contribution of thermal bridges in W/m² as shown in figures(7.5, 7.6, 7.8). The primary objective is to assess the total thermal bridge impact per square meter of the entire building and evaluate its overall environmental footprint per square meter later. This approach simplifies the calculations and allows for a clear representation of results in percentage form, facilitating better comparison and interpretation. A similar approach to area-normalized thermal bridge impact calculations is discussed in the *Thermal Bridging Guide*, where total junction heat losses are divided by the exposed building envelope area to determine an equivalent thermal performance indicator [20].

7.1.1 Total transmission Loss (W/m²)

The total transmission loss per unit area for the building envelope is calculated as:

$$\text{Total Transmission Loss W/m}^2 = \frac{\text{Total design Transmission losses (W)}}{\text{Total External Surface Area (m}^2\text{)}} \tag{7.1}$$

7.1.2 Thermal Bridges (W/m²)

The heat loss contribution from thermal bridges per unit area is determined using:

$$\text{Thermal Bridges W/m}^2 = \frac{\text{Total Thermal Bridge Loss (W)}}{\text{Total External Surface Area (m}^2\text{)}} \tag{7.2}$$

7.1.3 Percentage of Thermal Bridges from Transmission losses

The relative impact of thermal bridges on total transmission losses is calculated as:

$$\text{Thermal Bridges percentage} = \frac{\text{Thermal Bridges W/m}^2}{\text{Total Transmission Loss W/m}^2 + \text{Thermal Bridges W/m}^2} \times 100 \tag{7.3}$$

These calculations provide a standardized approach to assessing the significance of thermal bridges in total building transmission losses.

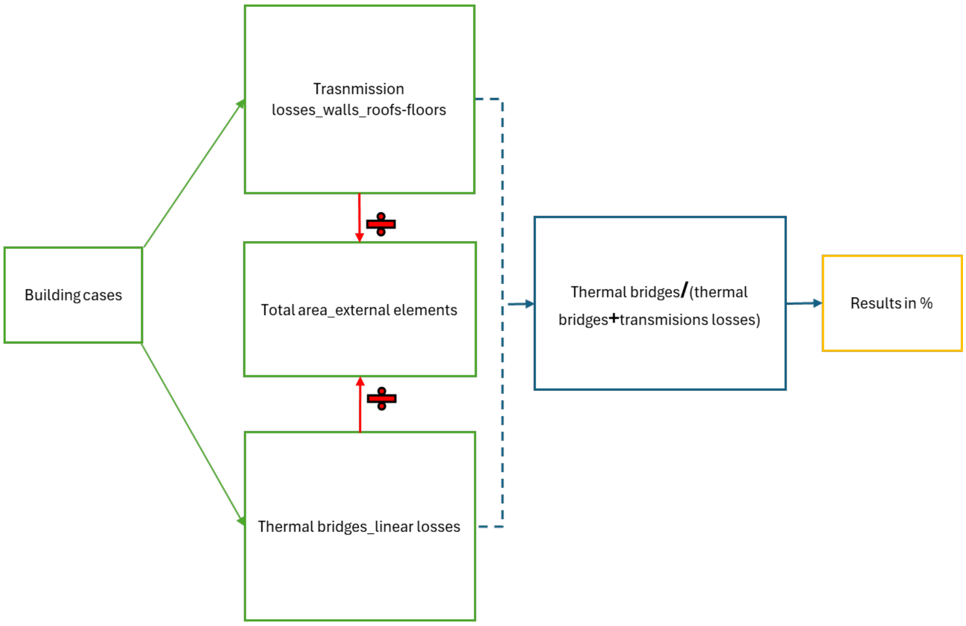


Figure 7.1: Calculations in diagram-figures(7.5, 7.6, 7.8)

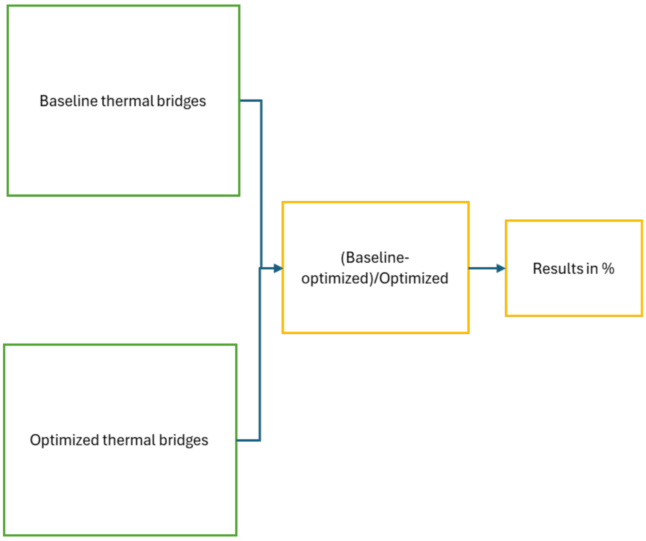


Figure 7.2: Calculations in diagram figures (7.8, 7.9)

7.2 Baseline

External walls, roofs and floors	Area (m²)	U (W/m²K)	b	Ht (W/K)	Loss (W)	Foundations and joints at windows	l (m)	Loss (W/mK)	b	Ht (W/K)	Loss (W)	Windows and outer doors	Number	Orient	Area (m²)	U (W/m²K)	b	Ht (W/K)	Ff (-)	g (-)	Fc (-)	Loss (W)	Elements	Loss (W)
	365			35,4	1064		163			12,799	358		20		54,1			48,69				1558	Walls	641
Lightweight outer wall	159	0,12	1	19,08	611	Line loss_walls_windows/doors	109	0,03	1	3,27	105	Door	2	180	2,1	0,9	1	3,78	0,7	0,5	1	121	Roofs	307
Sloping wall-roof	120	0,08	1	9,6	307	Line loss_foundations with UFH	41	0,13	1,3	6,929	171	Window, kitchen-dining room	1	180	13,5	0,9	1	12,15	0,9	0,5	1	389	Floors	115
Terrain deck	72	0,08	1	5,76	115	Line loss_roof_windows	13	0,2	1	2,6	83	Door, 1st floor	1	0	2,1	0,9	1	1,89	0,7	0,5	1	60	Windows	910
Lightweight outer wall	12	0,08	1	0,96	31							Windows Living room	2	270	0,6	0,9	1	1,08	0,7	0,5	1	35	Doors	648
												Skylight - 3 layers of energy glass - according to BR20	3	270	1,3	0,9	1	3,51	0,7	0,5	1	112	Line loss_walls_windows/doors	105
												Windows 1st floor	2	90	3,4	0,9	1	6,12	0,7	0,5	1	196	Line loss_foundations with UFH	171
												Windows 1st floor	1	90	4,6	0,9	1	4,14	0,7	0,5	1	132	Line loss_roof_windows	83
												Door	1	90	2,1	0,9	1	1,89	0,7	0,5	1	60		
Walls	171											Door with side part	2	90	3,2	0,9	1	5,76	0,7	0,5	1	184	Total heat loss	2980
												Door with side section	1	90	3,5	0,9	1	3,15	0,7	0,5	1	101	total heat loss excluding windows and doo	1422
												Door, room	1	0	2,1	0,9	1	1,89	0,7	0,5	1	60		
						Single family house						Door, stairwell, living room	1	270	2,1	0,9	1	1,89	0	0	1	60		
												Windows Living room	1	270	0,8	0,9	1	0,72	0,7	0,5	1	23		
												Skylight - 3 layers of energy glass - according to BR20	1	270	0,8	0,9	1	0,72	0,7	0,5	1	23		

External walls, roofs and floors	Area (m²)	U (W/m²K)	b	Ht (W/K)	Loss (W)	Foundations and joints at windows	l (m)	Loss (W/mK)	b	Ht (W/K)	Loss (W)	Windows and outer doors	Number	Orient	Area (m²)	U (W/m²K)	b	Ht (W/K)	Ff (-)	g (-)	Fc (-)	Loss (W)	Elements	Loss (W)
	1.756			339,85	7724		752,54			112,22	3591		99		303,12		CtrlClick	452,17				14470	Walls	3994
North-wall A	328	0,158	1	52	1658	Foundation	128	0,34	1	43,52	1393	north-groundfloor-vindue 01	15	N	1,48	1,68	1	37,296	0,7	0,6	0,8	1193	Roofs	1949
South-wall A	203	0,158	1	32	1025	Joints at windows	624,54	0,11	1	68,699	2198	north-1st floor-vindue 01	18	N	1,48	1,68	1	44,755	0,7	0,6	0,8	1432	Floors	1780
East-wall C	65	0,157	1	10	328							north-2nd floor-vindue 01	18	N	1,48	1,68	1	44,755	0,7	0,6	0,8	1432	Windows and doors	14470
East-wall A	20	0,158	1	3	102							south-groundfloor-vindue 01	7	S	1,48	1,68	1	17,405	0,7	0,6	0,8	557	Line loss_walls_windows/doors	2198
West-wall C	70	0,157	1	11	350							south-1st floor-vindue 01	7	S	1,48	1,68	1	17,405	0,7	0,6	0,8	557	Line loss_foundations	1393
West-wall A	20	0,158	1	3	102							south-2nd floor-vindue 01	7	S	1,48	1,68	1	17,405	0,7	0,6	0,8	557		
Roof	469	0,13	1	61	1949							south-groundfloor-vindue 02	6	S	10,47	1,37	1	86,063	0,8	0,6	1	2754		
Ground floor	469	0,38	1	125	1780							south-1st floor-vindue 02	6	S	10,47	1,37	1	86,063	0,8	0,6	1	2754		
Staircase-walls	113	0,38	1	43	429							south-2nd floor-vindue 02	6	S	10,47	1,37	1	86,063	0,8	0,6	1	2754	Total heat loss	25784
												East-groundfloor-vindue 01	1	E	1,48	1,68	1	2,4864	0,7	0,6	0,8	80	total heat loss excluding windows and doo	11315
												East-1st floor-vindue 01	1	E	1,48	1,68	1	2,4864	0,7	0,6	0,8	80		
Walls	819											East-2nd floor-vindue 01	1	E	1,48	1,68	1	2,4864	0,7	0,6	0,8	80		
												East-groundfloor-vindue 05	1	E	0,61	2,05	1	1,2505	0,6	0,6	1	40		
												East-1st floor-vindue 05	1	E	0,61	2,05	1	1,2505	0,6	0,6	1	40		
												East-2nd floor-vindue 05	1	E	0,61	2,05	1	1,2505	0,6	0,6	1	40,016		
												west-groundfloor-vindue 05	1	W	0,61	2,05	1	1,2505	0,6	0,6	1	40,016		
						Multi storey building						west-1st floor-vindue 05	1	W	0,61	2,05	1	1,2505	0,6	0,6	1	40,016		
												west-2nd floor-vindue 05	1	W	0,61	2,05	1	1,2505	0,6	0,6	1	40,016		

External walls, roofs and floors	Area (m²)	U (W/m²K)	b	Ht (W/K)	Loss (W)	Foundations and joints at windows	l (m)	Loss (W/mK)	b	Ht (W/K)	Loss (W)	Windows and outer doors	Number	Orient	Area (m²)	U (W/m²K)	b	Ht (W/K)	Ff (-)	g (-)	Fc (-)	Loss (W)	Elements	Loss (W)
	1013			255,6	8601		203,8			24,47	925,6		99		303,12		CtrlClick	452,17				5449,7	Walls	2504
(Y23) - Wall, external AD (001.EST) - Hollow external wall - 35 cm brick/lay	84	0,33	1	27,9	892	(Y23) - Wall, external AD (001.EST) - Hollow extern	91,2	0,04	1,00	3,65	116,7	East facade - Multi-pane sash - Windows - 2-layer energy glass	2	90	5,49	1,4	1	15,372	0,6	0,6	1	491,9	Roofs	3121
(Y87) - Wall, external AD (001.EST) - Beam of wood - 200 mm insulation	20	0,2	1	3,9	126	Wall, external AD (001.EKL) - Facade element - 24	14,5	0,04	1,00	0,58	18,6	East facade - Multi-pane sash - Exterior door - 2-layer energy glass	2	90	2,28	1,4	1	6,384	0,6	0,6	1	204,3	Floors	2976
Wall, external AD (001.EKL) - Facade element - 24 cm concrete/concrete	17	0,69	1	12,0	385	HB2021 - Foundation - Basement external wall in c	57,2	0,26	0,70	10,40	475,5	East facade - Multi-pane sash - Windows - 2-layer energy glass	2	90	4,8	1,4	1	13,44	0,6	0,6	1	430,1	Windows and doors	5450
Wall, internal AD (001.EST) - Light wall towards unheated room - wood/tim	4	0,22	1	0,9	28	HB2021 - Foundation - Ground floor - Brick, light c	41,0	0,24	1,00	9,84	314,9	West facade - Multi-pane sash - Exterior door - 2-layer energy glass	2	270	2,28	1,4	1	6,384	0,6	0,6	1	204,3	Line loss_walls_windows/doors	135
Floor BF (001.EST) - Ground floor - Concrete with stratum floor - 50 mm m	235	0,26	1	61,1	1955							West facade - Multi-pane sash - Windows - 2-layer energy glass	2	270	4,8	1,4	1	13,44	0,6	0,6	1	430,1	Line loss_foundations	790
Floor BF (001.EKL) - Basement floor - Concrete with screed layer - 150 mm	145	0,22	1	22,3	1021							West facade - Multi-pane sash - Windows - 2-layer energy glass	2	270	5,49	1,4	1	15,372	0,6	0,6	1	491,9		
(Y65) - Wall, external AD (001.EKL) - Basement external wall 0-1m depth	31	0,39	1	12,0	385							South facade - Multi-pane sash - Windows - 2-layer energy glass	1	180	7,17	1,4	1	10,038	0,6	0,6	1	321,2		
(Y102) - Wall, external AD (001.EKL) - Basement external wall 1-2m depth	31	0,31	1	9,6	306							South facade - Multi-pane sash - Exterior door - 2-layer energy glass	1	180	2,09	1,4	1	2,926	0,6	0,6	1	93,6		
(Y118) - Wall, external AD (001.EKL) - Basement external wall over 2m - 3(	25	0,22	1	3,8	174							South facade - Multi-pane sash - Exterior door - 2-layer energy glass	1	180	1,9	1,4	1	2,66	0,6	0,6	1	85,1	Total heat loss	14976
(Y118) - Wall, external AD (001.EKL) - Basement external wall against soil	30	0,22	1	4,6	208,1							South facade - Multi-pane sash - Exterior door - 2-layer energy glass	2	180	2,18	1,4	1	6,54	0,6	0,6	1	209,3	total heat loss excluding windows and doo	9527
Roof construction AE (001.ETR) - Attic space - 100-200 mm insulation	159	0,35	1	55,7	1783,2							South facade - Multi-pane sash - Windows - 2-layer energy glass	3	180	0,36	1,4	1	1,512	0,6	0,6	1	48,4		
Roof construction AE (001.ETR) - Attic space - 100-200 mm insulation	232	0,18	1	41,8	1338							North facade - Multi-pane sash - Windows - 2-layer energy glass	1	0	7,17	1,4	1	10,038	0,6	0,6	1	321,2		
												North facade - Multi-pane sash - Exterior door - 2-layer energy glass	1	0	2,09	1,4	1	2,926	0,6	0,6	1	93,6		
												North facade - Multi-pane sash - Windows - 2-layer energy glass	2	0	1,43	1,4	1	4,004	0,6	0,6	1	128,1		
												North facade - Multi-pane sash - Windows - 2-layer energy glass	2	0	1,2	1,4	1	3,36	0,6	0,6	1	107,5		
						kindergarten						North facade - Multi-pane sash - Exterior door - 2-layer energy glass	2	0	2,18	1,4	1	6,54	0,6	0,6	1	209,3		
												Basement facade - Multi-pane sash - Exterior door - 2-layer energy gla	1	180	1,76	2,8	1	2,464	0,6	0,6	1	78,8		
												Basement facade - Single-pane - Windows - 2-layer thermopane	1	180	6,4	2,8	1	17,92	0,7	0,8	1	573,4		
												Basement facade - Single-pane - Windows - 2-layer thermopane	1	270	6,4	2,8	1	17,92	0,7	0,8	1	573,4		
												Basement facade - Single-pane - Exterior door - 2-layer thermopane	1	180	2,1	2,8	1	5,88	0,7	0,8	1	188,2		
												Facade - Skylight - 2-layer energy glass/acrylic	4	90	0,72	1,8	1	5,184	0,7	0,6	1	165,9		

Figure 7.3: calculation based on DS418

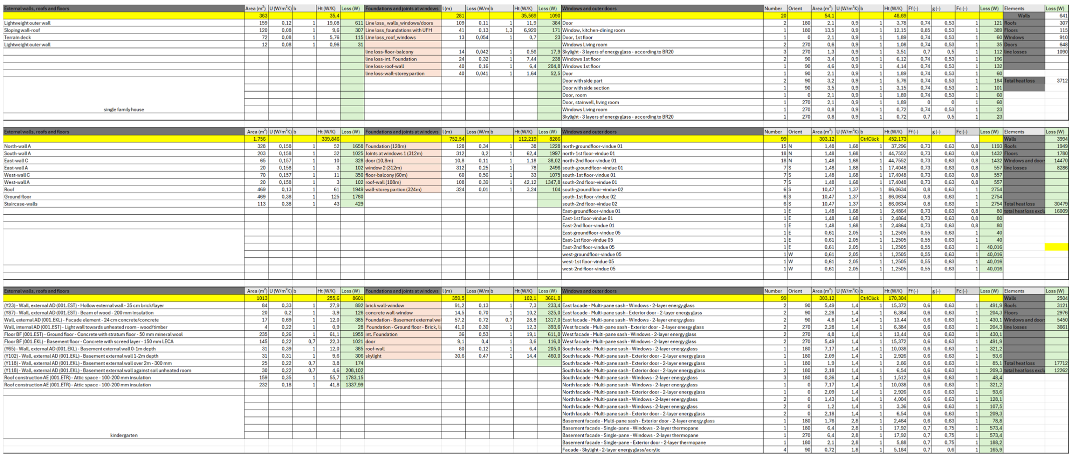


Figure 7.4: calculation based on Simulations-baseline

Transmissions losses				
Elements	single family house (2015)	Multi storey (1960)	Kindergarten (1980)(renovated 2017)	Units
building envelope-excluding windows and doors	1422,1	11314,8	9527	W
thermal bridges	358,4	3591	925,6	W
Areas				
Elements -Area	single family house (2015)	Multi storey (1960)	Kindergarten (1980)(renovated 2017)	Units
Total external surface area-excluding windows and doors	363,0	1755,0	1013,0	m2
results				
Elements	single family house (2015)	Multi storey (1960)	Kindergarten (1980)(renovated 2017)	Units
building envelope-excluding windows and doors w/m2	3,92	6,45	9,40	W/m2
thermal bridges w/m2	0,99	2,05	0,91	W/m2
results	20%	24%	9%	%

1. Building Envelope Transmission Loss (W/m²):

$$\frac{Building\ Envelope\ W/m^2}{Total\ Heat\ Loss\ for\ Building\ Envelope\ (W) Total\ External\ Surface\ Area\ (m^2)}$$

2. Thermal Bridge Transmission (W/m²):

$$\frac{Thermal\ Bridges\ W/m^2}{Total\ Thermal\ Bridge\ Loss\ (W) Total\ External\ Surface\ Area\ (m^2)}$$

3. Percentage of Transmission from Thermal Bridges:

$$\frac{Thermal\ Bridges\ W/m^2}{Building\ Envelope\ W/m^2\ +\ Thermal\ Bridges\ W/m^2} \times 100\%$$

Figure 7.5: Transmission loss analysis-DS418

Transmission losses				
Elements	single family house (2015)	Multi storey (1960)	Kindergarten (1980)(renovated 2017)	Units
building envelope-excluding windows and doors	1063,7	7723,8	8601	W
thermal bridges	1090,3	8286	3661,0	W

Areas				
Elements -Area	single family house (2015)	Multi storey (1960)	Kindergarten (1980)(renovated 2017)	Units
Total external surface area-excluding windows and doors	363,0	1755,0	1013,0	m2

results				
Elements	single family house (2015)	Multi storey (1960)	Kindergarten (1980)(renovated 2017)	Units
building envelope-excluding windows and doors w/m2	2,93	4,40	8,49	W/m2
thermal bridges w/m2	3,00	4,72	3,61	W/m2
results	51%	52%	30%	%

1. Building Envelope Transmission Loss (W/m²):

$$\frac{Building\ Envelope\ W/m^2}{Total\ Heat\ Loss\ for\ Building\ Envelope\ (W) Total\ External\ Surface\ Area\ (m^2)}$$

2. Thermal Bridge Transmission (W/m²):

$$\frac{Thermal\ Bridges\ W/m^2}{Total\ Thermal\ Bridge\ Loss\ (W) Total\ External\ Surface\ Area\ (m^2)}$$

3. Percentage of Transmission from Thermal Bridges:

$$\frac{Thermal\ Bridges\ W/m^2}{Building\ Envelope\ W/m^2 + Thermal\ Bridges\ W/m^2} \times 100\%$$

Figure 7.6: Transmission loss analysis-Simulations-baseline

7.3 Optimized

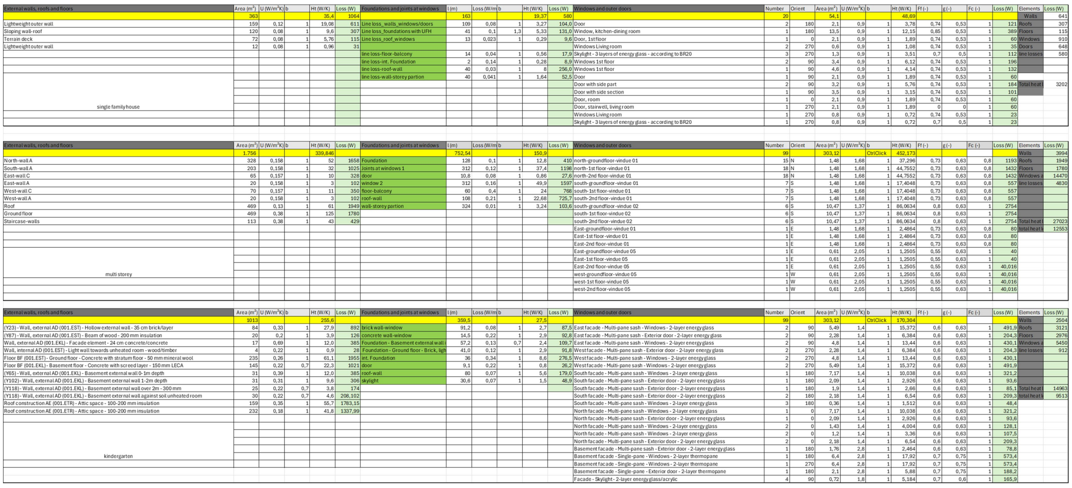


Figure 7.7: calculation based on Simulations-optimized

Transmission losses				
Elements	single family house (2015)	Multi storey (1960)	Kindergarten (1980)(renovated 2017)	Units
building envelope-excluding windows and doors	1063,7	7723,8	8601	W
thermal bridges	579,9	4830	912,4	W
Areas				
Elements -Area	single family house (2015)	Multi storey (1960)	Kindergarten (1980)(renovated 2017)	Units
Total external surface area-excluding windows and doors	363,0	1755,0	1013,0	m2
results-optimized				
Elements	single family house (2015)	Multi storey (1960)	Kindergarten (1980)(renovated 2017)	Units
building envelope-excluding windows and doors w/m2	2,93	4,40	8,49	W/m2
thermal bridges w/m2	1,60	2,75	0,90	W/m2
results	35%	38%	10%	%
results-baseline				
Elements	single family house (2015)	Multi storey (1960)	Kindergarten (1980)(renovated 2017)	Units
building envelope-excluding windows and doors w/m2	2,93	4,40	8,49	W/m2
Baseline-thermal bridges w/m2	3,00	4,72	3,61	W/m2
results	51%	52%	30%	%
Optimized-thermal bridges				
Reduction	1,41	1,97	2,71	W/m2
Reduction	46,8%	41,7%	75,1%	%

Figure 7.8: Transmission loss analysis-Simulations-Optimized

Building Type	Baseline Thermal Bridges (W/m^2)	Optimized Thermal Bridges (W/m^2)	Reduction in Thermal Bridges (%)	Baseline Total Transmission Losses (W/m^2)	Optimized Total Transmission Losses (W/m^2)	Reduction in Total transmission Losses (%)
Single Family House (2015)	3,00	1,60	46,8%	5,93	4,53	23,7%
Multi-storey (1960)	4,72	2,75	41,7%	9,12	7,15	21,6%
Kindergarten (1980, Renovated 2017)	3,61	0,90	75,1%	12,10	9,39	22,4%

Figure 7.9: Calculation based on Simulations-baseline vs optimized

7.4 Building energy consumption calculation in BE18

BE18 calculates a building's total energy demand based on transmission losses, ventilation losses, internal heat gains, solar gains, and system efficiencies.

Transmission losses are determined by the transmission area, thermal transmittance, and the temperature difference between indoor and outdoor conditions.

Ventilation losses depend on airflow and heat recovery. **Internal gains** include occupants, lighting, and appliances. **Solar gains** consider glazing, shading, and orientation. **Heating/cooling loads** are adjusted for system efficiency. **Energy supply** accounts for district heating, heat pumps, and renewables. Some of the values are assumed.

The final energy requirement (kWh/m² per year) ensures compliance with Danish energy regulations [27].

7.4.1 Single family house

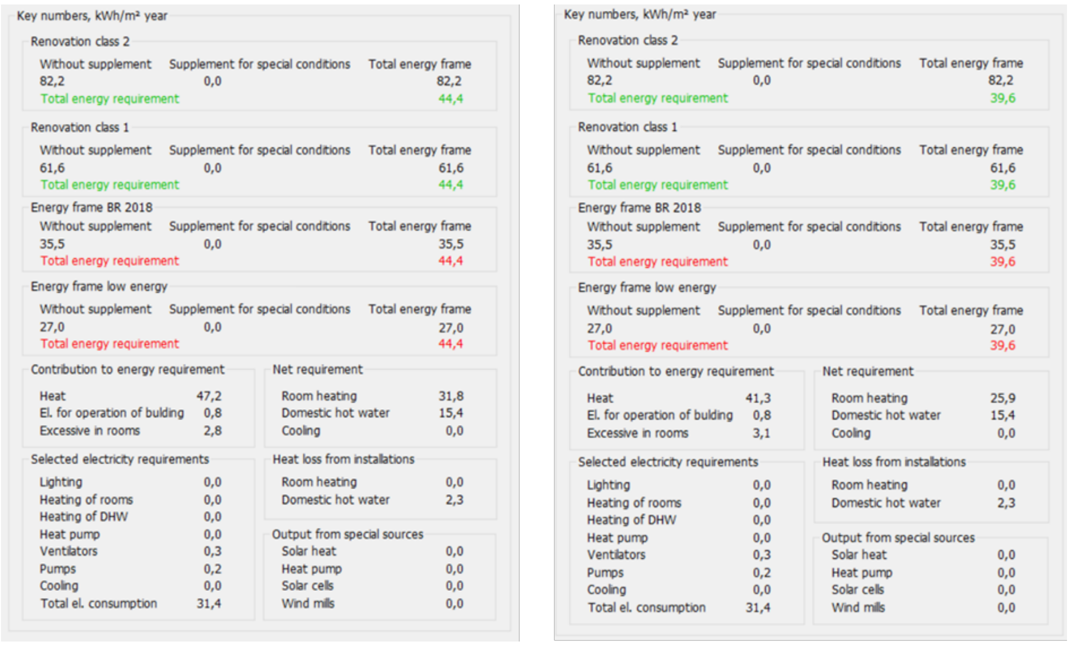


Figure 7.10: BE18-Single family house

7.4.2 Multi storey building

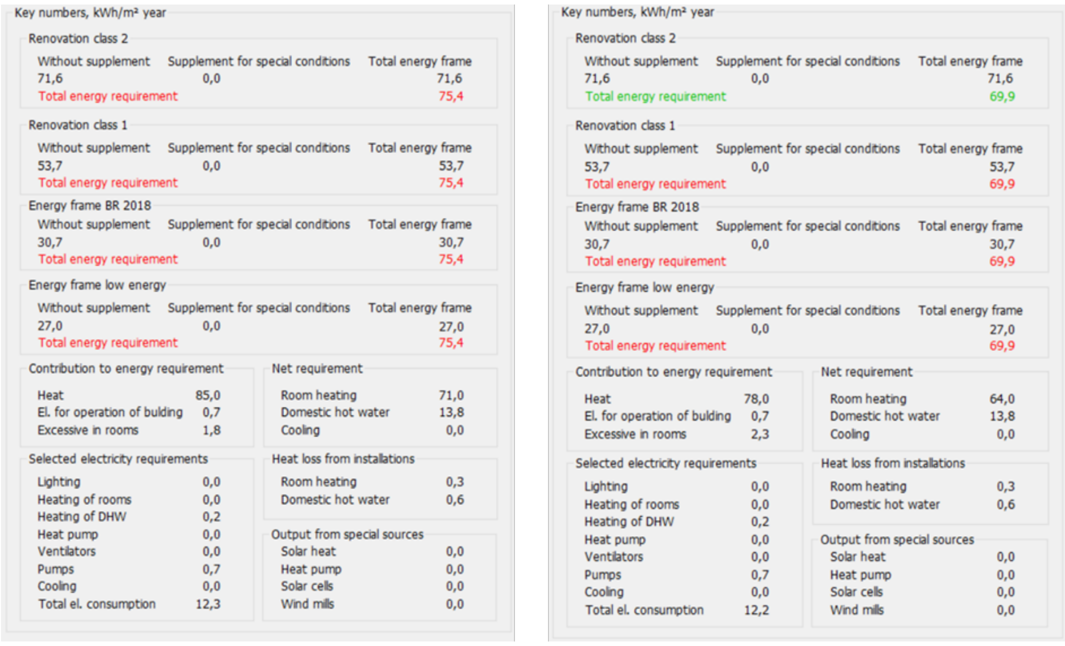


Figure 7.11: BE18-Multi storey building

7.4.3 Kindergarten building

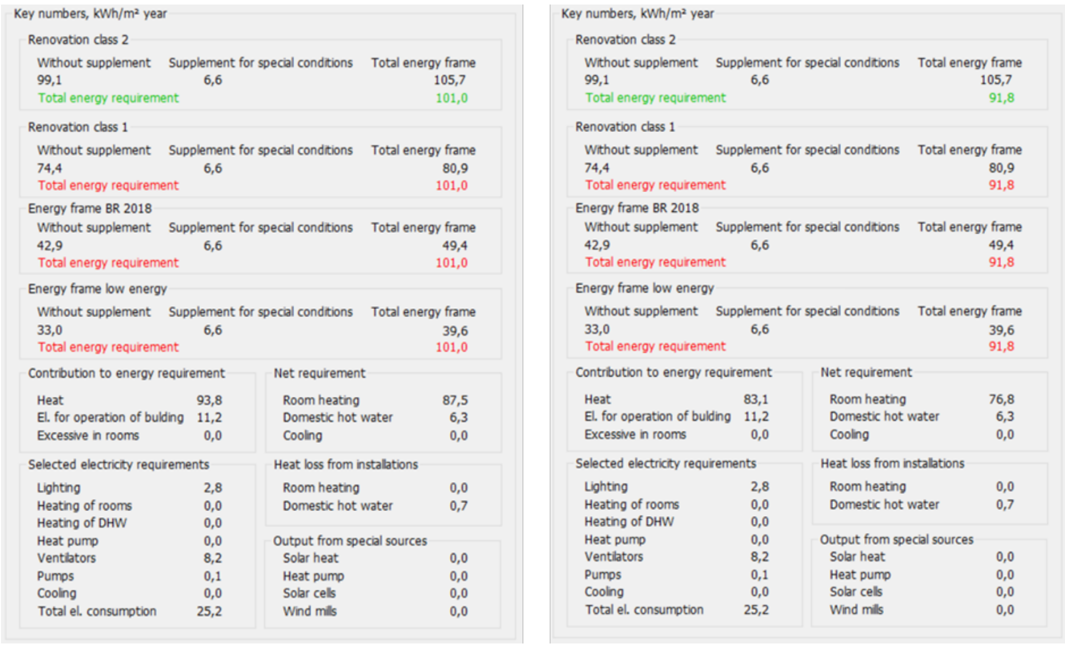


Figure 7.12: BE18-Kindergarten

Chapter 8

Appendix-C-Baseline-Simulations

8.1 HTflux simulation method

HTflux is utilized in this study to calculate the Ψ-value of thermal bridges by assessing additional heat loss at junctions. The calculation follows a steady-state thermal analysis approach, integrating material properties, geometric configurations, and boundary conditions. The Ψ-value is determined using the following equation:

$$\Psi = \frac{\Phi_{\text{total}}}{\Delta T} - \sum (U \times L) \tag{8.1}$$

where:

- Φ_{total} is the total heat flux through the analyzed junction (W).
- ΔT is the applied temperature difference (K).
- U represents the thermal transmittance (U-value) of adjacent building components (W/m²K).
- L is the corresponding length of each adjacent element (m).

The calculation process involves:

- Determining the total heat flux through the construction detail under defined temperature conditions.
- Computing the heat loss contribution from each adjacent building element using their respective U-values and lengths.
- Subtracting the conductive heat loss of adjacent elements from the total flux to isolate the impact of the thermal bridge.
- Normalizing the remaining heat loss by the temperature gradient and the length of the junction to obtain the linear thermal transmittance (Ψ-value).

This method enables precise evaluation of thermal bridge effects, facilitating the optimization of energy-efficient building designs by identifying critical areas of heat loss [19].

8.2 Single family house

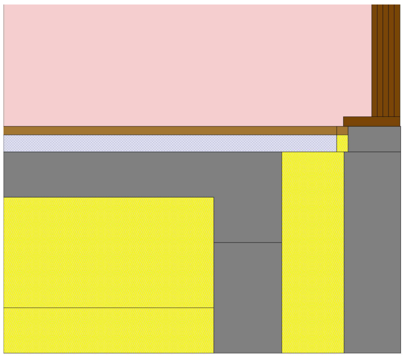
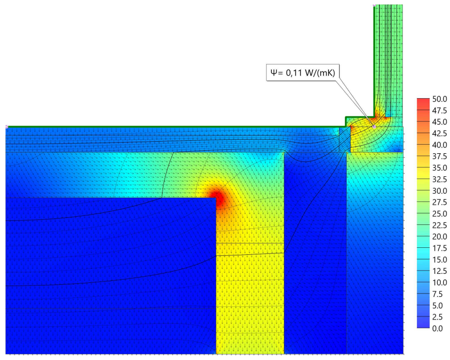
Materials	**Dimensions**
- Insulation **- Concrete** **- XPS** **- Thermal Break** **- Wood**	DS418-Annex C [31] Door frame 215 mm Floor 700 mm Foundation 400 mm
	

Table 8.1: Thermal bridge-Single family house-Door

8.3 Multi storey

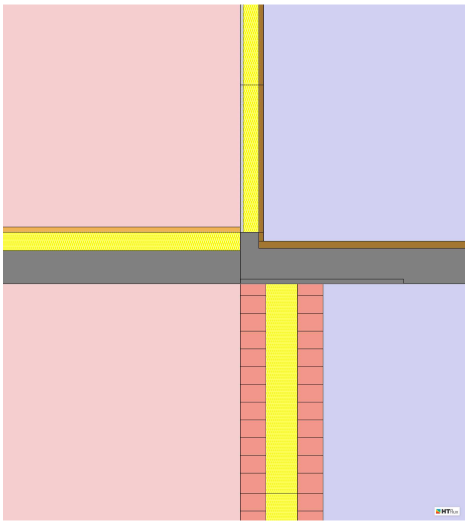
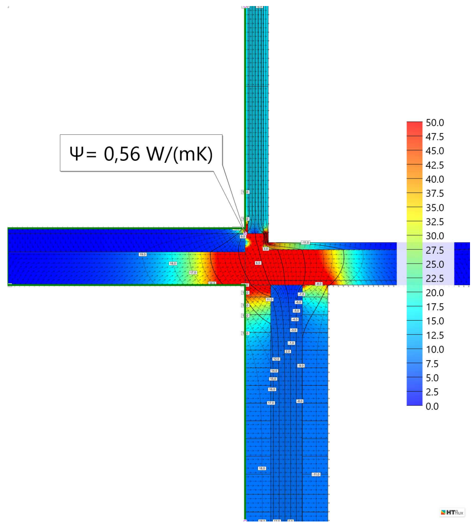
Materials	Dimensions
- **Insulation** - **Concrete** - **Wood** - **Brick**	ISO 14683 -Table C.2 [22] Light wall 1000 mm Floor 1000 mm Wall 1000 mm Balcony 600 mm
	

Table 8.2: Thermal bridge-Multi storey-balcony-floor

8.4 Kindergarten

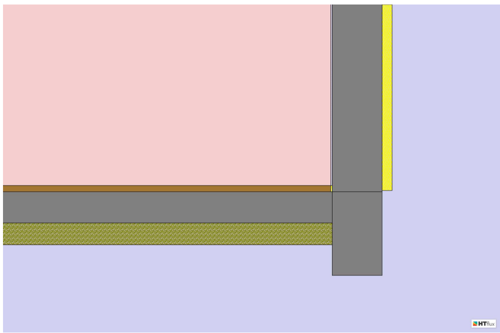
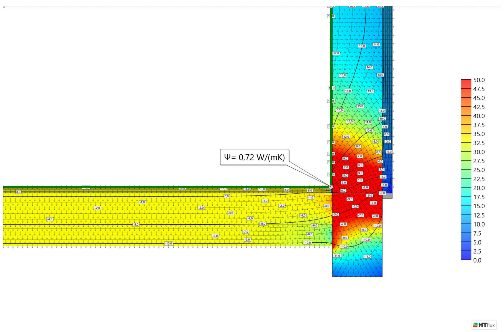
Materials	Dimensions
- **Insulation** - **Concrete** - **Wood** - **Sand**	DS418-Annex D [31] Basement wall 1500 mm Basement Floor 4000 mm
	

Table 8.3: Thermal bridge - Kindergarten: Basement wall-floor

8.5 Simulation validation

EXTERIOR WALL
27x145 mm Superwood SW12 Black, mounted vertically.
25 mm ventilated horizontal battens, spaced at 600 mm intervals.
225 mm DC-Panel (20 mm cement-bonded particle board, 185 mm PUR, 20 mm cement-bonded particle board).
1 layer of 12.5 mm standard gypsum board.

Layer	Thickness [mm]	Thermal Conductivity (λ) [W/m·K]
Cement-bonded particle board (outer layer, part of DC-Panel)	20	0.25
PUR Insulation (Polyurethane, core of DC-Panel)	185	0.028
Cement-bonded particle board (inner layer, part of DC-Panel)	20	0.25
Standard gypsum board (inner finish layer)	12.5	0.25

✔ **U-værdier for vinduer & døre (BR15 7.6.1)**
Dør er udført med U-værdi 0,90 W/m² K.
Vindue, køkken-alrum er udført med U-værdi 0,90 W/m² K.
Dør, 1. sal er udført med U-værdi 0,90 W/m² K.
Vinduer Stuen er udført med U-værdi 0,90 W/m² K.
Ovenlys - 3 lags energirude - efter BR20 er udført med U-værdi 1,10 W/m² K.
Vinduer 1. sal er udført med U-værdi 0,90 W/m² K.
Vinduer 1. sal er udført med U-værdi 0,90 W/m² K.
Dør er udført med U-værdi 0,90 W/m² K.
Dør m. sideparti er udført med U-værdi 0,90 W/m² K.
Dør m. sideparti er udført med U-værdi 0,90 W/m² K.
Dør, værelse er udført med U-værdi 0,90 W/m² K.
Dør, trapperum, stuen er udført med U-værdi 0,90 W/m² K.
Vinduer Stuen er udført med U-værdi 0,90 W/m² K.
Ovenlys - 3 lags energirude - efter BR20 er udført med U-værdi 1,10 W/m² K.

✔ **Linjetab (BR15 7.6.1)**
Linjetab mellem ydervæg og vinduer/døre er udført med transmissionstab 0,03 W/m K.
Linjetab ved fundament med gulvvarme er udført med transmissionstab 0,13 W/m K.
Linjetab mellem tagkonstruktion og vinduer er udført med transmissionstab 0,20 W/m K.

Figure 8.1: Thermal bridge-single family house-window-heat flux-validation

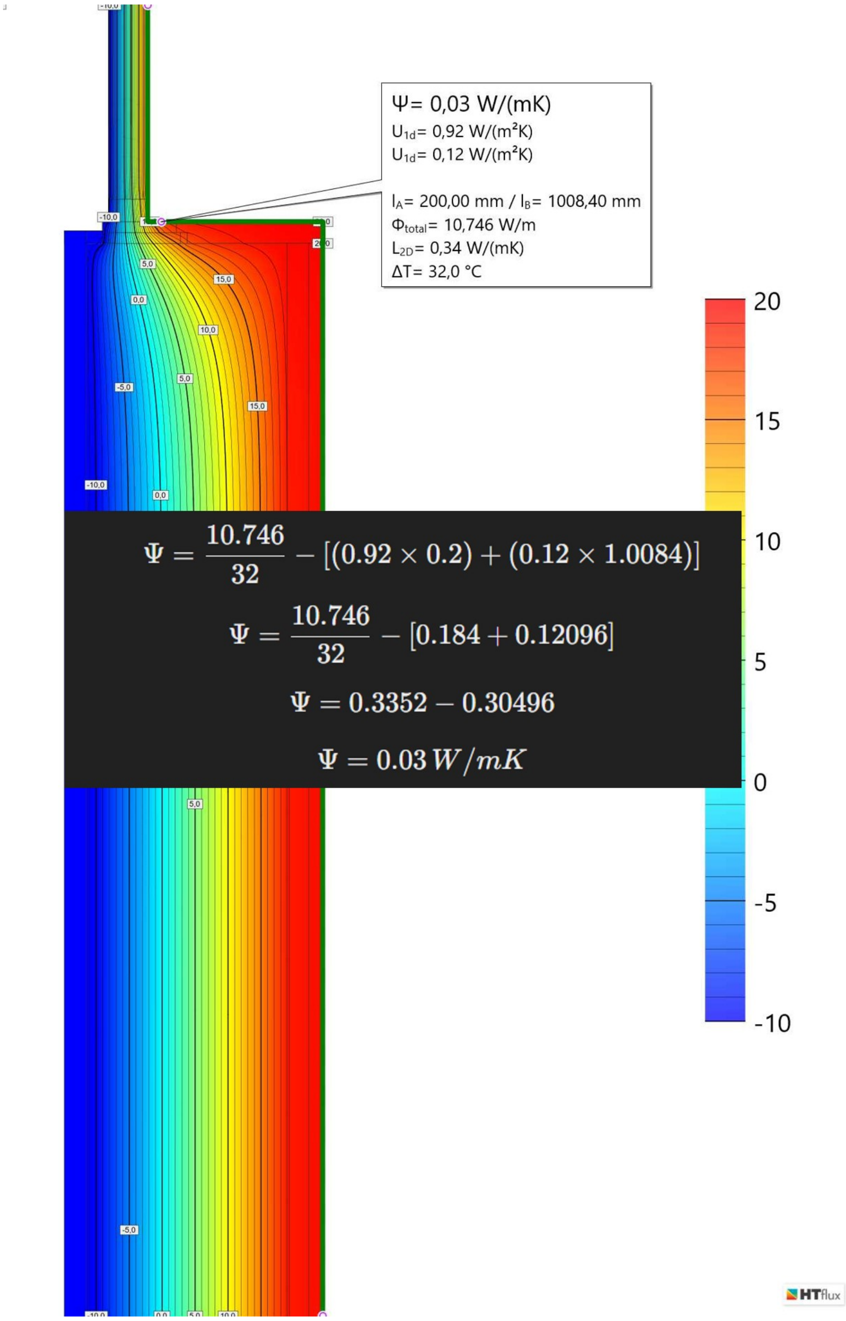


Figure 8.2: Thermal bridge-single family house-window-validation

Chapter 9

Appendix-D-LCA

9.1 Life cycle assessment

This study utilizes **LCAbyg**, a life cycle assessment (LCA) tool, to evaluate the environmental impact of various thermal bridge mitigation strategies. LCAbyg assesses building components throughout their life cycle, including material production, energy consumption, and end-of-life disposal. The analysis examines how different thermal bridge solutions influence both heat loss and the building's overall environmental footprint [7].

Mitigation strategies considered include enhanced insulation at critical junctions (e.g., window and door frames, wall intersections, and roof-wall connections) and the use of advanced materials. Each strategy is assessed for its effectiveness in reducing transmission losses while minimizing carbon emissions, resource consumption, and energy demand.

LCAbyg provides a comprehensive framework for evaluating thermal bridge design choices in relation to environmental sustainability. The results will guide decision-making by identifying strategies that optimize both energy efficiency and environmental performance.

The **Global Warming Potential (GWP)** metric quantifies CO_2-equivalent emissions across the building's life cycle. Key life cycle stages include:

- **A1–A3**: Raw material extraction, transportation, and manufacturing.
- **B4**: Emissions from material replacements during the operational phase.
- **C3**: Waste processing before final disposal.
- **C4**: Final disposal of materials.
- **D**: Benefits or burdens from material reuse, recycling, or energy recovery [30].

By analyzing these phases, this study aims to identify thermal bridge strategies that enhance sustainability while maintaining energy efficiency.

The environmental impact of thermal bridges is calculated based on the length of each construction element. For instance, door, wall-floor-balcony, and foundation-floor junctions are considered thermal bridge elements contributing to the building's total environmental impact. The length of each element follows the same methodology used for calculating thermal bridge linear losses, ensuring consistency in assessment (see Appendix 9).

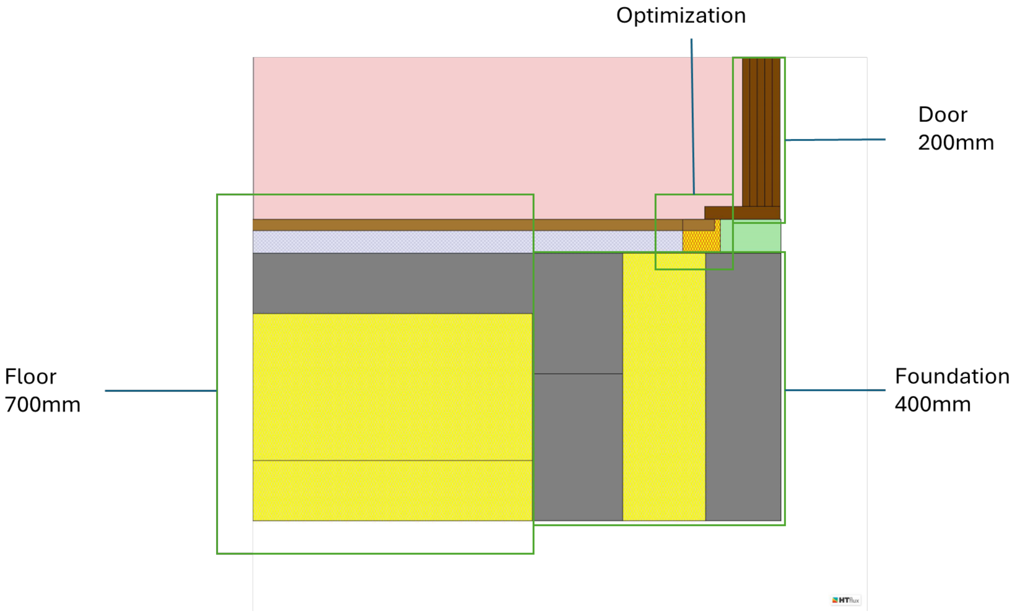


Figure 9.1: LCA-thermal bridge calculation method-single family house

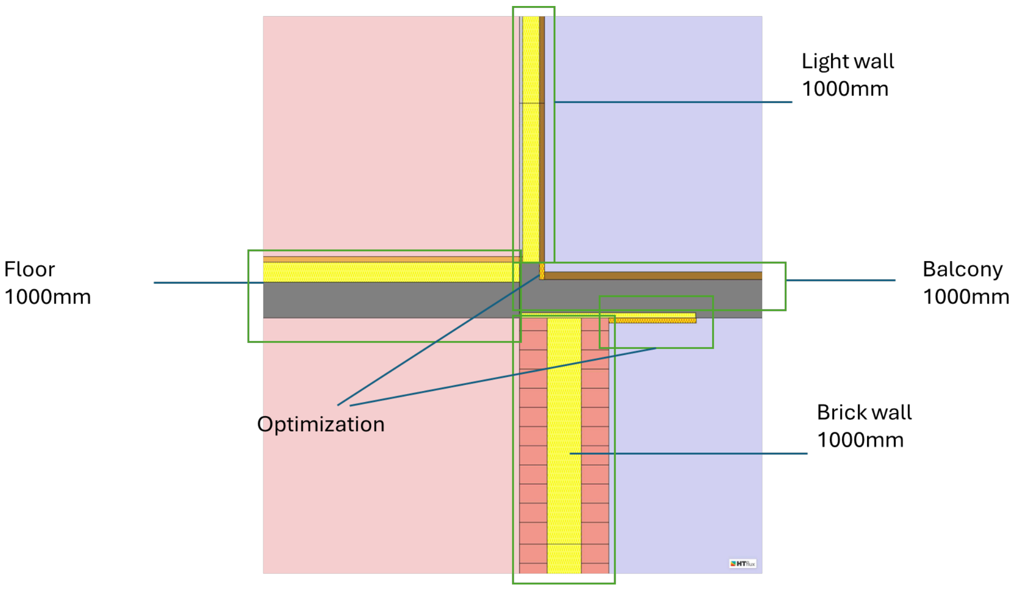


Figure 9.2: LCA-thermal bridge calculation method-Multi storey building

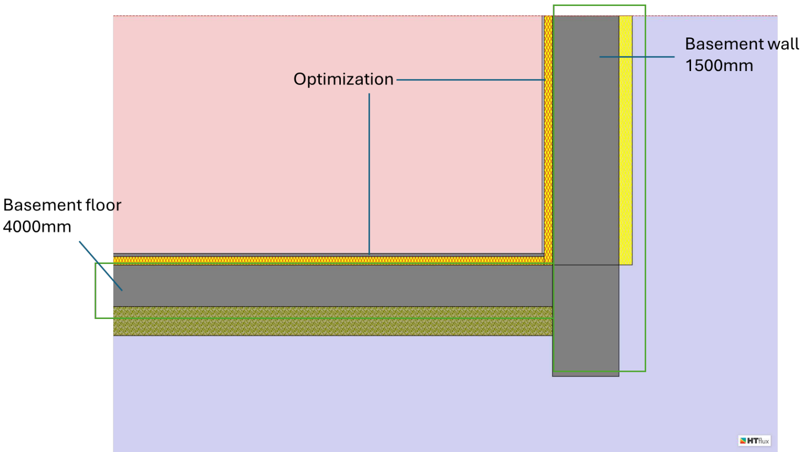


Figure 9.3: LCA-thermal bridge calculation method-Kindergarten building

9.1.1 Single family house

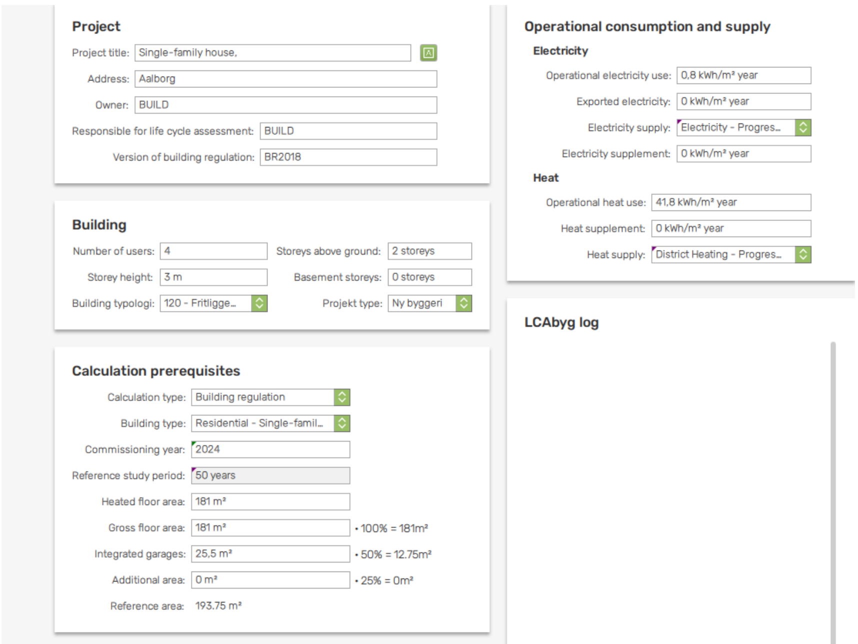


Figure 9.4: LCA calculation-single family house-1

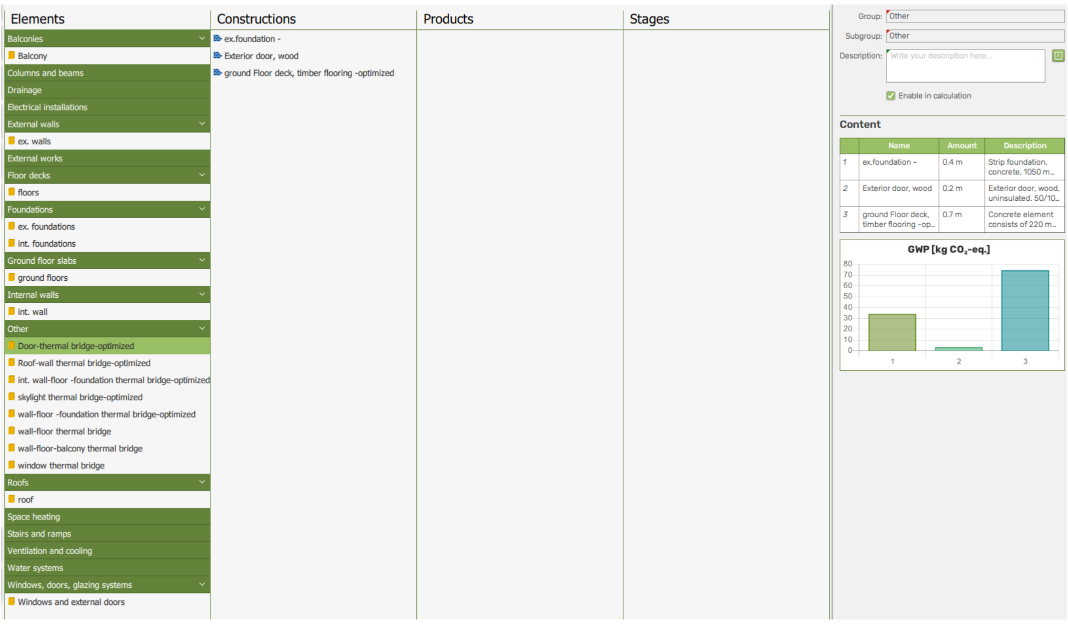


Figure 9.5: LCA calculation-single family house-2

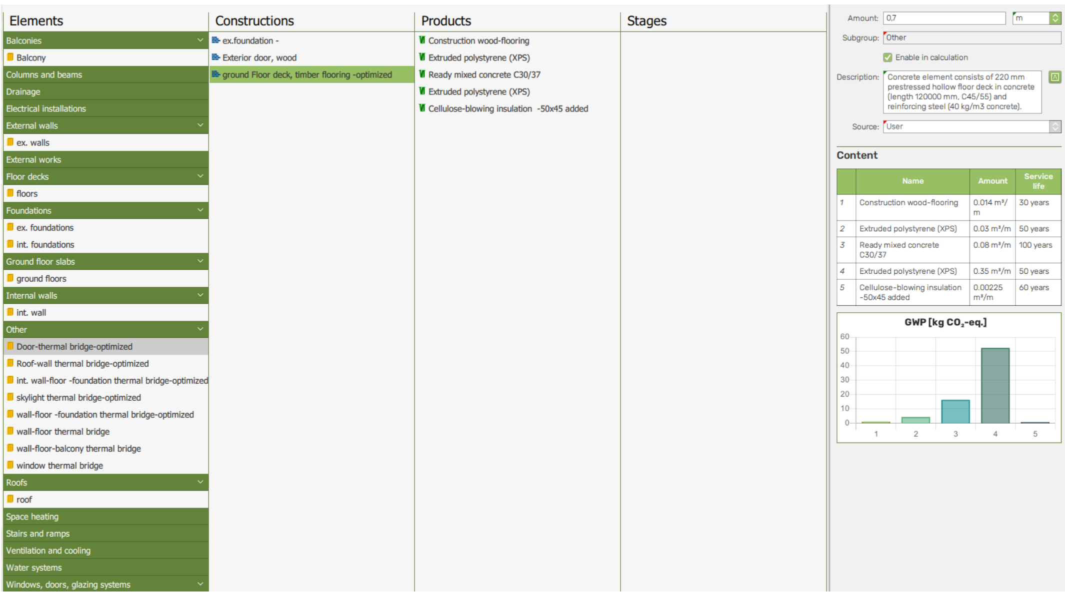


Figure 9.6: LCA calculation-single family house-3

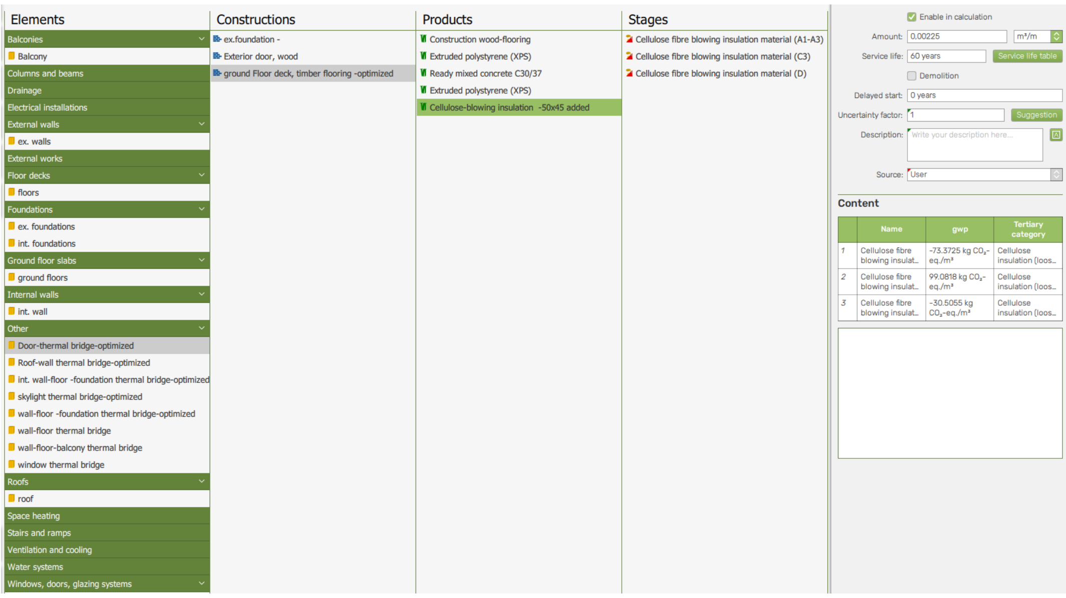


Figure 9.7: LCA calculation-single family house-4

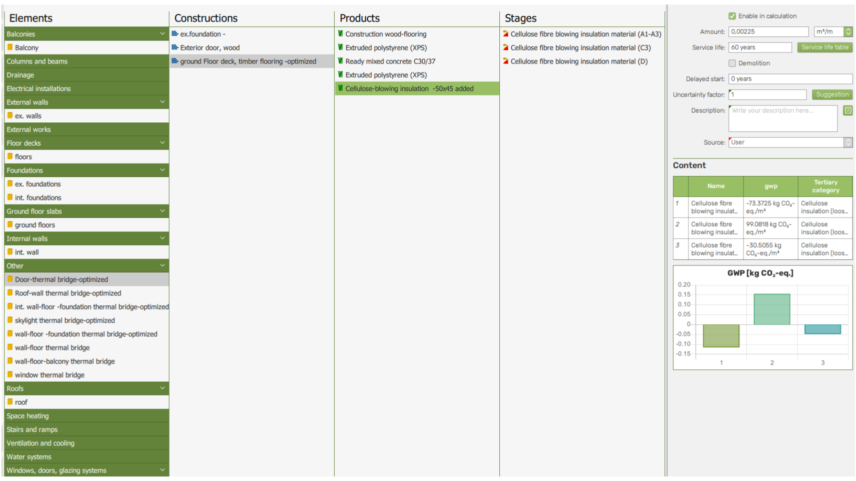


Figure 9.8: LCA calculation-single family house-5

Figure 9.9: LCA calculation-single family house-6

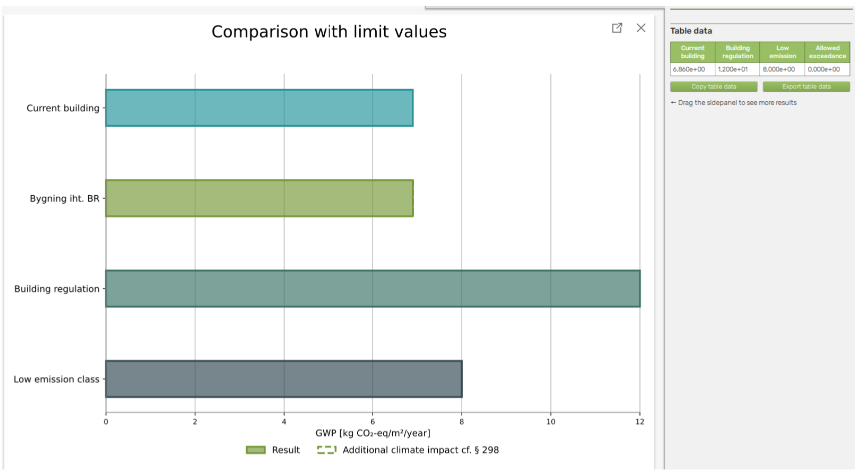


Figure 9.10: LCA calculation-single family house-7

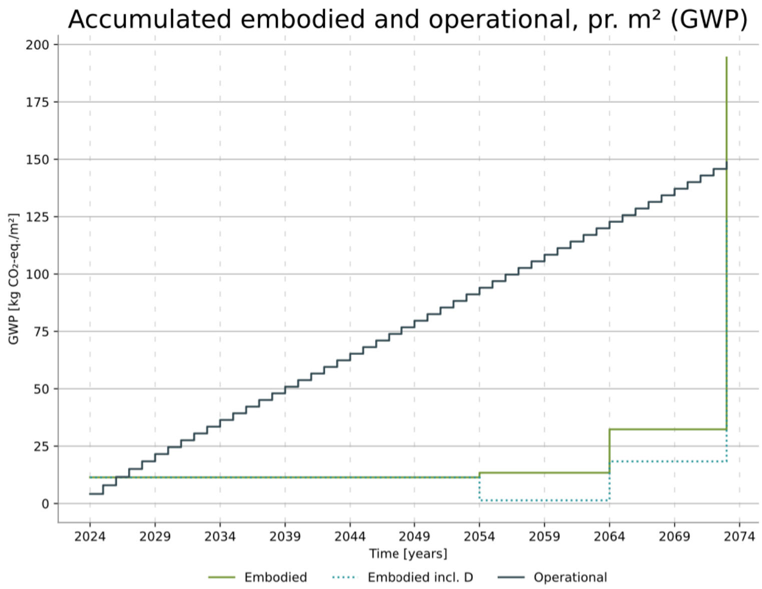


Figure 9.11: LCA calculation-single family house-8

Description	Name	GWP sum kg CO_2-eq.	GWP a1_3 kg CO_2-eq.	GWP b4 kg CO_2-eq.	GWP c3 kg CO_2-eq.	GWP c4 kg CO_2-eq.	GWP d kg CO_2-eq.
	Optimized						
Sum	Building-Optimized	6,86E+00	2,27E-01	4,18E-01	3,19E+00	5,15E-02	-1,40E+00
Sum	Operation	2,97E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Sum	Element	3,89E+00	2,27E-01	4,18E-01	3,19E+00	5,15E-02	-1,40E+00
Group	Balconies	2,14E-01	1,68E-01	8,70E-03	3,72E-02	2,91E-04	-1,06E-01
Group	Thermal bridges	1,04E-01	3,75E-02	5,47E-03	5,94E-02	1,23E-03	-3,34E-02
Element	Door-Thermal Bridge-Optimized	1,16E-02	6,30E-03	2,41E-04	4,99E-03	8,46E-05	-2,78E-03
Construction	Ground Floor Deck, Timber Flooring -Optimized	7,71E-03	3,60E-03	5,77E-05	4,02E-03	2,87E-05	-2,25E-03
Products	Ready Mixed Concrete C30/37	1,70E-03	1,63E-03	0,00E+00	3,88E-05	2,87E-05	-2,66E-05
Products	Construction Wood-Flooring	1,15E-04	-6,60E-04	5,77E-05	7,17E-04	0,00E+00	-8,60E-04
Products	Cellulose-Blowing Insulation -50X45 Added	4,18E-06	-1,19E-05	0,00E+00	1,61E-05	0,00E+00	-4,96E-06
Products	Extruded Polystyrene (Xps)	4,65E-04	2,09E-04	0,00E+00	2,56E-04	0,00E+00	-1,07E-04
Products	Extruded Polystyrene (Xps)	5,43E-03	2,44E-03	0,00E+00	2,99E-03	0,00E+00	-1,25E-03
Construction	Ex.Foundation -	3,54E-03	3,40E-03	0,00E+00	7,55E-05	5,59E-05	-5,17E-05
Products	Ready Mixed Concrete C30/37	3,20E-03	3,07E-03	0,00E+00	7,33E-05	5,42E-05	-5,01E-05
Products	Lightweight Concrete Block, Gray Eps Insulation	3,34E-04	3,30E-04	0,00E+00	2,28E-06	1,68E-06	-1,56E-06
Construction	Exterior Door, Wood	3,69E-04	-7,10E-04	1,84E-04	8,95E-04	7,04E-10	-4,74E-04
Products	Grey Cast Iron Part	1,69E-06	1,69E-06	0,00E+00	0,00E+00	7,04E-10	-4,06E-07
Products	Timber Pine (12% Moisture / 10.7% H2O	3,42E-04	-6,64E-04	1,71E-04	8,35E-04	0,00E+00	-4,41E-04
Products	Timber Pine (12% Moisture / 10.7% H2O	2,48E-05	-4,80E-05	1,24E-05	6,04E-05	0,00E+00	-3,19E-05
Element	Roof-Wall Thermal Bridge-Optimized	6,69E-03	-6,45E-03	1,53E-03	1,15E-02	9,56E-05	-2,59E-03
Element	Int. Wall-Floor -Foundation Thermal Bridge-	3,18E-02	2,08E-02	8,24E-05	1,05E-02	3,55E-04	-5,30E-03
Construction	Ground Floor Deck, Tiles	1,24E-02	7,86E-03	0,00E+00	4,33E-03	1,79E-04	-1,83E-03
Products	Cement Screed	1,29E-03	1,19E-03	0,00E+00	0,00E+00	9,76E-05	0,00E+00
Products	Ready Mixed Concrete C30/37	2,43E-03	2,33E-03	0,00E+00	5,55E-05	4,10E-05	-3,80E-05
Products	Tile Adhesive	9,00E-04	8,60E-04	0,00E+00	0,00E+00	4,06E-05	-7,07E-06
Products	Extruded Polystyrene (Xps)	7,75E-03	3,48E-03	0,00E+00	4,27E-03	0,00E+00	-1,79E-03
Construction	Ground Floor Deck, Timber Flooring -	1,11E-02	4,89E-03	8,24E-05	6,09E-03	4,10E-05	-3,32E-03
Products	Ready Mixed Concrete C30/37	2,43E-03	2,33E-03	0,00E+00	5,55E-05	4,10E-05	-3,80E-05
Products	Construction Wood-Flooring	1,65E-04	-9,42E-04	8,24E-05	1,02E-03	0,00E+00	-1,23E-03
Products	Cellulose-Blowing Insulation -50X45 Added	9,73E-05	-2,78E-04	0,00E+00	3,75E-04	0,00E+00	-1,15E-04
Products	Extruded Polystyrene (Xps)	6,64E-04	2,98E-04	0,00E+00	3,66E-04	0,00E+00	-1,53E-04
Products	Extruded Polystyrene (Xps)	7,75E-03	3,48E-03	0,00E+00	4,27E-03	0,00E+00	-1,79E-03
Construction	Int. Foundation -	4,24E-03	4,08E-03	0,00E+00	9,71E-05	7,18E-05	-6,65E-05
Products	Ready Mixed Concrete C30/37	4,24E-03	4,08E-03	0,00E+00	9,71E-05	7,18E-05	-6,65E-05
Construction	Int. Foundation - Lightweight Con. Optimized	2,84E-03	2,80E-03	0,00E+00	2,31E-05	1,72E-05	-1,59E-05
Products	Lightweight Concrete Added	2,84E-03	2,80E-03	0,00E+00	2,31E-05	1,72E-05	-1,59E-05
Construction	Int. Walls -	1,21E-03	1,16E-03	0,00E+00	1,07E-05	4,53E-05	-5,59E-05
Products	Gypsum Plaster Board	1,54E-04	1,41E-04	0,00E+00	0,00E+00	1,32E-05	0,00E+00
Products	Gypsum Plaster Board	1,54E-04	1,41E-04	0,00E+00	0,00E+00	1,32E-05	0,00E+00
Products	Gypsum Plaster Board	1,54E-04	1,41E-04	0,00E+00	0,00E+00	1,32E-05	0,00E+00
Products	Mineral Wool	5,98E-04	5,82E-04	0,00E+00	1,04E-05	5,77E-06	0,00E+00
Products	Structural Steel:	1,52E-04	1,52E-04	0,00E+00	2,49E-07	0,00E+00	-5,59E-05
Element	Skylight Thermal Bridge-Optimized	7,12E-03	1,64E-04	2,71E-03	4,21E-03	3,48E-05	-3,66E-03
Element	Wall-Floor -Foundation Thermal Bridge-	2,32E-02	1,39E-02	0,00E+00	8,86E-03	3,60E-04	-3,17E-03
Construction	Ground Floor Deck, Tiles	1,24E-02	7,86E-03	0,00E+00	4,33E-03	1,79E-04	-1,83E-03
Products	Cement Screed	1,29E-03	1,19E-03	0,00E+00	0,00E+00	9,76E-05	0,00E+00
Products	Ready Mixed Concrete C30/37	2,43E-03	2,33E-03	0,00E+00	5,55E-05	4,10E-05	-3,80E-05
Products	Tile Adhesive	9,00E-04	8,60E-04	0,00E+00	0,00E+00	4,06E-05	-7,07E-06
Products	Extruded Polystyrene (Xps)	7,75E-03	3,48E-03	0,00E+00	4,27E-03	0,00E+00	-1,79E-03
Construction	Ex.Foundation Optimized	9,10E-03	7,75E-03	0,00E+00	1,21E-03	1,40E-04	-4,44E-04
Products	Ready Mixed Concrete C30/37	8,00E-03	7,68E-03	0,00E+00	1,83E-04	1,35E-04	-1,25E-04
Products	Lightweight Concrete Block, Gray Eps Insulation	8,34E-04	8,24E-04	0,00E+00	5,70E-06	4,21E-06	-3,90E-06
Products	Cellulose Fibre Blowing Insulation Material	2,65E-04	-7,57E-04	0,00E+00	1,02E-03	0,00E+00	-3,15E-04
Construction	Middle Layer, Wood Frame Wall 45/185 Mm, 200	1,69E-03	-1,67E-03	0,00E+00	3,32E-03	4,08E-05	-8,88E-04
Products	Construction Wood, Pine And Spruce, Wet And	1,14E-04	-1,62E-03	0,00E+00	1,74E-03	0,00E+00	-8,85E-04
Products	Mineral Wool (Partition Walls Insulation)	7,56E-04	7,36E-04	0,00E+00	1,32E-05	7,30E-06	0,00E+00
Products	Gypsum Interior Plaster -	1,65E-04	1,48E-04	0,00E+00	0,00E+00	1,67E-05	0,00E+00
Products	Gypsum Interior Plaster - (Clone)	1,65E-04	1,48E-04	0,00E+00	0,00E+00	1,67E-05	0,00E+00
Products	Chipboard	4,89E-04	-1,08E-03	0,00E+00	1,57E-03	0,00E+00	-3,63E-06
Element	Wall-Floor Thermal Bridge	6,21E-03	-1,22E-03	2,94E-04	7,04E-03	8,94E-05	-5,28E-03
Element	Wall-Floor-Balcony Thermal Bridge	1,40E-02	4,91E-03	6,11E-04	8,40E-03	1,00E-04	-9,15E-03
Element	Window Thermal Bridge	3,02E-03	-9,68E-04	0,00E+00	3,88E-03	1,08E-04	-1,53E-03

Figure 9.12: LCA calculation for a single-family house, including selected thermal bridge junctions. The full dataset is large in scale.

9.1.2 Multi-storey

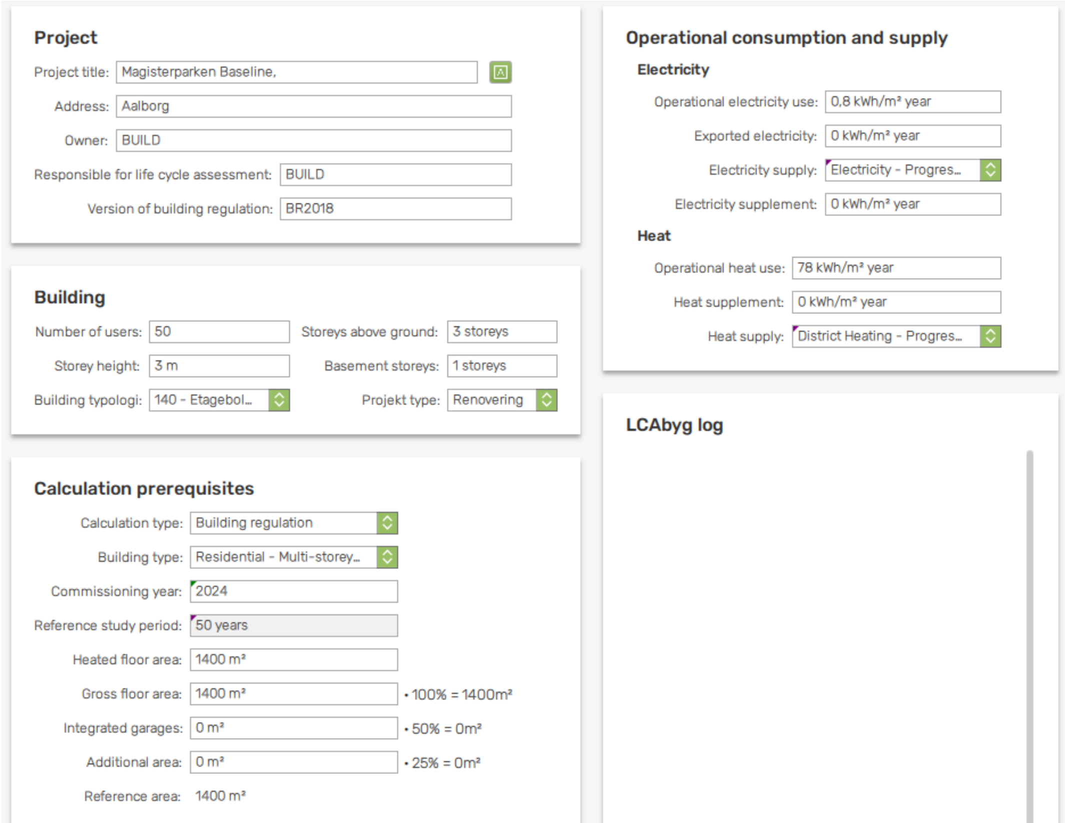


Figure 9.13: LCA calculation-multi storey-1

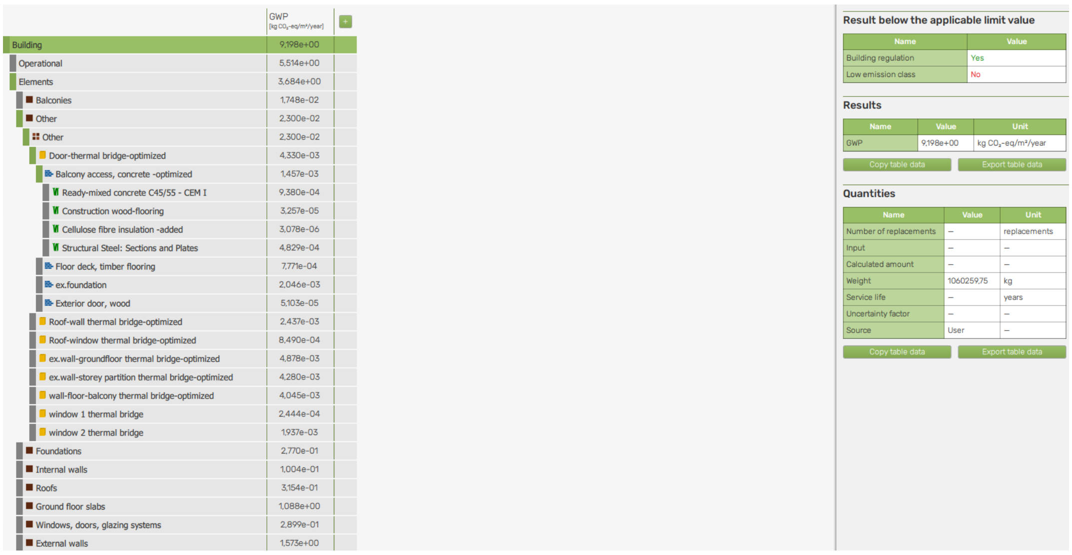


Figure 9.14: LCA calculation-multi storey-2

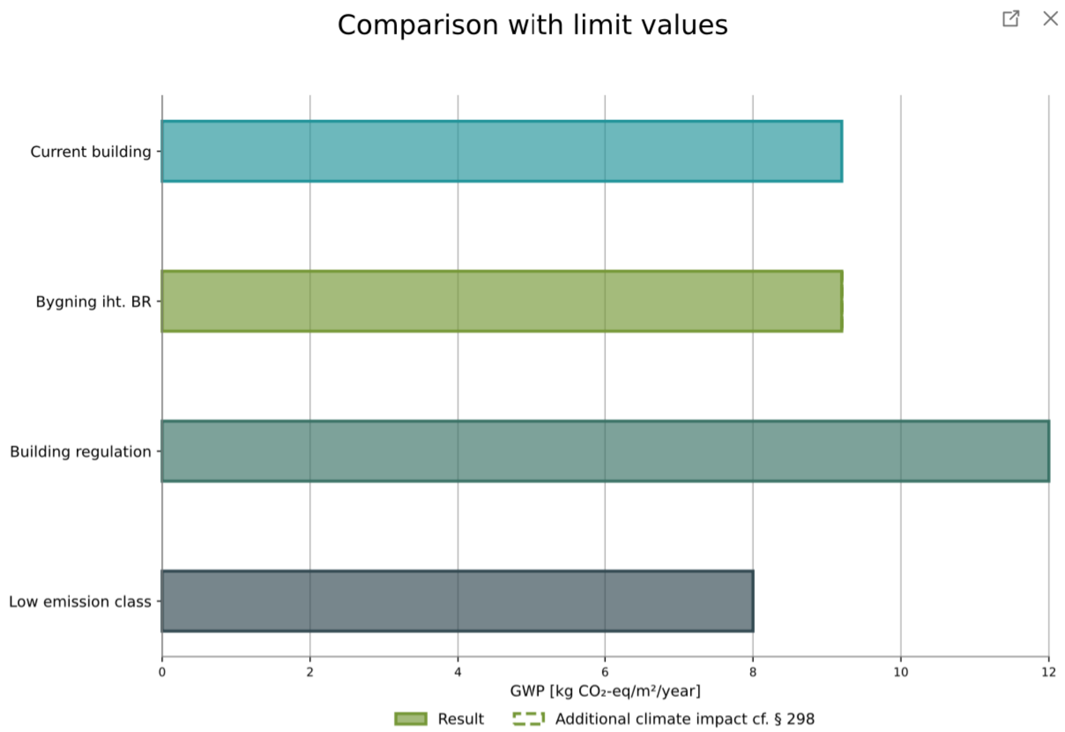


Figure 9.15: LCA calculation-multi storey-3

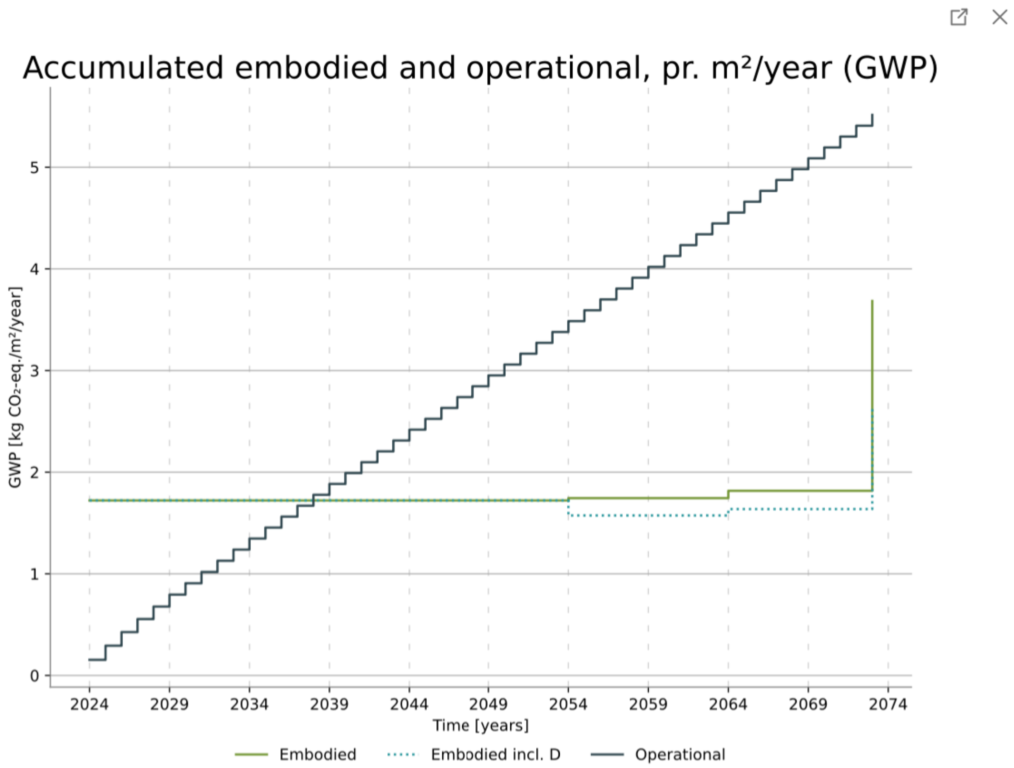


Figure 9.16: LCA calculation-multi storey-4

Description	Name	GWP	GWP	GWP	GWP	GWP	GWP
		sum	a1_3	b4	c3	c4	d
	Optimized	kg CO_2-eq.	kg CO_2-eq.	kg CO_2-eq.	kg CO_2-eq.	kg CO_2-eq.	kg CO_2-eq.
Sum	Building-Optimized	9,20E+00	1,72E+00	9,51E-02	1,83E+00	3,74E-02	-1,05E+00
Sum	Operation	5,51E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Operational electricity use	Electricity (Progression)	3,93E-02	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Operational heat use	District Heating (Progression)	5,48E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Sum	Element	3,68E+00	1,72E+00	9,51E-02	1,83E+00	3,74E-02	-1,05E+00
Group	Balconies	1,75E-02	1,44E-02	1,95E-04	2,76E-03	1,28E-04	-5,20E-03
Subgroup	Balustrades and handrails	1,75E-02	1,44E-02	1,95E-04	2,76E-03	1,28E-04	-5,20E-03
Element	Balcony	1,75E-02	1,44E-02	1,95E-04	2,76E-03	1,28E-04	-5,20E-03
Group	Thermal bridges	2,30E-02	1,43E-02	4,06E-04	8,10E-03	1,58E-04	-4,75E-03
Subgroup	Other	2,30E-02	1,43E-02	4,06E-04	8,10E-03	1,58E-04	-4,75E-03
Element	Door-Thermal Bridge-Optimized	4,33E-03	3,61E-03	5,80E-05	6,10E-04	4,99E-05	-7,77E-04
Element	Roof-Wall Thermal Bridge-Optimized	2,44E-03	-4,85E-04	1,41E-04	2,78E-03	1,43E-06	-1,08E-03
Element	Roof-Window Thermal Bridge-Optimized	8,49E-04	-2,12E-03	1,41E-04	2,81E-03	9,78E-06	-1,15E-03
Element	Ex.Wall-Groundfloor Thermal Bridge-Optimized	4,88E-03	4,52E-03	1,63E-05	3,01E-04	4,18E-05	-2,91E-04
Element	Ex.Wall-Storey Partition Thermal Bridge-	4,28E-03	3,95E-03	1,63E-05	3,03E-04	1,30E-05	-2,75E-04
Element	Wall-Floor-Balcony Thermal Bridge-Optimized	4,05E-03	3,20E-03	3,28E-05	7,94E-04	2,29E-05	-8,47E-04
Element	Window 1 Thermal Bridge	2,44E-04	-1,46E-04	2,56E-07	3,81E-04	9,34E-06	-2,38E-04
Element	Window 2 Thermal Bridge	1,94E-03	1,81E-03	0,00E+00	1,20E-04	1,01E-05	-9,96E-05
Group	Foundations	2,77E-01	2,68E-01	0,00E+00	5,15E-03	3,81E-03	-3,53E-03
Subgroup	Pile foundations	2,77E-01	2,68E-01	0,00E+00	5,15E-03	3,81E-03	-3,53E-03
Element	ex. foundations	2,62E-01	2,53E-01	0,00E+00	4,81E-03	3,55E-03	-3,29E-03
Element	int. foundations	1,51E-02	1,45E-02	0,00E+00	3,46E-04	2,56E-04	-2,37E-04
Group	Internal walls	1,00E-01	9,69E-02	0,00E+00	2,02E-03	1,50E-03	-8,45E-03
Subgroup	Load-bearing walls	1,00E-01	9,69E-02	0,00E+00	2,02E-03	1,50E-03	-8,45E-03
Element	int. wall	1,00E-01	9,69E-02	0,00E+00	2,02E-03	1,50E-03	-8,45E-03
Group	Roofs	3,15E-01	-1,03E+00	6,62E-02	1,28E+00	2,56E-04	-4,98E-01
Subgroup	Roofs	3,15E-01	-1,03E+00	6,62E-02	1,28E+00	2,56E-04	-4,98E-01
Element	roof	3,15E-01	-1,03E+00	6,62E-02	1,28E+00	2,56E-04	-4,98E-01
Group	Ground floor slabs	1,09E+00	7,43E-01	2,28E-02	3,06E-01	1,60E-02	-3,53E-01
Subgroup	Ground floor slabs	1,09E+00	7,43E-01	2,28E-02	3,06E-01	1,60E-02	-3,53E-01
Element	ground floors	1,09E+00	7,43E-01	2,28E-02	3,06E-01	1,60E-02	-3,53E-01
Group	Windows, doors, glazing systems	2,90E-01	1,26E-01	5,46E-03	1,44E-01	1,41E-02	-1,48E-01
Subgroup	Doors	2,90E-01	1,26E-01	5,46E-03	1,44E-01	1,41E-02	-1,48E-01
Element	Windows and external doors	2,90E-01	1,26E-01	5,46E-03	1,44E-01	1,41E-02	-1,48E-01
Group	External walls	1,57E+00	1,49E+00	3,84E-05	8,11E-02	1,43E-03	-3,25E-02
Subgroup	External walls	1,57E+00	1,49E+00	3,84E-05	8,11E-02	1,43E-03	-3,25E-02
Element	ex. walls	1,57E+00	1,49E+00	3,84E-05	8,11E-02	1,43E-03	-3,25E-02

Figure 9.17: LCA calculation-multi storey-5

9.1.3 Kindergarten

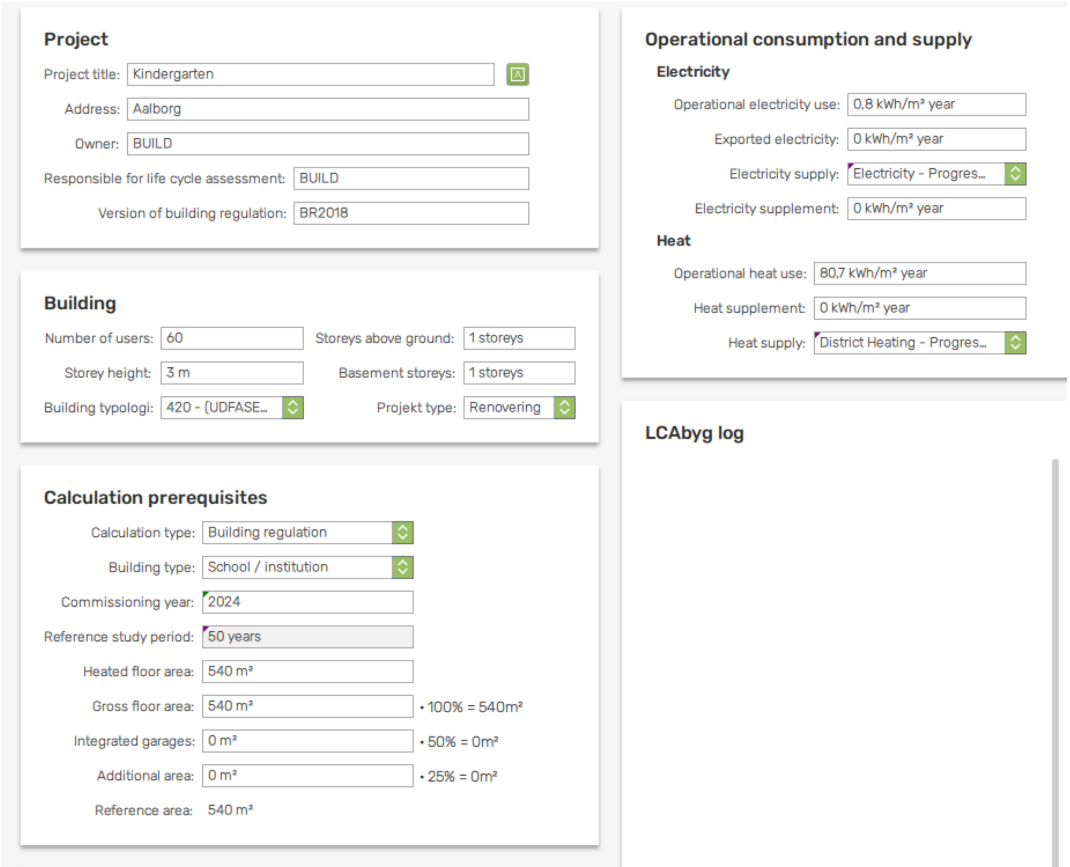


Figure 9.18: LCA calculation-Kindergarten-1

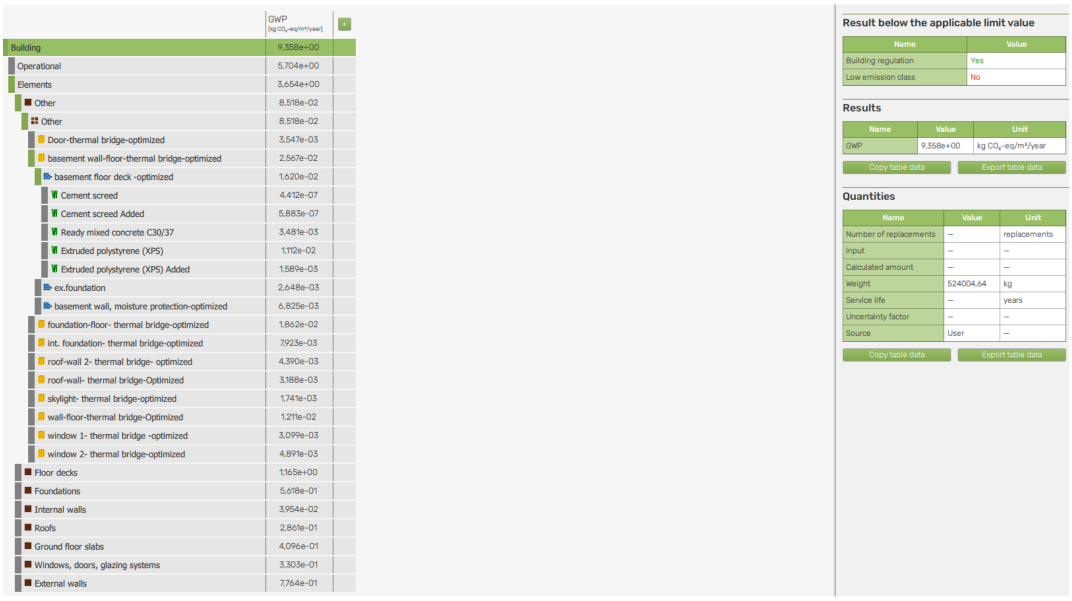


Figure 9.19: LCA calculation-Kindergarten-2

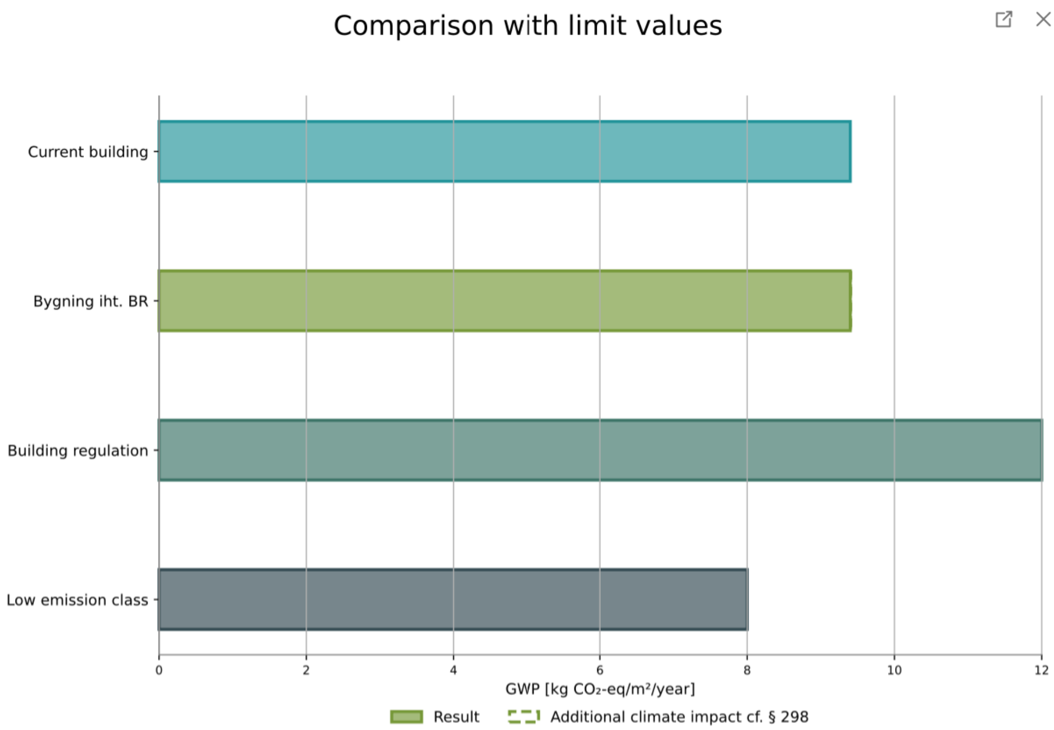


Figure 9.20: LCA calculation-Kindergarten-3

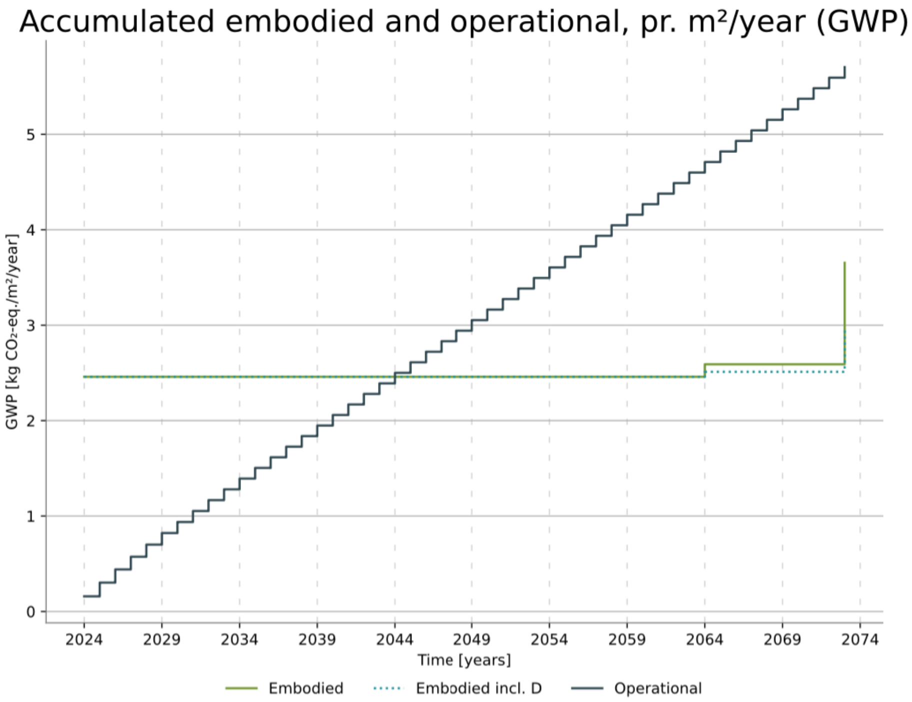


Figure 9.21: LCA calculation-Kindergarten-4

Description	Name	GWP sum kg CO_2-eq.	GWP a1_3 kg CO_2-eq.	GWP b4 kg CO_2-eq.	GWP c3 kg CO_2-eq.	GWP c4 kg CO_2-eq.	GWP d kg CO_2-eq.
	optimized						
Sum	Building-Optimized	9,358E+00	2,46E+00	1,31E-01	1,01E+00	4,89E-02	-6,95E-01
Sum	Operation	5,704E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Operational electricity use	Electricity (Progression)	3,934E-02	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Operational heat use	District Heating (Progression)	6,044E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Sum	Element	3,654E+00	2,46E+00	1,31E-01	1,01E+00	4,89E-02	-6,95E-01
Group	Thermal bridges	8,52E-02	6,81E-02	1,30E-03	1,44E-02	1,34E-03	-8,07E-03
Subgroup	Other	8,52E-02	6,81E-02	1,30E-03	1,44E-02	1,34E-03	-8,07E-03
Element	Door-thermal bridge-optimized	3,55E-03	2,94E-03	3,22E-04	2,14E-04	7,38E-05	-1,87E-04
Element	Basement wall-floor-thermal bridge-optimized	2,57E-02	1,81E-02	4,58E-05	7,34E-03	2,25E-04	-3,16E-03
Element	Foundation-floor- thermal bridge-optimized	1,86E-02	1,65E-02	1,66E-04	1,44E-03	4,82E-04	-6,49E-04
Element	Int. foundation- thermal bridge-optimized	7,92E-03	7,18E-03	0,00E+00	5,77E-04	1,64E-04	-4,10E-04
Element	Roof-wall 2- thermal bridge- optimized	4,39E-03	3,38E-03	0,00E+00	9,73E-04	3,60E-05	-4,82E-04
Element	Roof-wall- thermal bridge-Optimized	3,19E-03	1,55E-03	0,00E+00	1,61E-03	1,87E-05	-8,04E-04
Element	Skylight- thermal bridge-optimized	1,74E-03	5,07E-04	7,06E-04	5,21E-04	6,12E-06	-1,24E-03
Element	Wall-floor-thermal bridge-Optimized	1,21E-02	1,14E-02	3,05E-05	4,80E-04	2,01E-04	-2,44E-04
Element	Window 1- thermal bridge -optimized	3,10E-03	2,14E-03	0,00E+00	9,31E-04	3,23E-05	-5,86E-04
Element	Window 2- thermal bridge-optimized	4,89E-03	4,45E-03	3,05E-05	3,12E-04	9,84E-05	-3,09E-04
Group	Floor decks	1,17E+00	1,01E+00	0,00E+00	1,39E-01	1,49E-02	-6,92E-02
Subgroup	Floor deck	1,17E+00	1,01E+00	0,00E+00	1,39E-01	1,49E-02	-6,92E-02
Element	floors-	1,17E+00	1,01E+00	0,00E+00	1,39E-01	1,49E-02	-6,92E-02
Group	Foundations	5,62E-01	5,36E-01	0,00E+00	1,61E-02	9,40E-03	-1,01E-02
Subgroup	Pile foundations	5,62E-01	5,36E-01	0,00E+00	1,61E-02	9,40E-03	-1,01E-02
Element	ex. foundations-	4,33E-01	4,12E-01	0,00E+00	1,32E-02	7,22E-03	-8,11E-03
Element	int. foundations -	1,29E-01	1,24E-01	0,00E+00	2,96E-03	2,19E-03	-2,02E-03
Group	Internal walls	3,95E-02	3,83E-02	0,00E+00	7,17E-04	5,38E-04	-5,21E-03
Subgroup	Load-bearing walls	3,95E-02	3,83E-02	0,00E+00	7,17E-04	5,38E-04	-5,21E-03
Element	int. wall -	3,95E-02	3,83E-02	0,00E+00	7,17E-04	5,38E-04	-5,21E-03
Group	Roofs	2,86E-01	-1,97E-01	0,00E+00	4,77E-01	5,51E-03	-2,41E-01
Subgroup	Roofs	2,86E-01	-1,97E-01	0,00E+00	4,77E-01	5,51E-03	-2,41E-01
Element	roof-	2,86E-01	-1,97E-01	0,00E+00	4,77E-01	5,51E-03	-2,41E-01
Group	Ground floor slabs	4,10E-01	2,04E-01	0,00E+00	1,99E-01	6,67E-03	-1,20E-01
Subgroup	Ground floor slabs	4,10E-01	2,04E-01	0,00E+00	1,99E-01	6,67E-03	-1,20E-01
Element	basement floor-	4,10E-01	2,04E-01	0,00E+00	1,99E-01	6,67E-03	-1,20E-01
Group	Windows, doors, glazing systems	3,30E-01	1,30E-01	1,27E-01	6,72E-02	6,26E-03	-1,94E-01
Subgroup	Doors	3,30E-01	1,30E-01	1,27E-01	6,72E-02	6,26E-03	-1,94E-01
Element	Windows and external doors -	3,30E-01	1,30E-01	1,27E-01	6,72E-02	6,26E-03	-1,94E-01
Group	External walls	7,76E-01	6,68E-01	2,76E-03	1,01E-01	4,27E-03	-4,76E-02
Subgroup	External walls	7,76E-01	6,68E-01	2,76E-03	1,01E-01	4,27E-03	-4,76E-02
Element	ex. walls-	7,76E-01	6,68E-01	2,76E-03	1,01E-01	4,27E-03	-4,76E-02

Figure 9.22: LCA calculation-Kindergarten-5