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An Integrated Decision- support Framework for Optimising Industrial Hall Design - A Case Study of Valmet

Master's thesis in the Master's Programme Infrastructure and Environmental Engineering

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ABSTRACT

Industrial machine halls are large-volume buildings with demanding spatial, structural, energy, and operational requirements. Decisions made at the early design stage, especially those related to basement configuration, can have a major effect on energy demand, embodied carbon, construction cost, operating cost, safety, and maintenance accessibility. This thesis develops an integrated decision-support framework to help compare industrial hall design alternatives during the early design stage. The framework uses Key Performance Indicators (KPIs) across four performance dimensions: energy, environmental, economic, and operational performance.

The framework is applied to a Valmet tissue machine hall case study. Valmet is a global technology company that provides process technologies, automation, and services for the pulp, paper, and energy industries. In this study, three tissue machine hall alternatives are compared: a two-pit solution, an extended basement solution, and a full basement solution. These alternatives are evaluated under Swedish and Spanish climate scenarios.

The energy assessment considers heating demand and ventilation fan electricity, while the environmental assessment focuses on embodied carbon from structural materials. The economic assessment includes CAPEX and OPEX, and the operational assessment evaluates safety and maintenance accessibility using structured scoring. The results show that no single alternative performs best in all dimensions. The two-pit solution has the lowest energy use, embodied carbon, and operating cost, but scores lowest in operational performance. The full basement solution performs best in terms of safety and maintenance accessibility, but has the highest material use, embodied carbon, construction cost, and energy demand. The extended basement solution provides the most balanced performance overall. The study shows that a KPI-based framework can support clearer and more systematic early-stage decision-making by making trade-offs between different performance dimensions visible.

Keywords: Industrial machine hall, Decision- support framework, Key Performance Indicators, Valmet Tissue Hall.

Contents

Preface

This Master's Thesis was done at the Department of Architecture and Civil Engineering, Division of Sustainable Built Environment, Chalmers University of Technology, Gothenburg, Sweden, during the spring of 2026. The work was conducted in partnership with Valmet, a global supplier of industrial process technologies for the pulp, paper, and energy industries.

I would like to sincerely thank my industrial supervisors at Valmet, Ola Thomasson and Ulf Johnsson, for their valuable industry knowledge, technical input, and continuous support during the thesis. I am also very grateful to my academic supervisor, Quan Jin, for her guidance, feedback, and academic support throughout this work.

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Finally, I would like to thank the Valmet professionals who participated in the operational survey for their time, practical insights, and honest responses.

Gothenburg, June 2026

Swathi Mohan Kanhirathingal

Notations

Abbreviations

ACH	Air Changes per Hour
CAPEX	Capital Expenditure
DCT	Dry Creping Technology
DVUT	Dimensionerande vinterutetemperatur
EPD	Environmental Product Declaration
EPG	Energy Performance Gap
HDD	Heating Degree Days
HVAC	Heating, Ventilation and Air Conditioning
IDAE	Instituto para la Diversificación y Ahorro de la Energía
KPI	Key Performance Indicator
OPEX	Operational Expenditure
SMHI	Sveriges meteorologiska och hydrologiska institut
TMH	Tissue Machine Hall

Symbols

Cp	specific heat capacity of air
$\dot{m}$	air mass flow rate
ΔT	temperature difference between indoor and outdoor design temperature in °C.
Q_{gross}	ventilation heat load
$Q_{recovery}$	available internal or recovered heat
$E_{ventilation}$	annual Ventilation Fan Electricity Demand
$P_{installed}$	total installed ventilation fan power
LF	average operating load factor
$t_{operation}$	annual fan operating time
E_{annual}	annual purchased energy demand
P_{energy}	Energy price

1. Introduction

1.1 Background

The growth of population and increasing urbanization, mainly in developing countries, has led to greater emphasis on expanding manufacturing sectors, which in turn have increased the need for industrial building infrastructure (Guo & Liu, 2022) (Lavopa & Szirmai, 2024). Industrial buildings play a crucial role in day-to-day manufacturing systems, supporting production processes through spatial features, structural design, and technical infrastructure (Patterson, Singh, & Cho, 2022). Thus, industrial halls represent a distinct building type characterised by large internal volumes, complex layouts, and high energy demands. Different from residential or commercial buildings, industrial halls, especially machine halls, must accommodate heavy equipment, which significantly influences their design and performance (Whittleton & Wood, 2002)

In recent years, more attention has been directed towards sustainable development within the industrial sector. Companies are now not solely focused on productivity and cost efficiency but are also required to address environmental impact, resource efficiency, and long-term operational performance. Industrial buildings contribute significantly to energy consumption and carbon emissions, particularly due to heating and ventilation requirements in large volumes, and due to construction materials used for the building. As a result of these, improving the design of such facilities has become an important factor in achieving sustainability goals.

It is during the early design stage of a building project that key decisions regarding layout, structural systems, and spatial configuration are made. These decisions have long-term effects on energy use, environmental impact, construction cost, and operational efficiency (Bragança, 2014). However, in practice, industrial hall designs are often developed using experience-based approaches and simplified assumptions, which may not fully capture the complex interactions between different performance aspects.

Thus, to support informed decision-making, performance-based design approaches can be adopted. These approaches evaluate building alternatives using measurable indicators, which enable designers to assess and compare different solutions systematically. Use of Key Performance Indicators (KPIs) allows different dimensions of building performance, such as energy, environmental, economic, and operational aspects, to be quantified and analyzed (Mosca & Perini, 2022). Furthermore, there is a lack of integrated frameworks that combine energy, environmental, economic, and operational performance into a unified evaluation approach suitable for early design stages. This creates a gap in decision-support tools for industrial building design, particularly when considering the complexity and scale of a machine hall project.

1.2 Purpose

The purpose of this thesis is to develop a practical decision-support framework for comparing industrial machine hall design alternatives at an early design stage. The framework combines energy, environmental, economic, and operational aspects into one KPI-based evaluation method.

By using this structured approach, different design options can be compared more clearly and consistently, rather than relying only on experience or isolated cost and energy calculations. The framework is applied to a real Valmet case study, where three machine hall alternatives are evaluated under two climate conditions. Although the results are specific to this case, the method is intended to be adaptable for other industrial machine hall projects.

1.3 Aim

The aim of this thesis is to develop a structured decision-support framework for evaluating industrial machine hall designs during the early design stage, based on multiple performance dimensions and corresponding Key Performance Indicators (KPIs).

To achieve this aim, the following objectives are defined:

- To identify key performance dimensions relevant to industrial machine hall design, including energy, environmental, economic, and operational aspects.
- To develop a set of measurable KPIs that can be used to evaluate these performance dimensions.
- To construct a framework that enables systematic comparison of different design alternatives.
- To apply the developed framework to a real industrial case study provided by Valmet.
- To analyse and compare the performance of different machine hall design concepts under varying climate conditions.

Research Question:

How can a framework be developed to optimize industrial hall design by integrating energy, economic, environmental, and operational performance, and how can this framework be applied to Valmet's Hall concepts?

1.4 Scope and Limitations

This thesis focuses on evaluating industrial machine hall design alternatives at an early design stage, mainly considering building layout and structural configuration. The study is limited to the building level and does not include the detailed design of production processes or machinery.

The energy analysis includes heating and ventilation demand related to the building space, while energy use from industrial processes is excluded. Transmission heat losses are assumed to be small compared with ventilation-related heat flows. The environmental assessment is limited to carbon emissions from building materials, using emission factors instead of a full life cycle assessment.

The case study is based on a Valmet tissue machine hall. Although the framework is intended to be adaptable to other industrial projects, the numerical results are specific to this case and should not be directly applied elsewhere without adjustment.

2. Literature review

2.1 Industrial Buildings and Energy Consumption

Buildings use a large amount of energy both during construction and operation, making the building sector important for improving energy efficiency and sustainability. Industrial buildings are especially energy-intensive and account for more than 25% of total energy use in Europe. This is mainly because of the production (Dervishi & Karamani, 2020).

It is important to distinguish between process-related energy consumption and building-related energy use. While industrial production typically dominates total process energy demand, building-related energy primarily associated with heating, ventilation, and air conditioning (HVAC) systems remains substantial which cannot be neglected (Wang, Cao, & Meng, 2019). Thus, improving the energy performance of industrial buildings is essential for reducing overall energy consumption and supporting sustainability goals. This indicates a need for more focused studies that address the specific characteristics and performance challenges associated with industrial building typologies.

2.2 Energy Use Characteristics in Industrial Buildings

Due to the diversity of industrial processes, indoor environmental control requirements vary considerably across different types of industrial buildings. For example, buildings with high pollution emissions and clean room facilities require fundamentally different environmental conditions. In addition, there are notable differences in architectural characteristics. Industrial buildings are typically simpler and more functional in form, often having lower shape coefficients and smaller window-to-wall ratios compared to civil buildings.

Consequently, the principles and technological strategies used for energy efficiency design in industrial buildings differ from those applied in civil buildings. Direct application of energy efficiency methods developed for civil buildings often leads to unsatisfactory results in industrial contexts. Therefore, even though general energy-efficiency principles used in residential and commercial buildings can act as useful guidance, industrial buildings require design approaches that are specifically adapted to their unique conditions. These approaches must consider factors such as internal heat gains from equipment, the characteristics of the building envelope, and the performance of technical systems (Wang, Cao, & Meng, 2019)

Energy efficiency design in industrial buildings cannot be treated as a uniform approach due to the significant diversity in industrial processes and indoor environmental requirements. While considerable progress has been made in building energy efficiency standards over recent decades, these standards have predominantly focused on civil buildings, with limited consideration of industrial applications. As a result, there is a need for more tailored approaches specifically addressing industrial building characteristics (Wang, Cao, & Meng, 2019).

A major issue in large industrial halls is reducing heat losses caused by ventilation. HVAC systems are one of the largest energy users in buildings, often accounting for around 40-50% of total energy use in commercial and industrial facilities (Yang, Hu, & Spanos, 2019). Hafez et al. (2023) found that HVAC optimization and passive design strategies are among the main focus areas in research on energy-efficient buildings. Their review also showed that EnergyPlus and DesignBuilder are commonly used tools for building energy simulation. In large industrial halls, HVAC energy demand can be even higher because the large open volume requires more air to be heated and ventilated. Warm air also tends to rise and collect near the roof, which makes conventional heating systems less effective (Hafez, et al., 2023).

Gourlis and Kovacic showed that energy performance in industrial buildings is strongly influenced by building geometry, envelope insulation, and HVAC design (Gourlis & Kovacic, 2016). This highlights that industrial buildings should not be assessed using the same simplified assumptions as smaller and more uniform building types.

2.3 Energy Performance in Industrial Halls

Industrial halls represent a distinct category of buildings characterized by simple geometries, single-floor layouts, and comparatively loose thermal comfort requirements, while simultaneously exhibiting high internal heat gains from industrial processes (Lee, Trcka, & Hensen, 2013). These characteristics result in energy performance behaviour that differs significantly from conventional building types such as offices. As highlighted in previous studies, the energy consumption of industrial halls is largely associated with building services, particularly lighting and space conditioning, where even small efficiency improvements can lead to substantial cost savings. Due to their relatively simple construction, energy performance in such buildings can be effectively analysed through a limited set of demand-side parameters, including insulation levels, airtightness, and daylighting. Building energy simulation and optimization techniques have been widely applied to evaluate the impact of these parameters and to identify optimal design configurations that minimize total energy consumption. Results from such analyses indicate that significant energy savings, in the range of 25% to 37%, can be achieved compared to standard baseline designs (Lee, Trcka, & Hensen, 2013).

However, even with advanced simulation tools, industrial buildings often show an "energy performance gap" (EPG). This means that the actual energy use during operation can be quite different from what was predicted during the design stage (Bandak, Sreenivasan, Abdul Hamid, & de Wilde, 2025). In the context of Swedish buildings, this gap is due to a weak system, due to several recurring factors like insufficient commissioning and optimization of heating and ventilation systems following occupancy, inaccurate input assumptions during the design phase, and limited availability of reliable and up-to-date reference data for energy calculations (Bandak, Sreenivasan, Abdul Hamid, & de Wilde, 2025).

This gap is mainly caused by optimization after occupancy, inaccurate assumptions during design, and limited availability of reliable data (Bandak, Sreenivasan, Abdul Hamid, & de Wilde, 2025).

Additionally, the results show that the energy consumption in industrial halls is highly sensitive to variations in the process loads and occupancy patterns, which can be uncertain and subject to changes over time. Process loads and occupancy patterns shift as production demands change, and these shifts directly affect the balance between heating, cooling, and lighting energy use. When process loads are high, cooling becomes the dominant concern, while heating requirements reduce. This means that a design optimised for one set of operating conditions may perform poorly under different ones. As a result, evaluating design alternatives under a fixed set of assumptions is not always sufficient; accounting for variability in input conditions strengthens the reliability of any performance assessment. Therefore, the inclusion of uncertainty analysis is critical to assess the robustness of design solutions and ensure reliable performance under real-world conditions (Lee, Trcka, & Hensen, 2013).

2.4 Environmental & Economic Assessment of Industrial Buildings

Life cycle assessment (LCA) is the internationally recognised methodology for evaluating the environmental impacts of buildings and processes across their full lifespan, from raw material extraction through manufacturing, construction, operation, and end of life (ISO14040/14044, 2006). In buildings, LCA helps to distinguish between operational carbon, which comes from the process energy use, and embodied carbon, which comes from the materials, manufacturing, transportation, construction, etc.

As buildings become more energy efficient, operational emissions are reduced. This makes embodied carbon important, especially in highly efficient buildings where it can represent a large share of total life-cycle emissions (Röck, et al., 2020).

In the case of industrial buildings, which often require large amounts of concrete and steel to support heavy equipment and large spans, this is highly relevant. Since these materials have high environmental impacts, early decisions about structural systems and envelope materials can strongly influence the building’s overall carbon footprint (Röck, et al., 2020).

A common challenge in using LCA during the early design stage is the lack of detailed building information. A full LCA usually requires detailed material quantities, component data, and bills of quantities, which are often not available at the conceptual design phase (Kanafani, 2019) . To address this, researchers often use simplified LCA methods. These methods rely on emission factors and estimated material quantities to provide an early indication of environmental impact, even before detailed design information is available

Economic evaluation at the early design stage helps compare the initial construction cost, known as CAPEX, with the expected operating cost, known as OPEX. This comparison is important because a design with lower construction cost may not always be the most cost-effective option over time. It also forms the basis for life-cycle cost methods, such as those described in ISO (15686-5, 2017). Research on building investment models shows that a full financial assessment should ideally include investment, energy, maintenance, replacement, and end-of-life costs. However, during the early design stage, reliable data for future costs is often limited or unavailable, making detailed financial predictions difficult (Schade, 2007).

2.5 Performance-Based Benchmarking Approaches

Jiang et al. (2014) highlight certain weaknesses in China's energy benchmarking methods for public buildings. They found that current standards often overlook base load energy use, such as equipment and appliances, while relying on outdated baseline data, and focus mainly on technical solutions rather than also considering user behavior and building management. To address such limitations, the study proposes a performance-based benchmarking method, which evaluates both space conditioning energy and base load energy using actual operational performance data (Jiang, Chen, Dong, & Huang, 2014).

The literature focuses on the importance of reliable data for effective benchmarking. The main data requirements may include building type, location, floor area, total energy consumption, and energy sources, which have to be regularly collected and updated. Indicators such as energy use per unit area (kWh/m^2) and carbon emissions per unit area ($kg\ CO_2/m^2$) are suggested to enable a consistent comparison across different buildings. Thus, the study shows that better benchmarking systems should include all major forms of energy use, use more reliable baseline data, and consider both technical and operational factors.

2.6 KPI-Based Evaluation of Building Performance

The use of Key Performance Indicators (KPIs) as a tool for evaluating the sustainability of building renovation projects has gained increasing traction within the research community. Kylili, Fokaides, and Lopez Jimenez (2016) conducted a comprehensive review of previous studies that employed the KPI approach in building renovation within the context of the built environment. The authors identified eight generic categories of KPIs that have been employed across the literature: economic, environmental, social, technological, time, quality, disputes, and project administration.

Economic KPIs were identified as fundamental to decision-making in renovation. In the literature, these were classified into direct cost, which includes capital investment, lifecycle cost, and project profitability, and indirect cost, which includes ecosystem rehabilitation and material price stability. While Dijkstra (2013, as cited in Kylili et al., 2016) used Net Present Cost (NPC) to compare Dutch residential renovation concepts. Environmental KPIs were extensively employed with energy-related indicators such as energy saving per annum, energy payback time, etc., reflecting the influence of the European Energy Performance of Buildings Directive (EPBD). Atmospheric indicators, mainly GHG emissions and embodied, were also used. Social KPIs were assessed mainly through stakeholder Likert-scale surveys, covering five sub-categories: cultural heritage, public access, public perception, functionality, and occupational safety. Beyond the core sustainability pillars, Kylili et al. (2016) identified further KPI categories.

In addition to quantitative metrics, KPIs are often evaluated using qualitative approaches, such as stakeholder-based assessments and Likert scale methods. This reflects the multidimensional nature of sustainability, where not all performance aspects can be measured purely through numerical data. As a result, KPI-based evaluation provides a structured approach for integrating both technical and non-technical aspects of building performance (Kylili, Fokaides, & Lopez Jimenez, 2016).

Even though there is widespread use of KPIs in building performance evaluation, several challenges remain. One of the main issues is the lack of a standardized framework for KPI selection and its application. Different studies use varying sets of indicators and methodologies, leading to inconsistencies in evaluation results and making it difficult to compare findings across projects (Kylili, Fokaides, & Lopez Jimenez, 2016).

2.7 Energy Certification, Benchmarking, and Labelling Frameworks

Energy performance assessment in buildings has been widely supported through the development of structured evaluation frameworks such as energy certification schemes. These schemes emerged in the early 1990s as a response to increasing energy consumption in buildings, which accounted for approximately 20–40% of total energy use in developed countries (Pérez-Lombard, Ortiz, González-Falcón, & Rodríguez Maestre, 2009). The primary objective of energy certification is to reduce energy consumption and associated carbon emissions while maintaining an acceptable level of comfort, health, and productivity. Within this framework, building performance is evaluated using standardized indicators, mainly the Energy Performance Index (EPI), which is used to express energy use in relation to building output, typically per unit area.

The energy certification systems integrate several key components like benchmarking, energy rating, and energy labelling, which comprehensively provide a structured approach for assessing and comparing building performance. Benchmarking enables the comparison of a building's energy use against a database of similar buildings, which facilitates identifying its relative performance and potential for improvement. Energy rating methods evaluate building performance either through calculated approaches, based on simulation models, or through measured approaches, based on actual operational data. Energy labelling further translates these evaluations into simplified classes, typically using an A–G scale, to facilitate communication and decision-making among stakeholders (Pérez-Lombard, Ortiz, González-Falcón, & Rodríguez Maestre, 2009)

Implementation of energy certification requires addressing many challenges, such as including the definition of appropriate performance indicators, selecting calculation methods, defining efficiency thresholds, and developing reliable comparison benchmarks. Besides this, mismatches between predicted and actual energy performance may occur due to uncertainties in occupant behaviour, climatic conditions, and operational conditions. Also, the definition of labelling scales is often influenced by policy decisions instead of purely technical considerations, which may affect the consistency and comparability of results (Pérez-Lombard, Ortiz, González-Falcón, & Rodríguez Maestre, 2009).

While such an energy certification framework provides a good foundation for performance evaluation, they are primarily created for general building types and focuses on energy-related indicators. Thus, they do not fully address the specific characteristics of industrial buildings, particularly machine halls, which involve large special volumes, ventilation requirements, and complex operational conditions. These approaches typically cover energy performance with limited representation of economic, environmental, and operational aspects. This highlights the need for more comprehensive and integrated evaluation frameworks, such as KPI-based approaches.

2.8 Research Gap and Relevance to Industrial Buildings

Although significant progress has been made in the evaluation of building performance, existing research is largely focused on residential, commercial, and public buildings. Industrial buildings, especially machine halls, remain underrepresented in the literature, despite their high energy demand and operational complexity.

Moreover, existing evaluation methods are often fragmented, addressing energy, economic, environmental, and operational performance separately rather than in an integrated manner. Many approaches also rely on detailed simulations and extensive data inputs, which limit their applicability during the early design stage when information is limited but the decision is high.

In addition, the specific characteristics of industrial machine halls, such as large spatial volumes, high internal heat gains, and ventilation requirements, are not adequately addressed by conventional evaluation frameworks. Operational dimensions like maintenance and safety are also often overlooked, despite their importance in industrial settings.

To address these limitations, this study proposes a structured decision-support framework based on Key Performance Indicators (KPIs), integrating multiple performance dimensions into a unified evaluation approach. The framework is specifically designed for early-stage design assessment, enabling systematic comparison of alternative machine hall configurations under limited data availability.

3. Methodology

3.1 Research Approach

This chapter presents the development of the evaluation framework proposed in this thesis. The framework is built into two parts. The first provides a general, reusable foundation, one that is independent of any project context. It sets out the performance dimensions to be assessed, identifies suitable KPI types for each dimension, and specifies the calculation approaches available to quantify them. This layer is designed to be applicable to any industrial machine hall project, regardless of the specific design alternatives or geographic context under consideration. The second layer describes how the general framework was implemented in this thesis, the specific KPIs selected, the data sources used, and the choices made in applying the framework to the Valmet case study.

The decision to separate the framework into two layers was intentional. In building research, a common problem with applied frameworks is that the general method and the case-specific details become too intertwined, making it difficult for others to reuse the framework in a different context without carrying over assumptions that belong to the original study. By keeping the two layers distinct, the framework developed here can be picked up and adapted for other industrial hall projects with practitioners replacing the input data, KPIs, and calculation methods to suit their own context, while the underlying structure remains unchanged.

The methodology is developed to support the evaluation and comparison of industrial hall design alternatives. It is based on a structured, indicator-based approach, where performance is assessed through selected KPIs and organised into a decision-support structure. A theory-driven approach is adopted to ensure that relevant performance aspects are systematically captured, and the methodology integrates insights from the literature with practical application to a real case study.

Figure 1 illustrates the two main stages of the methodology. The first stage covers the development of the general framework, where the theoretical structure, performance dimensions, and KPIs are defined. The second stage involves applying this framework to three machine hall design alternatives across two climate scenarios.

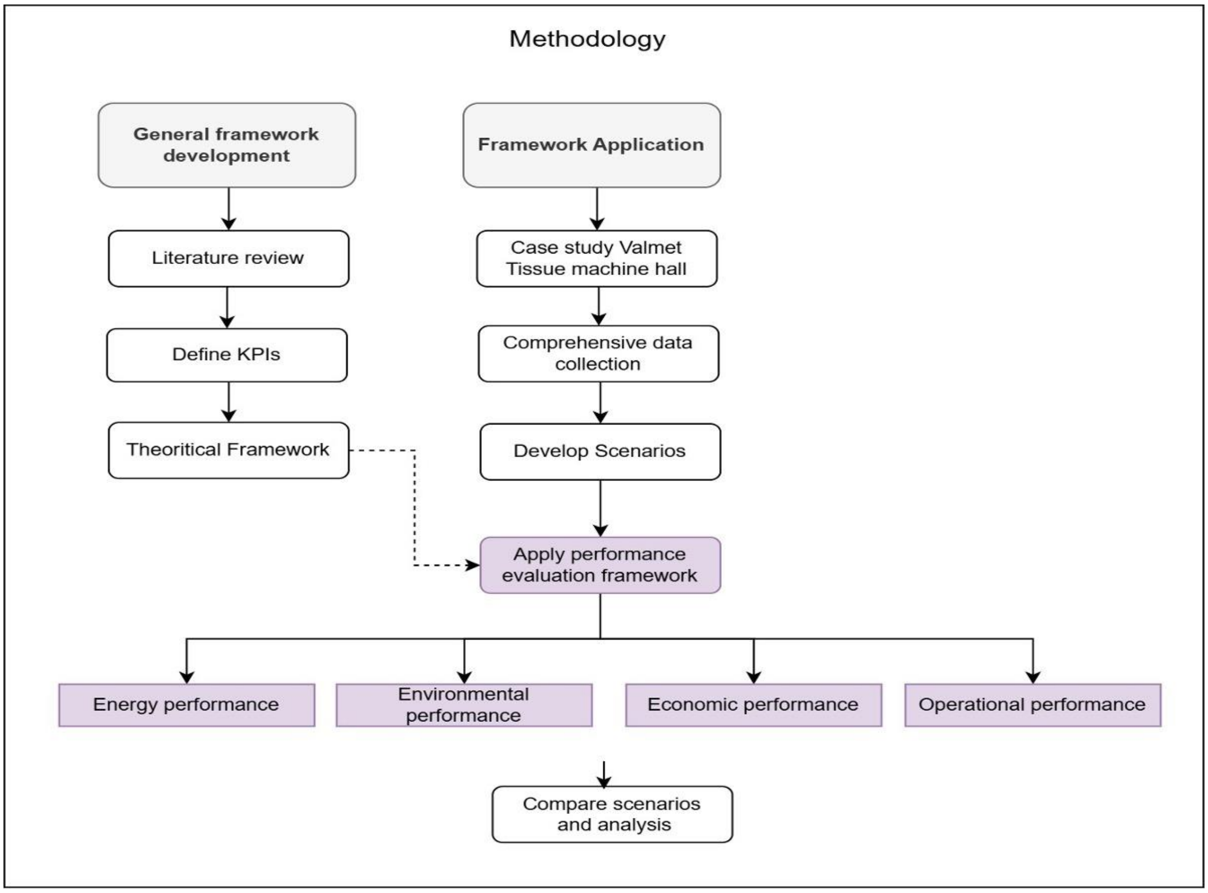

Figure 1: Overview of the two-stage research methodology: general framework development and case study application.

Though every KPI is quantifiable, for the operational dimension, a structured survey was used in place of numerical calculation. Professionals with relevant experience in tissue machine hall design and operation were therefore asked to assess the three design alternatives using a 1–5 scale. The responses were converted into numerical scores and averaged to allow comparison, but the basis of the assessment is qualitatively rooted in professional judgement and perceived performance rather than directly measurable quantities.

The framework is designed to support decision-making at the early design stage, when choices such as design configuration can have lasting consequences for energy use, construction cost, and operational efficiency. Rather than producing a single combined score, the framework presents each KPI individually across the four dimensions, like energy, environmental, economic, and operational. This approach keeps the results transparent and avoids situations where strong performance in one area masks poor performance in another. Decision-makers can therefore interpret the results considering their own project priorities, rather than following a fixed ranking.

3.2 Theoretical Basis for Framework Design

The evaluation framework draws on two theoretical foundations. The first concerns decision-support in building design, particularly the role of early-stage decisions in shaping long-term performance. The second concerns multi-criteria evaluation, which provides the basis for assessing alternatives across several performance dimensions simultaneously. Both are described in the sections below.

Early-Stage Design Theory

Decision-support frameworks in building design are grounded in the understanding that early design decisions carry significant consequences for long-term building performance. This is captured by the MacLeamy Curve (MacLeamy, 2004), which shows that the ability to influence performance outcomes is greatest at early project stages, while the cost of making changes increases as the project progresses. (see Appendix 1)

In this study, the key early-stage decision under evaluation is the choice of basement configuration. This single design choice directly determines structural material quantities, construction cost, energy demand, and operational accessibility, all of which are assessed through the framework. At the same time, this stage is characterised by limited data availability, which restricts the use of detailed simulation tools and requires simpler, more practical calculation approaches.

The framework is therefore designed to work within these constraints, relying only on data typically available at the early design stage: drawings, structural dimensions, material quantities, and climate data. In the context of this study, all these inputs were available for the Valmet machine hall alternatives.

Multi-Criteria Evaluation Perspective

Industrial building design involves multiple competing demands that a single indicator cannot capture. A basement configuration that minimises construction cost may, for instance, perform poorly in terms of energy use or operational safety. The framework, therefore, evaluates all four dimensions, like energy, environmental, economic, and operational, rather than reducing results to one combined score.

Although full Multi-Criteria Decision Analysis (MCDA) methods were considered, they were not adopted in this study. This is because such methods usually require predefined weights for each criterion before the results can be combined. At the early design stage, however, project priorities are often still uncertain. The importance of energy use, cost, environmental impact, or operational aspects may differ depending on the client, site conditions, and intended use of the building. Assigning fixed weights at this point could therefore introduce subjectivity into the evaluation. For this reason, the KPIs are kept separate in the proposed framework, allowing the trade-offs between alternatives to remain visible and supporting a more transparent discussion during decision-making.

The result is a transparent performance profile for each design alternative. The four dimensions, like energy, environmental, economic, and operational, were selected because they reflect the key aspects of sustainable building assessment most relevant to industrial machine halls, as identified in the literature (Kylili, Fokaides, & Lopez Jimenez, 2016) (Pérez-Lombard, Ortiz, González-Falcón, & Rodríguez Maestre, 2009).

3.3 Performance Dimensions and KPI Selection

3.3.1 Performance Dimensions

Based on the literature review, four performance dimensions were selected: energy, environmental, economic, and operational. These reflect the key aspects of sustainable building assessment and are specifically relevant to the characteristics of industrial machine halls.

- Energy: addresses thermal and ventilation-related performance of the building and its interaction with internal process heat generated by production machinery.
- Environmental: focuses on the carbon impact of building materials, reflecting the embodied emissions associated with different structural configurations.
- Economic: considers both initial investment (CAPEX) and recurring operational costs (OPEX), providing a wider perspective on the financial consequences of each design choice.
- Operational: evaluates aspects directly relevant to industrial functionality that are critically affected by the spatial and structural characteristics of basement configurations.

3.3.2 KPI selection

The selection of Key Performance Indicators was guided by four explicit criteria, applied consistently across all four performance dimensions. These criteria ensure that each KPI is both theoretically appropriate and practically usable at the early design stage.

- Relevance to the design decision: Each KPI must be directly influenced by the choice between the design alternatives.
- Calculability at the early design stage: each KPI must be quantifiable using data available during early design, namely floor plans, structural configuration, material specifications, and climate data.
- Coverage of the performance dimension: each dimension is represented by the minimum number of KPIs that adequately capture what actually matters.
- Independence between KPIs: to the extent possible, KPIs should not double count the same underlying phenomenon across dimensions.

Applying these criteria, seven KPIs were selected across the four dimensions. These are summarised in Table 1, together with their units, the selection criteria each satisfies, the calculation method applied, and the data source that can be used.

Table 1: Selected KPIs, units, selection criteria, and calculation methods.

Dimension	KPI	Unit	Selection criteria met	Calculation method	Data source
Energy	Heating energy demand	kWh/year	Relevance, calculability, coverage	EN 12831 standard method	Climate data (SMHI/AEMET), building geometry
Energy	Ventilation fan electricity demand	kWh/year	Relevance, calculability, coverage	EN 12831 standard method	Ventilation system design data, airflow rates, fan specifications, operating schedules
Environmental	Embodied carbon from materials	CO2-e	Relevance, calculability, independence	Material quantities × emission factors	Material quantities and environmental product declarations (EPDs) or emission factor databases
Economic	CAPEX	EUR	Relevance, calculability, coverage	Material & construction cost estimate	Case data, ISO 15686-5, unit cost data or cost-estimation references
Economic	OPEX	EUR/year	Relevance, calculability, independence	Energy demand × local energy price	Energy results, Standard unit electricity price/ local tariff data
Operational	Safety score	Score 1–5	Relevance, coverage	Structured qualitative rubric	Design drawings, expert review
Operational	Maintenance accessibility score	Score 1–5	Relevance, coverage	Structured qualitative rubric	Design drawings, expert review

3.3.3 Energy Dimension

Within the framework, energy performance can be represented through indicators related to space conditioning, particularly heating and ventilation fan electricity demand, which are typically dominant in large-volume industrial halls with high internal heat gains (Wang, Cao, & Meng, 2019)

In this study, two KPIs are selected: heating energy demand and ventilation fan electricity demand. Large-volume industrial machine halls often have significant ventilation requirements and may include internal heat gains from production equipment. Therefore, heating and ventilation fan electricity demand are relevant KPIs for evaluating energy performance.

The calculation of these KPIs is based on standard methods such as EN 12831, incorporating approaches that account for internal heat gains in the building's thermal balance. The relationship between internal heat gains and ventilation heat losses defines a balance point temperature, below which additional heating is required.

3.3.4 Environmental Dimension

The environmental dimension can be represented through indicators related to material impacts, particularly embodied carbon emissions. In this study, carbon emissions from building materials are selected as the primary environmental KPI. While a full Life Cycle Assessment (LCA) is not always feasible at the early design stage, embodied carbon in structural materials such as concrete and steel represents a significant and design-dependent environmental impact (Lützkendorf & Balouktsi, 2022).

Emissions are calculated by multiplying material quantities with appropriate emission factors, typically obtained from Environmental Product Declarations (EPDs). The emission factors should be selected according to the intended assessment boundary and data availability, for example, covering product-stage emissions only or including additional construction-stage impacts.

3.3.5 Economic Dimension

The economic dimension evaluates the financial implications of different industrial hall design alternatives. In early stage building design, economic performance is commonly represented through indicators that capture both initial investment and recurring operational costs.

In this framework, the economic dimension is assessed using two KPIs: capital expenditure (CAPEX) and operational expenditure (OPEX). CAPEX represents the initial cost associated with the construction and implementation of a design alternative, including cost elements affected by building geometry, structural configuration, material quantities, and construction complexity. OPEX represents recurring costs during operation, particularly energy-related costs associated with heating and ventilation.

Together, CAPEX and OPEX offer a balanced view of both the initial investment and the longer-term running costs of a building. This aligns with the principles of Life Cycle Cost Analysis (LCCA) as defined in ISO 15686-5, while still being practical for early-stage decision-making, where full lifecycle cost data is rarely available. The framework does not demand a complete LCCA. Instead, it draws on CAPEX and selected recurring operational costs as straightforward economic indicators, making it possible to meaningfully compare design alternatives without requiring exhaustive financial data upfront.

3.3.6 Operational Dimension

The operational dimension can be assessed using indicators that reflect the functional performance of the building, particularly in terms of safety and maintenance accessibility. These aspects are critical in industrial environments, where building layout and structural design directly influence usability, accessibility, and long-term operation.

In this study, these aspects can be evaluated using qualitative KPIs in the form of a structured scoring system. Each design alternative is assessed based on predefined criteria derived from layout characteristics or through surveys, and scores are assigned on a scale from 1 to 5.

Although qualitative in nature, this approach is consistent with established practices in multi-criteria building assessment, where certain performance aspects cannot be meaningfully quantified without loss of context (Kylili et al., 2016). The use of a structured scoring method ensures transparency, consistency, and comparability across all design alternatives. The details of the method used in this case study are shown in section 4.6

The selected KPIs and their relationship to the four performance dimensions are illustrated in Figure 2. The framework evaluates each design alternative across energy, environmental, economic, and operational dimensions, with each dimension represented by its corresponding KPIs as defined in Table 1.

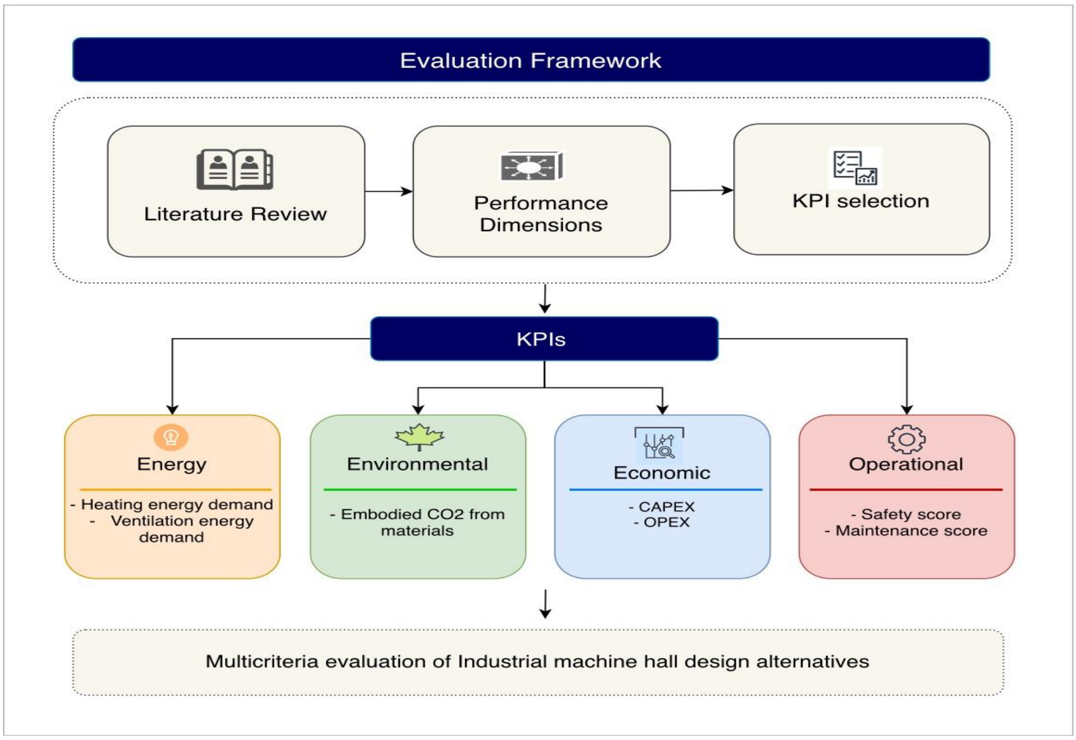

Figure 2 : General evaluation framework for assessment

3.4 Calculation Methods

This section presents the general calculation methods used to quantify the selected KPIs. While Section 3.3 explained the relevance and purpose of each KPI, this section focuses on the calculation procedure and formulas. The methods are presented at a general framework level and are later applied to the case study in Chapter 4.

Energy Dimension

The energy dimension is quantified using two KPIs: heating energy demand and ventilation fan electricity demand. The calculation methods for these KPIs are presented below.

1) Heating Energy Demand

The heating energy demand calculation is based on the design heat-load approach described in SS-EN 12831-1:2017. The standard defines the design heat load as the heat supply required to maintain the specified internal design temperature under external design conditions. The standard design heat load includes transmission heat losses, ventilation heat losses, additional heating-up power, and possible heat gains (SS-EN-12831, 2017). However, in the context of thesis case study, transmission heat losses through the building envelope are considered to be negligible compared to ventilation-heat demand, which dominates in the large volume industrial halls with high air change rates.

$$Q_{gross} = \dot{m} \cdot Cp \cdot \Delta T$$

Where,

Q_{gross} is the ventilation heat load (kW)

ṁ is the air mass flow rate (kg/s)

Cp is the specific heat capacity of air (kJ/kg·K)

ΔT is the temperature difference between the indoor and outdoor design temperature in K or °C.

If internal or recovered heat is available, it is subtracted from the gross heating load:

$$Q_{net} = Q_{gross} - Q_{recovery}$$

Where,

Q_{net} is net heating load (kW)

$Q_{recovery}$ is available internal or recovered heat (kW)

If the recovered or internal heat exceeds the calculated heat load, the net heating demand is set to zero. In this case, the result is interpreted as heat surplus rather than negative energy consumption.

Annual heating energy demand can then be calculated as:

$$E_{heating} = Q_{net} \cdot t_{heating}$$

Where,

$E_{heating}$ is the annual heating energy demand

$t_{heating}$ is the annual heating operating time

1) Ventilation Fan Electricity Demand

Ventilation Fan Electricity Demand is calculated from the installed fan power, operating load factor, and annual operating time.

$$E_{ventilation} = P_{installed} \cdot LF \cdot t_{operation}$$

Where,

$E_{ventilation}$ is the annual Ventilation Fan Electricity Demand (kWh/year)

$P_{installed}$ is the total installed ventilation fan power (kW)

LF is the average operating load factor

$t_{operation}$ is the annual fan operating time h/year

The installed fan power should include all relevant ventilation equipment serving the machine hall, such as supply air fans, exhaust fans, wall supply air units, and other ventilation-related fans included within the defined system boundary. The load factor accounts for the fact that ventilation systems may not operate continuously at full installed capacity throughout the year.

Where detailed operational profiles are unavailable, a representative load factor may be used as an early-stage assumption, provided that this assumption is clearly stated in the case-specific application.

Environmental Dimension

Embodied carbon emissions are calculated by multiplying material quantities by appropriate emission factors. The emission factors may be obtained from Environmental Product Declarations, national databases, or other recognized carbon data sources. The general calculation method can be expressed as:

$$EC_i = Q_i \cdot EF_i$$

Where,

EC_i is the embodied carbon of material i

Q_i is the quantity of material i

EF_i is the emission factor for material i

The total embodied carbon is calculated as the sum of the embodied carbon of all included materials:

$$EC_{total} = \sum EC_i$$

In an embodied carbon assessment, the system boundary should be clearly defined. Building life-cycle modules are commonly divided into product, construction, use, and end-of-life stages. Modules A1–A5 represent the early life-cycle stages from material production to construction. A1–A3 cover the product stage, including raw material supply, transport to manufacturing, and manufacturing. A4 represents transport to the construction site, while A5 represents construction and installation processes.

The selected life-cycle modules depend on the aim of the assessment and the availability of data. For early-stage design comparison, the assessment may focus on the modules most directly affected by material quantities and construction activities. The specific modules included in this thesis application are defined in the case study chapter.

Economic Dimension

Economic performance is calculated using CAPEX and OPEX.

CAPEX may be calculated or obtained from cost estimates, depending on available project data. When material-based cost data is available, CAPEX can be calculated as:

$$CAPEX = \sum (Q_i \cdot C_i)$$

Where,

Q_i is Quantity of cost item i (m^3, kg, m^2, or item)

C_i is the unit cost of the cost item i (€/unit)

OPEX is calculated from the annual purchased energy demand and the corresponding energy price:

$$OPEX = E_{annual} \cdot P_{energy}$$

Where,

OPEX is the annual operational expenditure (€/year)

E_{annual} is the annual purchased energy demand (kWh/year or MWh/year)

P_{energy} is the Energy price (€/kWh or €/MWh)

When different energy sources are used, the OPEX calculation should be separated by energy type:

$$OPEX = \sum (E_j \cdot P_j)$$

Where,

E_j is the annual purchased energy from source j (kWh/year or MWh/year)

P_j is Price of energy source j (€/kWh or €/MWh)

The specific energy prices and OPEX scenarios used in the case study are defined in Chapter 4.

Operational Dimension

Operational performance is quantified using a structured scoring method. For each operational KPI, a set of assessment criteria is defined, and each criterion is scored using a scale from 1 to 5. The final KPI score is calculated as the average of the individual criterion scores. The assumptions and method used in the case study are shown in section 4.5.7 and section 4.6.

$$Score_{KPI} = \frac{1}{n} \sum Score_i$$

Where,

$Score_{KPI}$ is the final score for the operational KPI

$Score_i$ is the score assigned to criteria i

n is the number of criteria included in the KPI.

The scoring scale that can be used in the framework is shown in Table 2.

Table 2 °Operational KPI scoring scale

Score	Interpretation
1	Very poor
2	Poor
3	Acceptable
4	Good
5	Very good

4. Framework Application to the Valmet Case Study

This chapter applies the evaluation framework developed in Chapter 3 to a case study provided by Valmet. The case study focuses on the comparison of three tissue machine hall configurations: a two-pit solution, an extended basement solution, and a full basement solution. The details of the design configurations are shown in Section 4.3. These alternatives are evaluated using the selected performance dimensions: energy, environmental, economic, and operational performance.

The purpose of the case study is to demonstrate how the framework can be used to compare industrial hall design alternatives under different climate conditions. The chapter introduces the industrial context, available data, design alternatives, and climate scenarios. It then defines the case-specific assumptions and context used in the calculations before applying the KPI calculation methods.

4.1 Industrial Context: Valmet and Tissue Machine Halls

Valmet is a global company specialising in industrial process technologies for the pulp, paper, and energy industries. The company develops and supplies complete tissue production lines, including a tissue machine with Yankee dryer, hood, and air system, and main process machinery that influences the spatial and thermal characteristics of tissue machine halls.

Tissue machine halls are large-volume industrial buildings designed to house continuous tissue production machinery. Their main characteristics include large internal volumes, high internal heat gains from the Yankee dryer and the hood with air system, significant ventilation requirements, and the need for continuous operation. These characteristics make tissue machine halls a relevant case for early-stage performance evaluation.

The choice of basement configuration can directly influence structural material quantities, construction cost, building-related energy demand, and operational accessibility. The basement configuration was the main design variable in the case study. Valmet provided project-specific technical documentation for three tissue machine hall configurations. This allowed the framework to be applied to actual engineered solutions rather than purely hypothetical design alternatives.

4.2 Data Sources and Documentation Structure

The data provided by Valmet were two categories: machine hall information and site-specific information. Machine hall information included layout drawings, 3D models of the basement level, operating floor plans, mezzanine floor plans, and the machine hall technical specification for each design alternative. Site-specific information included Mill Conditions documents, which provided climate and utility data for the corresponding reference projects.

The three design alternatives were based on three separate Valmet reference projects, each located in a different geographic context.

- The two-pit solution was based on a reference project located in Spain. The ventilation technical specification and layout drawings for this project were used directly for the Spanish climate scenario. The same design was then applied to the Swedish scenario by substituting the Swedish outdoor design temperature.
- The extended basement solution was based on a reference project located in Sweden. The ventilation data and layout were used directly for the Swedish climate scenario. The Spanish scenario was derived by applying the Spanish outdoor design temperature to the same design parameters.
- The full basement solution was based on a reference project located in the UAE. Since neither selected climate scenario matches the UAE climate, the full basement design was applied independently to both Sweden and Spain by substituting the respective outdoor design temperatures into the ventilation calculations.

This approach, where a fixed design is evaluated under different outdoor temperature conditions, is consistent with the aim of the thesis. The purpose is not to evaluate site-optimised final designs, but to compare how different structural configurations perform under contrasting climate assumptions.

4.3 Design Alternatives

Three design alternatives are considered in the case study, each representing a different machine hall configuration based on the extent of the basement structure. While the overall function of the machine hall remains the same, the alternatives differ in terms of structural layout, excavation volume, material use, and accessibility.

The three alternatives are:

1. Two-pit solution
2. Extended basement solution
3. Full basement solution.

.

4.3.1 Two pit solution (Reference: Spain)

The two-pit design consists of two separate recessed areas within the machine hall floor. Each pit is designed to accommodate specific equipment, such as the fan pump and the pulper, while the rest of the process equipment remains at the main floor level.

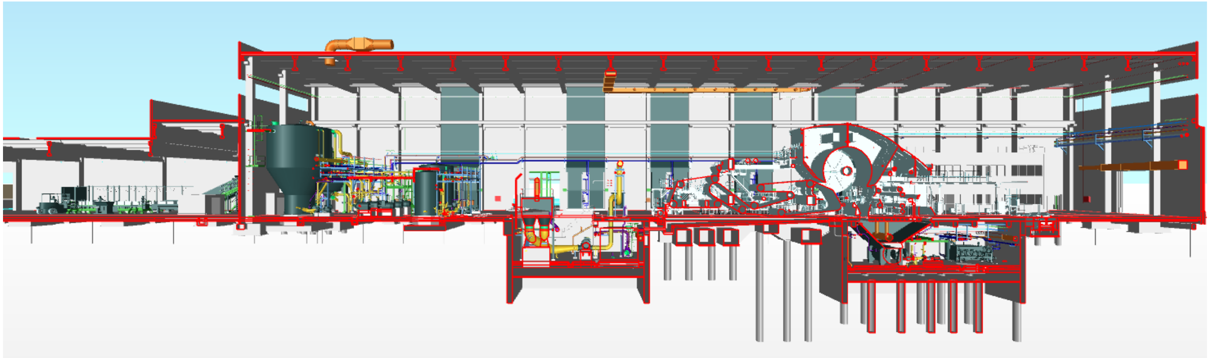

Figure 3 : Three-dimensional cross-sectional view of the two-pit solution machine hall layout

In this configuration, the recessed areas are limited to only the locations where they are required. The pits are clearly separated from each other, creating a layout where most of the hall maintains a uniform floor level, with only localized interruptions. The main machine hall volume above is 103.0 m long, 40.0 m wide, and 18.0 m high (total volume 74,160 m³). Two basement spaces contribute additional volume: Basement 1 (15.0 m × 17.5 m × 5.5 m, volume 1,444 m³) and Basement 2 (15.7 m × 14.7 m × 5.5 m, volume 1,269 m³), giving a total ventilated volume of 76,873 m³ for this design.

4.3.2 Extended Basement Design (Reference: Sweden)

In the extended basement design, the recessed area is larger and more continuous compared to the two-pit configuration. Instead of having separate pits, the basement extends along the length of the tissue machine and is slightly wider than the machine itself.

Figure 4 : Three-dimensional cross-sectional view of the extended basement machine hall layout

This creates a continuous lower-level space beneath the main equipment line, connecting areas that were previously separated in the two-pit design. However, the basement does not extend across the entire building footprint, with certain areas of the hall maintained at ground level. As a result, the layout is more integrated than the two-pit design, with fewer transitions between different floor levels. The main machine hall volume is 106.7 m long, 38.5 m wide, and 18.5 m high total volume of 56677 m³, excluding mezzanine. Basement space contributes additional volume of 66.1 m × 20.6 m × 6 m, volume 8,170 m³, and mezzanine volume of 120 m × 14 m × 11.5 m, volume 19320, giving a total ventilated volume of 84,170 m³ for this design.

4.3.3 Full Basement Design (Reference: UAE)

The full basement design extends the recessed area across the entire footprint of the machine hall. In this configuration, the lower-level floors create a single continuous space beneath the hall.

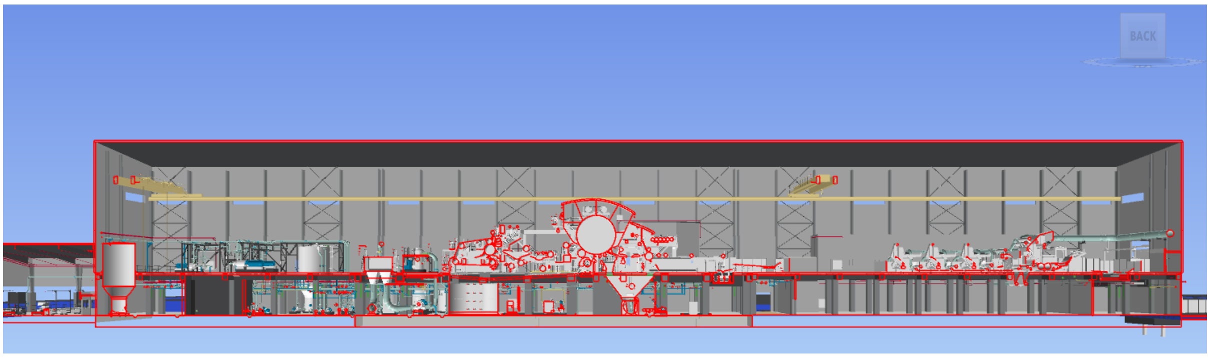

Figure 5 : Three-dimensional cross-sectional view of the full basement machine hall layout

Unlike the other two designs, there are no separate pits or partial basement areas. The entire structure follows a uniform level throughout, resulting in a fully continuous substructure. This creates the most uniform layout among the three alternatives, with no variation in floor levels within the hall footprint. The main machine hall is 163.5 m long, 36.8 m wide, and 17.5 m high, giving a volume of 105,294 m³. The basement space measures 78.0 m × 17.5 m × 5.5 m, contributing an additional 7,508 m³. The total ventilated volume used for the energy calculation is therefore 112,802 m³.

4.3.4 Structural Material Quantities by Design Alternatives

The structural material quantities for the three design alternatives, derived from take-off of the structural drawings provided by Valmet, are summarised in Table 3. The quantities include concrete, reinforcement steel, and structural steel, as these are the main design-dependent materials that differ between the three basement configurations. These quantities are used as input data for the environmental KPI calculation in section 4.6.

Table 3 : Structural material quantities by design alternative (from Valmet project drawings).

Design	**Concrete (m³)**	**Reinforcement steel (kg)**	**Structural steel (kg)**
Two-pit	4,078	400,190	37,592
Extended basement	5,757	626,759	38,926
Full basement	7,252	834,715	91,854

4.4 Climate Scenarios

The framework was applied under two different climate conditions to investigate the influence of geographic context on machine hall performance. The two climate scenarios represent contrasting thermal environments: Sweden, representing a colder heating-dominated climate, and Spain, representing a warmer climate with a shorter heating period.

4.4.1 Sweden

The Swedish scenario represents a cold northern European climate. It is characterised by long heating seasons, low outdoor temperatures during winter, and a relatively high heating demand. This is reflected by the high number of heating degree days, which indicates that heating is required for a large part of the year.

For the present study, the Swedish climate scenario is therefore considered to have a long winter/heating period. A simplified heating degree day value of approximately 3900 HDD_{18} per year was used to represent the selected Swedish location or design basis.

4.4.2 Spain

The Spain scenario represents a warmer southern European climate. Compared with Sweden, Spain has milder winters, higher summer temperatures, and a significantly lower annual heating demand. Therefore, the heating season is shorter, while the warm-period operation becomes more important.

For the present study, the Spanish climate scenario is considered to have a shorter winter/heating period and a longer warm/summer period. A simplified heating degree day value of approximately 1200 HDD_{18} per year was used to represent the selected Spanish location or design basis.

Input climate data

For the Swedish case, outdoor temperature data were based on DVUT/DSUT design temperature values, representing standardised outdoor conditions used for heating load calculations (SMHI & Boverket, 2022). For the Spanish case, climate data were obtained from IDAE, which provides representative climatic data for energy-related building analysis (IDAE, 2010) . These temperature inputs were used consistently across all design alternatives to ensure comparability in the energy calculations.

The key climate parameters applied in the energy calculations are summarised in Table 4.

Table 4: Climate parameters applied per scenario

Parameter	Sweden	Spain	Source
Outdoor design temperature, winter (°C)	−11.3	−4.6	SMHI DVUT
Indoor setpoint temperature (°C)	20	20	Machine hall specification
ΔT for heating calc (°C)	31.3	24.6	Calculated
Approx. HDD_{18} (°C·days/yr)	3,900	1,200	SMHI / IDAE

4.5 Context and Assumptions for the Valmet Case Study

The assumptions presented in this section define the boundary and premises used when applying the general framework to the Valmet case study. The general KPI definitions and calculation methods were presented in Chapter 3. Therefore, this section focuses only on the case-specific assumptions and boundaries required to apply the framework consistently to the selected tissue machine hall alternatives.

4.5.1 Case Study Boundary and General Assumptions

The Valmet case study was based on a DCT 200 tissue machine concept. To ensure a consistent comparison between the design alternatives, the tissue production process was kept constant in all cases. This means that the production capacity, main process equipment, and process-related energy demand were assumed to be the same for all alternatives.

The assessment was limited to the tissue machine hall and the building-related effects of the selected basement configuration. Therefore, the comparison focused on how the two-pit, extended basement, and full basement alternatives influence building-related energy demand, structural material quantities, CAPEX, OPEX, and operational accessibility. The same calculation procedure was applied to all three design alternatives and both climate scenarios, as mentioned in section 4.2.

The analysis was carried out for six case combinations, formed by applying the three design alternatives to the two climate scenarios. These combinations are shown in Figure 6.

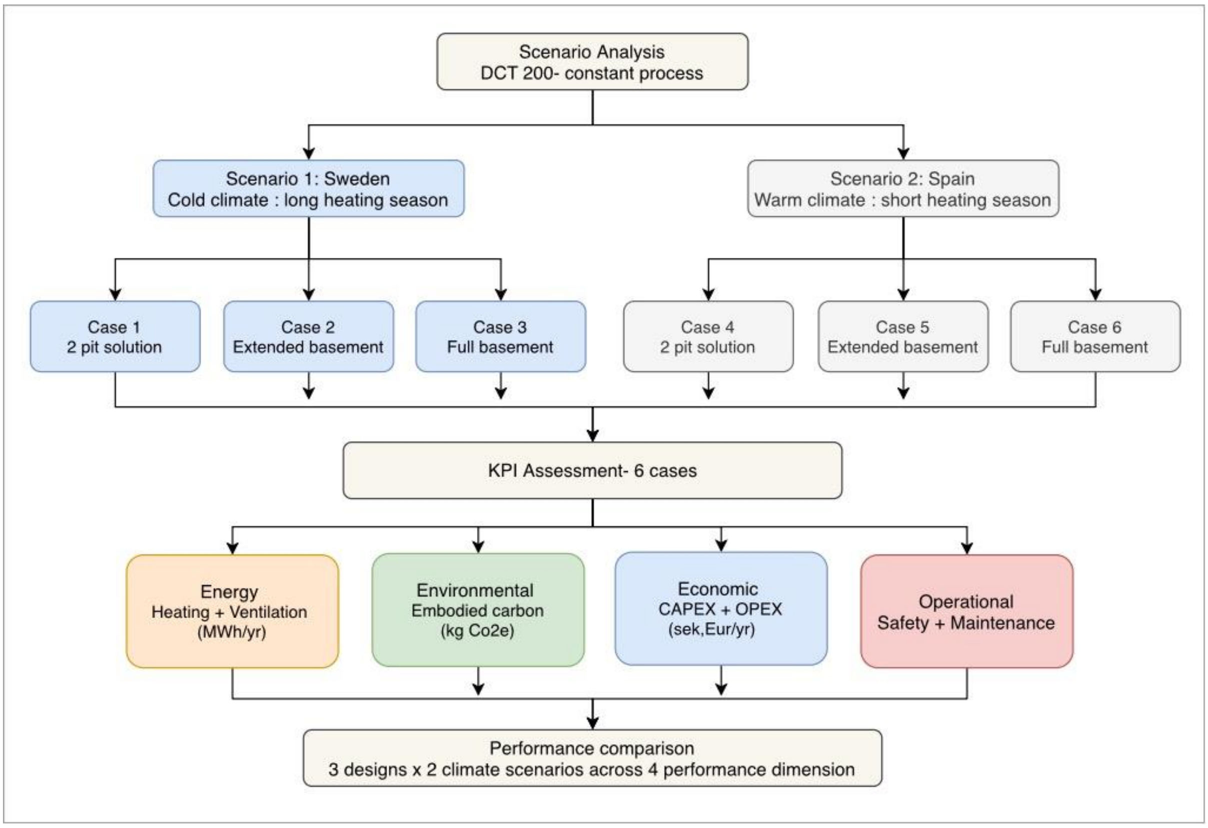

Figure 6 : Workflow used to apply the framework to the Valmet case study.

4.5.2 Energy Calculation Approach and Assumptions

The heating energy demand was calculated using the ventilation heat-load method adopted in the general framework. The ventilation/fan energy demand was calculated using the installed fan power method, which is explained in 4.5.4

Active mechanical cooling was not included in the energy calculation, since the studied machine hall concept does not include a mechanical cooling system within the defined system boundary. Therefore, the energy calculation focused on heating demand and ventilation/fan electricity.

The seasonal operating hours used in the energy calculation are shown in Table 5.

Table 5 : Seasonal operating hours used in the energy calculations for each climate scenario.

Country	Winter/heating period	Summer/warm period	Neutral/transition period	Total
Sweden	6000 h/year	1000 h/year	1760 h/year	8760 h/year
Spain	2500 h/year	4000 h/year	2260 h/year	8760 h/year

The seasonal operating hours were used only for the heating energy calculation. Sweden was assumed to have a longer heating period, while Spain was assumed to have a shorter heating period and a longer warm period. The remaining hours were treated as neutral or transition hours, during which no additional seasonal heating demand was included.

The ventilation fans were assumed to operate throughout the full year. Therefore, the annual operating time for ventilation/fan energy was taken as 8760 h/year for both Sweden and Spain. This means that seasonal operating hours were used for heating demand, while full-year operation was used for ventilation/fan electricity demand.

4.5.3 Heating Energy Calculation Assumptions

Heating energy was calculated only during the defined winter/heating period. As in Table 5, the heating operating time was taken as 6000 h/year for Sweden and 2500 h/year for Spain. The indoor setpoint temperature was assumed to be 20°C for both climate scenarios. The outdoor design temperature was changed according to the selected climate scenario.

If the recovered heat from the Yankee, hood, and air system exceeded the calculated gross heating load, the result was interpreted as a heat surplus. In such cases, the heating demand used for OPEX calculation was set to zero, since negative heating demand does not represent purchased heating energy.

Transmission heat losses through the building envelope were neglected in this calculation. This assumption was made because the thesis focuses on ventilation-related heat demand, which is expected to dominate the thermal balance in large-volume industrial machine halls with high ventilation rates and significant internal process heat. This simplification was adopted based on industry practice guidance from Valmet.

4.5.4 Ventilation Energy Calculation Assumptions

The ventilation fans were assumed to operate continuously throughout the year. As in Table 5, the annual fan operating time was taken as 8760 h/year for both Sweden and Spain.

Fan power was calculated as 70% of the installed fan power, following the Valmet case study assumption. This load factor represents average fan operation and accounts for the fact that the fans are not assumed to operate continuously at full installed capacity throughout the year.

No seasonal variation in fan load was included. Therefore, the same annual fan operating time and load factor were applied to all climate scenarios.

The annual fan energy was calculated as:

$$E_{fan} = 0.70 \cdot P_{installed} \cdot 8760$$

Where,

E_{fan} is the annual fan electricity demand in kWh/year

$P_{installed}$ is the installed fan power in kW.

4.5.5 Environmental Calculation Assumptions

The environmental assessment was limited to embodied carbon emissions from the main structural materials affected by the basement configuration. The included materials were concrete, reinforcement steel, and structural steel.

These materials were selected because they represent the main design-dependent material quantities in the three machine hall alternatives. Other materials, such as insulation and finishing materials, were excluded due to limited case-specific data and because they were not the focus of the comparison.

The assessment boundary included life-cycle modules A1–A5, covering the product stage, transport to site, and construction/installation stage. Operational carbon, maintenance, replacement, and end-of-life impacts were excluded. Separate emission factors were applied for Sweden and Spain to reflect country-specific material production (Boverket, 2025) (EPD, 2025). The emission factors used in the Valmet case study are shown in Table 4.5.

Table 6 : Embodied carbon emission factors by material and country for life-cycle stages A1–A5, based on Boverket for Sweden and EPD Library/EPD International for Spain

Material	Emission Factor (Sweden)	Emission Factor (Spain)	Unit
Concrete	199.16	221.40	kg CO_2e/m^3
Structural steel	2.52	2.56	kg CO_2e/kg
Reinforcement steel	0.69	0.51	kg CO_2e/kg

4.5.6 Economic Calculation Assumptions

The economic assessment included CAPEX and OPEX. CAPEX data were obtained from a civil engineering consultant company and were treated as case-specific input data. The CAPEX values were not independently recalculated in this thesis. Construction cost estimates at the early design stage are best treated as relative indicators for comparing alternatives rather than absolute forecasts. This is the approach adopted in this thesis, where costs are evaluated comparatively across three machine hall concepts.

OPEX was calculated based on annual energy cost. The OPEX calculation included the cost of ventilation/fan electricity and the cost of heating energy, depending on the heating-source scenario. Maintenance cost, labour cost, taxes, demand charges, equipment replacement cost, and energy price escalation were excluded.

The ventilation/fan energy demand was assumed to be supplied by electricity in all scenarios. The heating demand was treated as useful thermal energy. Therefore, heating demand was not automatically assumed to be electricity demand in every case. Instead, different heating-source scenarios can be considered.

Electricity prices were obtained from Eurostat for industrial consumers for the first and second semesters of 2024. Since the calculated energy demand is annual, the average of the two semester prices was used as the representative annual electricity price for each country.

Table 7: Industrial electricity prices used for OPEX calculation (Eurostat, 2024).

Country	2024 S1 €/kWh	2024 S2 €/kWh	Average €/kWh	Average €/MWh
Spain	0.1371	0.1426	0.1398	139.85
Sweden	0.0942	0.0853	0.0897	89.75

Table 4.6. Electricity prices used for OPEX calculation.

The heating demand used in the OPEX calculation was defined as:

$$E_{heating}, OPEX = \max(0, E_{heating})$$

This means that negative heating demand values were set to zero in the OPEX calculation, since negative heating demand represents heat surplus rather than purchased energy.

For the quantified base scenario, annual OPEX was calculated as:

$$OPEX_{base} = (E_{heating,OPEX} + E_{fan}) \cdot P_{electricity}$$

Where,

$E_{heating,OPEX}$ is the annual heating demand used for OPEX calculation

E_{fan} is the annual ventilation/fan electricity demand

$P_{electricity}$ is the country-specific electricity price.

Although only the electric heating base scenario was quantified in this thesis, other heating-source scenarios may also be relevant in practice. For example, the useful heating demand could be supplied by a heat pump, district heating, steam, or recovered process heat. These alternatives would change the purchased energy cost but were not quantified due to limited case-specific data on system efficiency, heat prices, and integration requirements. Figure 7 shows the relationship between heating demand and annual OPEX under different heating-source scenarios.

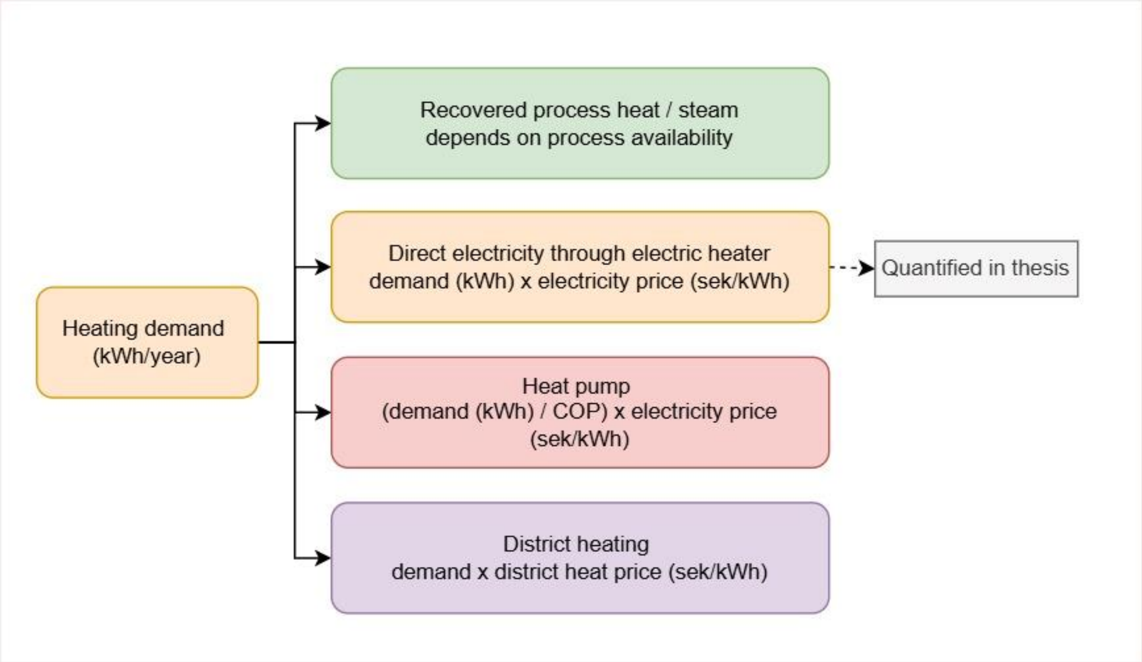

Figure 7 : Relationship between heating demand and annual OPEX under different heating-source scenarios.

For a heat pump scenario, the purchased electricity for heating would depend on the coefficient of performance:

$$OPEX_{HP} = \left(\frac{E_{heating,OPEX}}{COP} + E_{fan}\right) \cdot Pelectricity$$

For district heating-, the heating demand would be multiplied by the relevant heat price, while fan energy would still be calculated using the electricity price:

$$OPEX_{heat} = E_{heating,OPEX} \cdot P_{heat} + E_{fan} \cdot P_{electricity}$$

These equations are included to show how the framework can be adapted to other heating-source assumptions. However, the numerical OPEX results presented in this thesis are based only on the electric heating base scenario.

4.5.7 Operational Assessment Approach and Assumptions

The operational assessment was based on a structured survey of professionals with experience related to tissue machine halls. The purpose of the survey was to evaluate how the three basement design alternatives perform in terms of maintenance accessibility and safety. Each design alternative was evaluated using the scoring scale defined in the general framework section 3.4.

The maintenance accessibility KPI was assessed using questions related to access to equipment, inspection routes, available maintenance space, ease of equipment replacement, cleaning, and housekeeping. The safety KPI was assessed using questions related to access routes, working space, emergency access, and the perceived basement working environment.

The survey responses were converted into numerical scores. The final score for each operational KPI was calculated as the average of the relevant question scores for each design alternative. The operational assessment was therefore based on professional judgement but applied through a structured and comparable scoring procedure.

4.6 Application of KPI Calculation Methods

The assumptions and calculation boundaries defined in Section 4.5 were used to apply the KPI calculation methods to the six Valmet case combinations. The general KPI definitions and calculation methods were presented in Chapter 3. Therefore, this section focuses on how the methods were applied using the case-specific data provided by Valmet.

The application was carried out for four KPI dimensions: energy, environmental, economic, and operational performance. Energy performance was evaluated through heating energy demand and ventilation/fan electricity demand. Environmental performance was evaluated through embodied carbon emissions from structural materials. Economic performance was evaluated through CAPEX and OPEX. Operational performance was evaluated through maintenance accessibility and safety scores.

The resulting KPI values are presented and compared in Chapter 5.

Energy KPI Application

The energy KPI application included two components: heating energy demand and ventilation/fan electricity demand. The required input data were extracted from the machine hall ventilation technical specifications for each design alternative and applied according to the assumptions defined in Section 4.5.

1) Heating Energy Demand Calculation

Heating energy demand was calculated for each of the six case combinations using the method and assumptions defined in Sections 3.4 and 4.5.3. The calculation was based on the winter air mass flow rate, indoor and outdoor design temperatures, and available recovered process heat from the Yankee hood exhaust system. See Appendix 1 for main input parameters.

The gross ventilation heating load was calculated first. The recovered process heat was then subtracted to determine the net heating load. Finally, the net heating load was multiplied by the heating operating time defined for each climate scenario. Negative heating values were interpreted as heat surplus and were set to zero for the OPEX calculation.

The heating energy calculation procedure is summarised in Table 8.

Table 8 : Summary of heating energy demand calculation procedure.

Step	Input / Calculation	Source
1	Extract winter air mass flow rate	Machine hall technical specification
2	Define indoor and outdoor temperatures	Indoor setpoint and climate scenario
3	Calculate gross ventilation heating load	Section 3.4
4	Subtract recovered process heat	Machine hall technical specification
5	Convert net heating load to annual heating energy	Climate-specific heating operating time

2) Ventilation Fan Electricity Demand Calculation

Ventilation/fan electricity demand was calculated for each design alternative using the installed fan power method defined in Section 3.4 and the assumptions defined in Section 4.5.4.

The installed fan power was extracted from the machine hall technical specification for each design alternative. See Appendix 1 for the inputs used. Ventilation/fan electricity demand depended on the installed fan power of each design alternative, but not directly on whether the case was evaluated under the Swedish or Spanish climate scenario.

The ventilation fan energy calculation procedure is summarised in Table 9

Table 9: Summary of ventilation fan electricity demand calculation procedure.

Step	Input / Calculation	Source
1	Extract installed fan power	Machine hall technical specification
2	Sum relevant ventilation fan power	Included fan equipment within boundary
3	Apply 70% operating load factor	Valmet case study assumption
4	Apply annual fan operating time	8760 h/year
5	Calculate annual fan electricity demand	Installed fan power method

Total Annual Energy Demand

The total annual energy demand used for the quantified base OPEX scenario was calculated by combining the heating demand used for OPEX and the ventilation/fan electricity demand.

The total annual energy demand for the base scenario was therefore calculated as:

$$E_{total} = E_{heating,OPEX} + E_{fan}$$

Where,

E_{total} is the total annual energy demand used for the base OPEX calculation

$E_{heating,OPEX}$ is the heating demand

E_{fan} is the annual ventilation/fan electricity demand.

This total energy value was used only for the quantified electric heating base scenario. Alternative heating-source scenarios were not quantified.

Environmental KPI Application

The environmental KPI was applied by calculating the embodied carbon emissions of the main structural materials included in the assessment boundary. The calculation included concrete, reinforcement steel, and structural steel, as defined in Section 4.5.5.

Material quantities were taken from the structural drawings and material information provided by Valmet. Concrete quantities were expressed in cubic metres, while reinforcement steel and structural steel quantities were expressed in kilograms. The same material quantities were used for both climate scenarios for a given design alternative, since the structural design was kept constant.

Country-specific emission factors shown in Table 6 were then applied to the material quantities. This means that the embodied carbon results varied according to both the structural material quantities of each design alternative and the emission factors selected for Sweden and Spain.

The embodied carbon for each material was calculated using the general method defined in Section 3.4. The total embodied carbon for each design alternative was obtained by summing the embodied carbon contributions from concrete, reinforcement steel, and structural steel.

The environmental KPI calculation procedure is summarised in Table 10.

Table 10 : Summary of embodied carbon calculation procedure.

Step	Input / Calculation	Source
1	Extract structural material quantities	Valmet drawings and material quantities
2	Select included materials	Concrete, reinforcement steel, structural steel
3	Apply country-specific emission factors	Emission factor table in Section 4.5.5
4	Calculate embodied carbon per material	Method defined in Section 3.4
5	Sum material emissions	Total embodied carbon per case
6	Compare alternatives	Three design alternatives and two climate scenarios

Economic KPI Application

The economic KPI application included CAPEX and OPEX. CAPEX was treated as case-specific input data, while OPEX was calculated from annual energy demand and the electricity prices defined in Section 4.5.6.

CAPEX values were obtained from a civil engineering consultant company for the three design alternatives. These values were used directly in the comparison and were not independently recalculated in this thesis. The consultant's estimate was divided into two main cost components: the civil construction cost for the tissue machine hall and the groundwork cost. The groundwork cost was provided separately because it depends strongly on the assumed ground conditions, such as good ground conditions, rock, mass replacement, or piling. The scope of groundwork for each alternative and the corresponding groundwork cost estimates are presented in Appendix 1.

OPEX was quantified using the electric heating base scenario. In this scenario, both the heating demand and the ventilation/fan energy demand were assumed to be supplied by electricity. The annual energy demand used for the base OPEX calculation was therefore calculated from the heating demand after applying the zero-floor rule and the annual fan electricity demand. The zero-floor rule sets the minimum heating demand to zero i.e., if the calculated heating demand is negative (meaning the space gains more heat than it loses), it is treated as 0 kWh rather than a negative value.

The base OPEX was calculated as:

$$OPEX_{base} = \left(E_{heating,OPEX} + E_{fan}\right) \cdot P_{electricity}$$

Where,

$OPEX_{base}$ is the annual operating cost in EUR/year

$E_{heating,OPEX}$ is the heating demand used for OPEX calculation

E_{fan} is the annual ventilation/fan electricity demand

$P_{electricity}$ is the country-specific electricity price.

The Swedish electricity price was applied to the Swedish cases, and the Spanish electricity price was applied to the Spanish cases. The same calculation procedure was applied to all three design alternatives in each climate scenario.

The economic KPI calculation procedure is summarised in Table 11

Table 11 : Summary of economic KPI calculation procedure.

Step	Input / Calculation	Source
1	Obtain CAPEX values	Civil engineering consultant estimate
2	Use annual heating demand for OPEX	Energy KPI calculation
3	Apply zero-floor rule to heating demand	Section 4.5.6
4	Use annual fan electricity demand	Ventilation energy calculation
5	Apply country-specific electricity price	Electricity price table in Section 4.5.6
6	Calculate base OPEX	Electric heating base scenario

Operational KPI Application

The operational KPI application was based on the structured survey described in Section 4.5.7. The survey was used to evaluate the three design alternatives in terms of maintenance accessibility and safety.

The survey included 18 Valmet professionals with experience in tissue machine hall design, installation, and operation. The respondent group included engineering or design (7 numbers), operations (5), Installation or commissioning (4), mechanical maintenance (1) and electrical maintenance (1) professionals. The survey consisted of 10 rated questions, which were grouped as follows:

Maintenance accessibility KPI

Q1: Accessibility to fan pumps and hydraulic systems
Q2: Available space for maintenance work and general accessibility
Q3: Ease of performing inspection rounds

Q4: Ease of replacing equipment
Q5: Ease of cleaning

Safety KPI

Q6: Safety access route
Q7: Safety working space
Q8: Emergency access as ability to reach personnel in emergencies

General working environment

Q10: Perceived working environment, like temperature, air quality, ventilation, lighting, and safety feeling

For each KPI, the final score per respondent was calculated as the average of the relevant question scores. The overall KPI score was then calculated as the average across all 18 respondents. See Appendix 2 for the score per respondent and corresponding average.

The operational KPI calculation procedure is summarised in Table 12.

Table 12: Summary of operational KPI calculation procedure

Step	Input / Calculation	Source
1	Define operational KPI categories	Maintenance accessibility and safety
2	Design and distribute survey question on a 1-5 scale	Professional survey
3	Map questions to KPI categories	Survey question grouping
4	Calculate average KPI score	Method defined in Section 3.4
5	Compare alternatives	Three basement configurations

5. Results

This chapter presents the results obtained from applying the proposed evaluation framework to the Valmet tissue machine hall case study. The results are organised according to the four KPI dimensions defined in the framework: energy performance, environmental performance, economic performance, and operational performance.

5.1 Energy Performance Results

Energy performance was evaluated using three indicators: heating energy demand, ventilation/fan electricity demand, and total annual energy demand

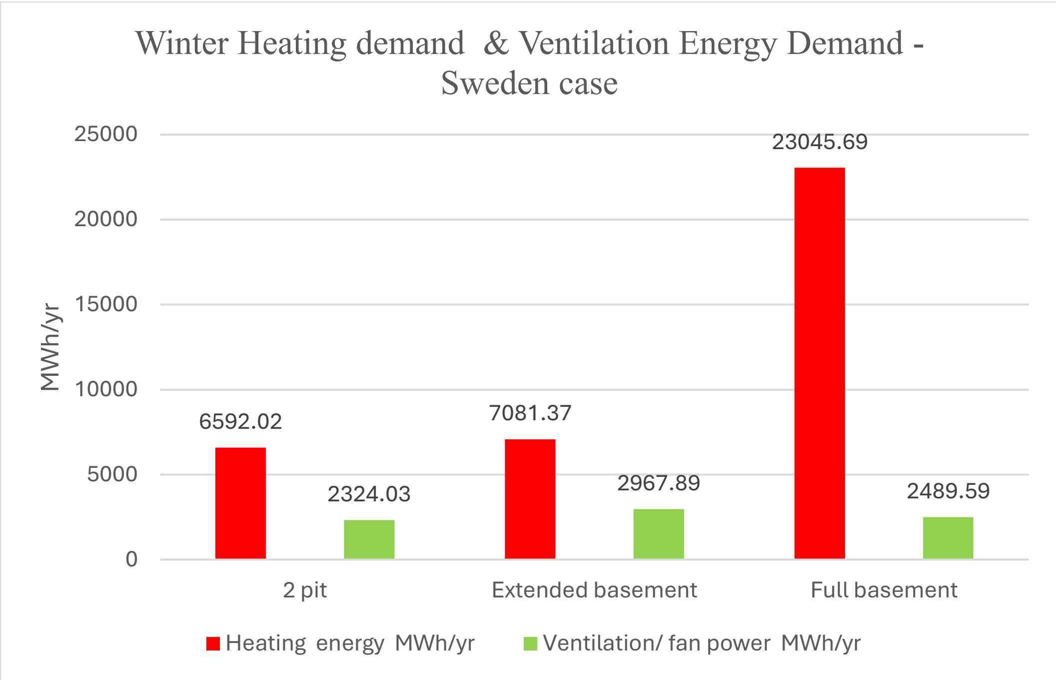

Figure 8: Annual energy demand by component for the three design alternatives – Sweden scenario (MWh/year). Heating energy represents winter demand only; ventilation/fan power covers the full year; summer cooling is excluded from the analysis.

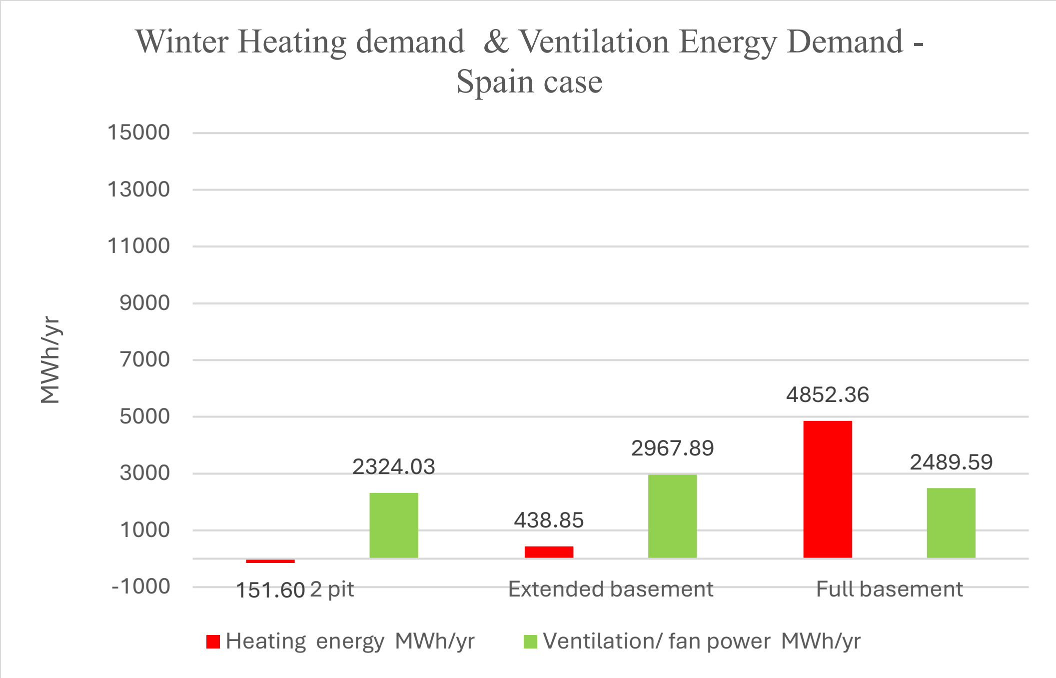

Figure 9: Annual energy demand by component for the three design alternatives – Spain scenario (MWh/year). Heating energy represents winter demand only; ventilation/fan power covers the full year; summer cooling is excluded from the analysis.

Figure 8 shows the results for the Swedish climate scenario. All three alternatives require positive heating energy due to the colder climate and longer heating period. The two-pit and extended basement solutions have similar heating demands, at 6,592 MWh/year and 7,081 MWh/year, respectively. The full basement solution has a much higher heating demand of 23,046 MWh/year, making it the most energy-intensive alternative in Sweden.

Figure 9 shows the results for the Spanish climate scenario. Heating demand is much lower than in Sweden because of the milder winter conditions and shorter heating period. The two-pit solution has a negative heating demand of -152 MWh/year, indicating a heat surplus after recovered process heat is included. This value does not represent negative purchased energy and is set to zero in the OPEX calculation. The extended basement solution has a low heating demand of 439 MWh/year, while the full basement solution has the highest Spanish heating demand at 4,852 MWh/year.

Ventilation/fan electricity demand is the same in both climate scenarios because the fans were assumed to operate for 8760 h/year in all cases. The two-pit solution requires 2,324 MWh/year, the extended basement solution requires 2,968 MWh/year, and the full basement solution requires 2,490 MWh/year. The extended basement solution, therefore, has the highest fan electricity demand.

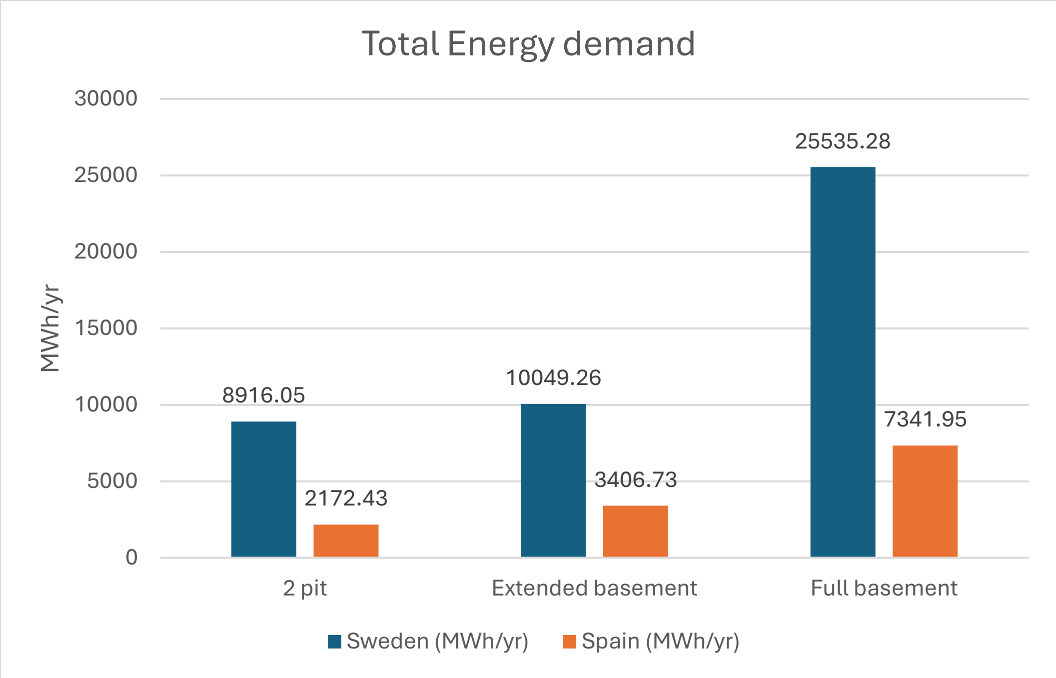

Figure 10: Total annual energy demand by design alternative and climate scenario (MWh/year).

Figure 10 presents the total annual energy demand used for the electric heating base OPEX scenario. In Sweden, the total energy demand is 8,916 MWh/year for the two-pit solution, 10,049 MWh/year for the extended basement solution, and 25,535 MWh/year for the full basement solution. In Spain, the corresponding values are 2,172 MWh/year for the two-pit solution, 3,407 MWh/year for the extended basement solution, and 7,342 MWh/year for the full basement solution.

Overall, the two-pit solution has the lowest total annual energy demand in both climate scenarios, while the full basement solution has the highest. The difference between Sweden and Spain is mainly caused by heating demand, since fan electricity demand remains constant for each alternative across the two climates.

5.2 Environment Performance Results

Environmental performance was evaluated by calculating the embodied carbon emissions of concrete, reinforcement steel, and structural steel. The emissions were calculated for both Sweden and Spain using the country-specific emission factors defined in Section 4.5.5.

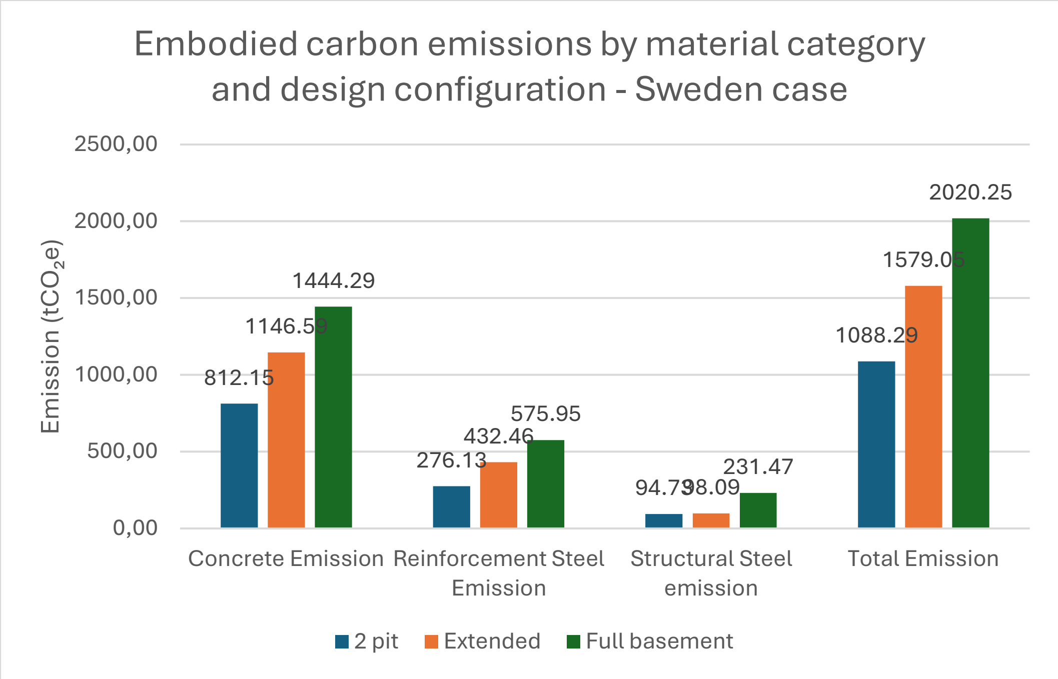

Figure 11: Embodied carbon emissions by material for the three design alternatives - Sweden scenario (tCO_2e).

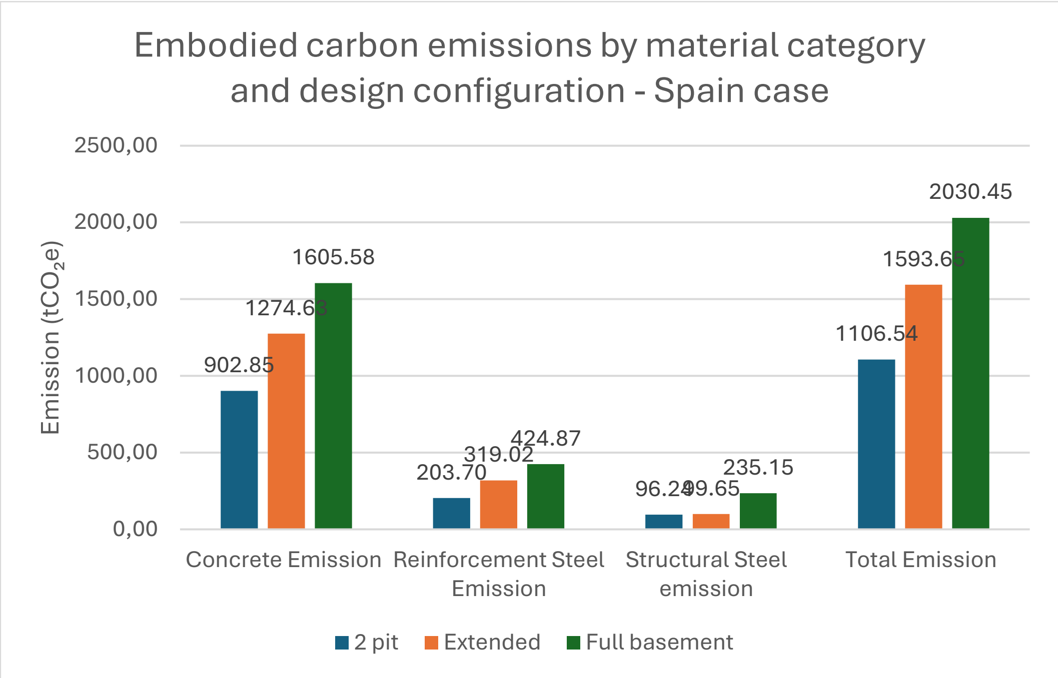

Figure 12: Embodied carbon emissions by material for the three design alternatives - Spain scenario (tCO_2e).

Figures 11 and 12 show that the full basement solution has the highest total emissions in both cases, followed by the extended basement solution and the two-pit solution. In Sweden, the total emissions are 1,088 tCO_2e for the two-pit solution, 1,579 tCO_2e for the extended basement solution, and 2,020 tCO_2e for the full basement solution. In Spain, the corresponding values are 1,107 tCO_2e, 1,594 tCO_2e, and 2,030 tCO_2e.

Figure 13 shows the total emissions in three design configurations under both the Sweden and Spain cases.

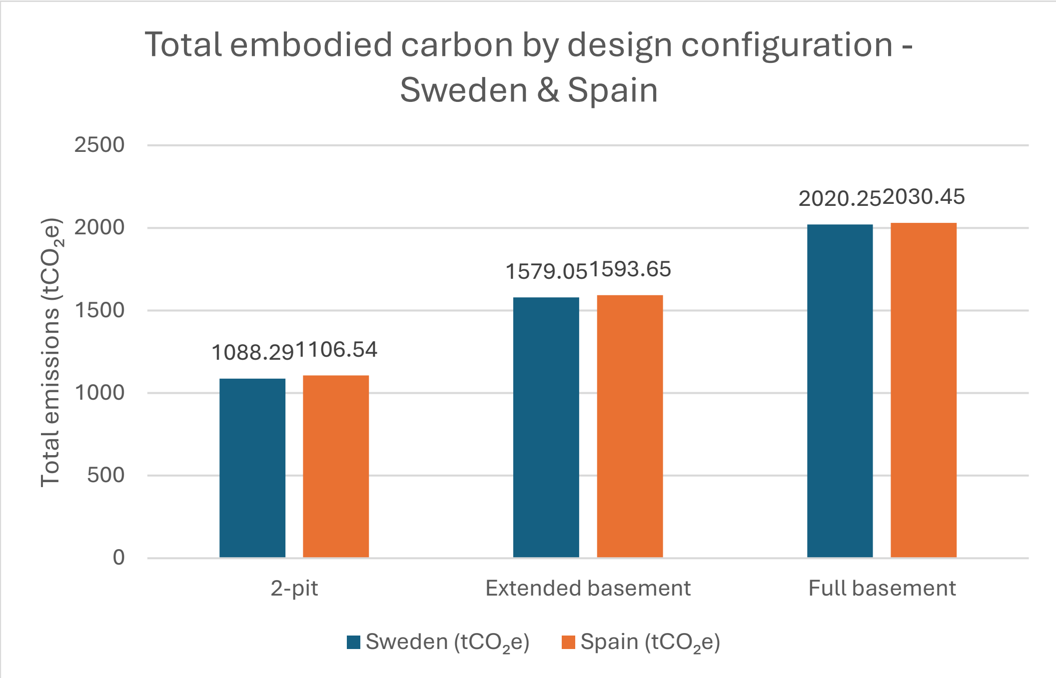

Figure 13 : Total embodied carbon emissions (tCO_2e) for three design configurations under the Sweden and Spain cases.

Concrete is the largest contributor to total embodied carbon in all alternatives, followed by reinforcement steel and structural steel. Overall, the results show that a larger basement structure leads to higher material-related emissions. The difference between design alternatives is greater than the difference between the Swedish and Spanish emission-factor cases.

5.3 Economic Performance Results

Economic performance was evaluated using CAPEX and OPEX. CAPEX was based on indicative civil construction cost estimates provided by a civil consulting company, while OPEX was calculated using the electric heating base scenario.

5.3.1 CAPEX

Cost report states that the costs are indicative, for comparative analysis, in SEK, based on the 2025 price level, and related to civil construction works excluding VAT. It also gives the civil construction cost excluding groundwork as full basement 495 MSEK, extended basement 380 MSEK, and two-pit 400 MSEK, as shown in Figure 14. The cost estimate for civil construction includes total investment for the building, Installations such as lightning, electrical system, ventilation, etc.

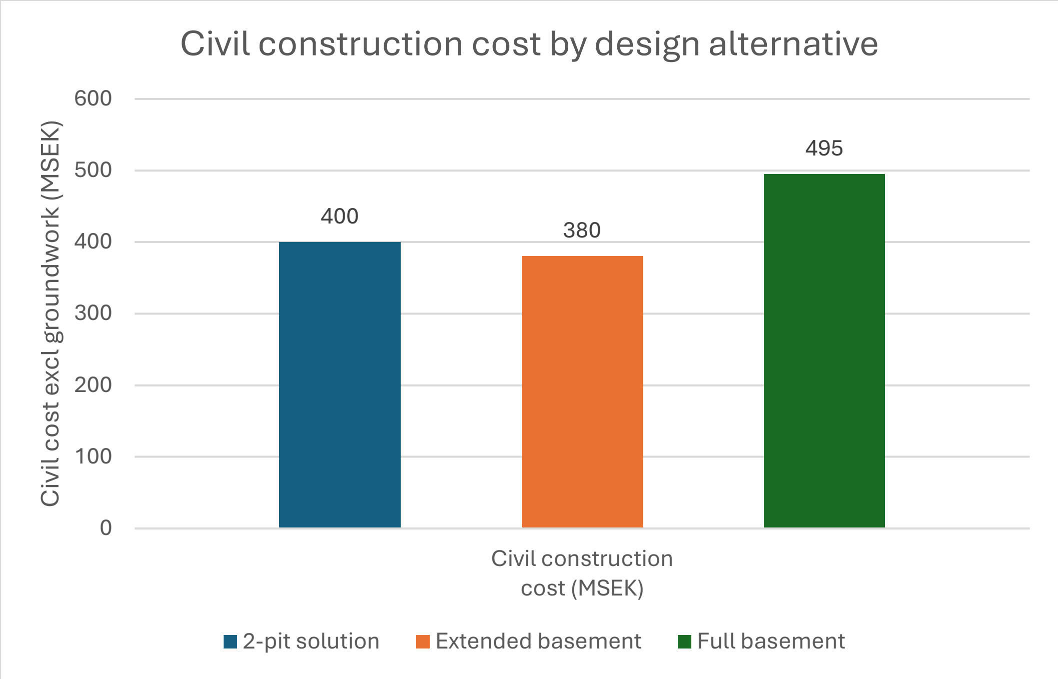

Figure 14: CAPEX by civil construction cost, excluding groundwork

The CAPEX results, excluding groundwork, show that the extended basement solution has the lowest estimated civil construction cost. The two-pit solution is 20 MSEK higher than the extended basement solution, while the full basement solution is 115 MSEK higher than the extended basement solution and 95 MSEK higher than the two-pit solution.

CAPEX cost, including both groundworks along with civil construction, is shown in Figure 15, where results are presented for four ground conditions: good ground conditions, good ground conditions including rock, poor ground conditions with mass replacement, and poor ground conditions with piling. In the reference projects, the full basement solution is constructed with a slab-on-grade foundation, while the extended basement and two-pit solutions have basements located below ground level. This distinction has a direct influence on the groundwork costs across all four conditions. A detailed cost breakdown for each condition is provided in Appendix 2.

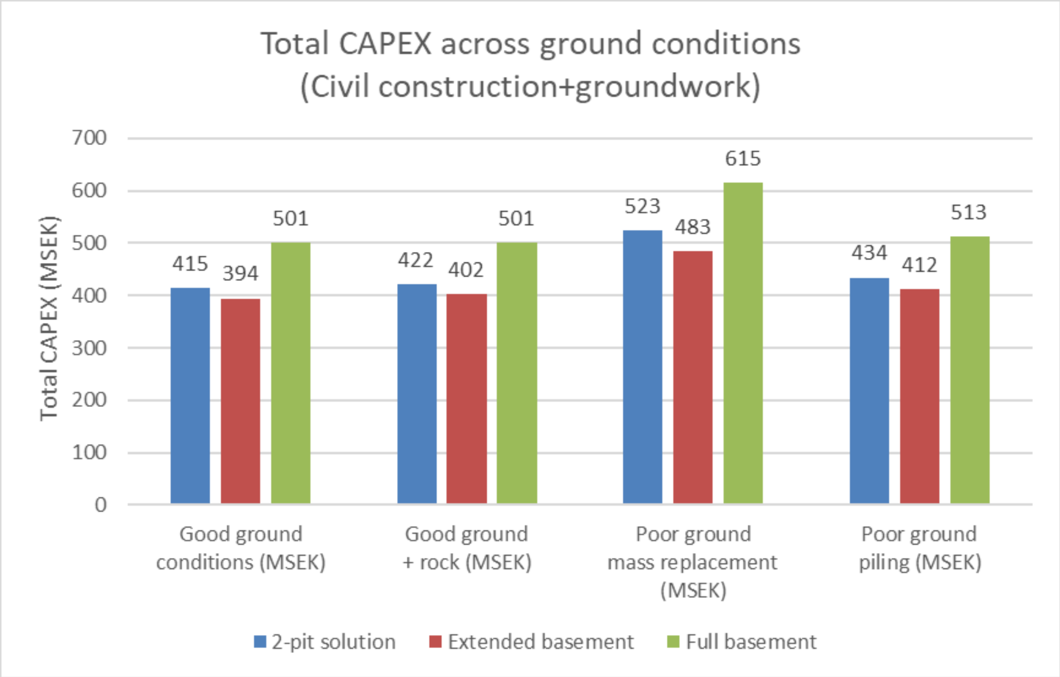

Figure 15: CAPEX including civil construction cost and groundwork cost

When groundwork is included, the extended basement solution has the lowest total CAPEX across all four ground conditions. Under good ground conditions, the extended basement has a total CAPEX of 394 MSEK, followed by the two-pit solution at 415 MSEK and the full basement at 501 MSEK. Under good ground conditions, including rock, the ranking remains unchanged, with costs of 402 MSEK, 422 MSEK, and 501 MSEK for extended basement, two-pit, and full basement, respectively.

Under poor ground conditions with mass replacement, costs increase significantly for all alternatives. The extended basement reaches 483 MSEK, the two-pit solution 523 MSEK, and the full basement 615 MSEK. Under poor ground conditions with piling, the extended basement has the lowest cost at 412 MSEK, followed by the two-pit solution at 434 MSEK and the full basement at 513 MSEK.

Across all four ground conditions, the extended basement consistently has the lowest total CAPEX, while the full basement has the highest. The two-pit solution remains intermediate in all scenarios.

Table 13 shows the delta with respect to the extended basement CAPEX cost, which includes both civil construction and groundwork under good ground conditions

Table 13: CAPEX comparison under good ground conditions, using the extended basement as the reference configuration since it represents the lowest-cost alternative across all ground condition scenarios.

Configuration	Total CAPEX (MSEK)	Delta vs. Reference (MSEK)
Extended basement	394	(Reference)
2-pit solution	415	+ 20.7
Full basement	501	+ 107.1

The extended basement has the lowest total CAPEX at 394 MSEK under good ground conditions and is therefore used as the reference. The two-pit solution is 20.7 MSEK higher at 415 MSEK, while the full basement has the highest CAPEX at 501 MSEK, which is 107.1 MSEK above the reference. The ranking remains consistent across all ground condition scenarios, as presented in Appendix 1

5.3.2 OPEX

OPEX was calculated using the electric heating base scenario. In this scenario, both heating energy demand and ventilation/fan electricity demand were assumed to be supplied by electricity. The OPEX values, therefore, represent annual energy cost and not the total operating cost of the facility. Figure 16 shows the annual OPEX results for Sweden and Spain.

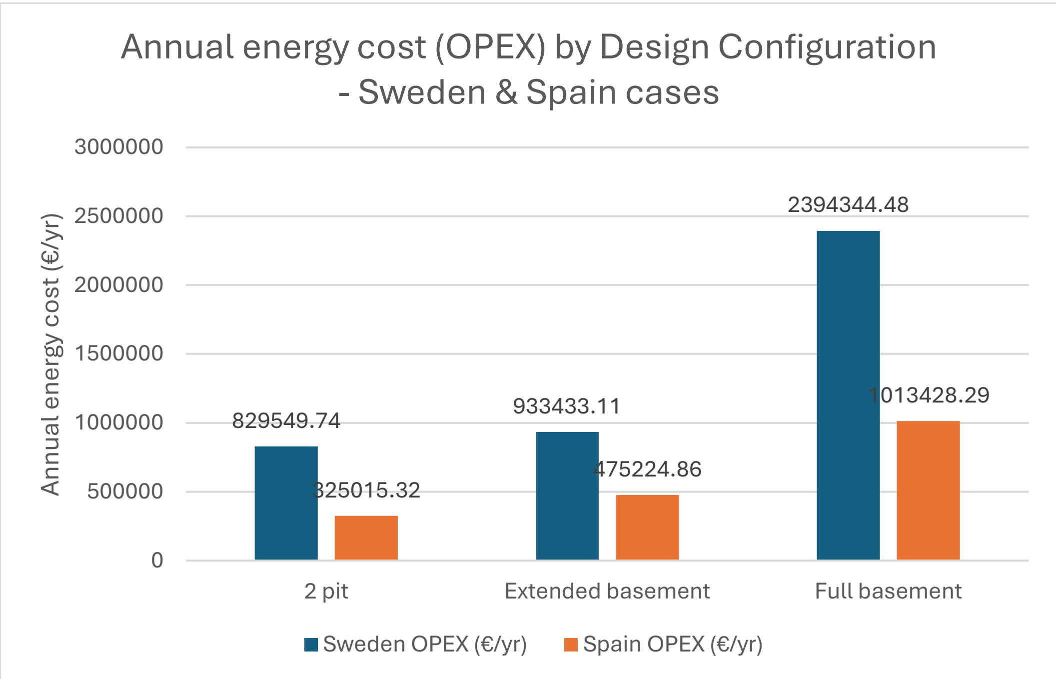

Figure 16: Annual OPEX by energy component for the three design alternatives - Sweden & Spain scenario (EUR/year).

In both climate scenarios, the full basement solution has the highest OPEX, while the two-pit solution has the lowest. In Sweden, the annual OPEX is 829,550 €/year for the two-pit solution, 933,433 €/year for the extended basement solution, and 2,394,344 €/year for the full basement solution.

In Spain, the annual OPEX is lower for all three alternatives due to the lower heating demand. The two-pit solution has an annual OPEX of 325,015 €/year, the extended basement solution has 475,225 €/year, and the full basement solution has 1,013,428 €/year.

The full basement solution has the highest OPEX in both countries because it has the highest total annual energy demand, mainly caused by its higher heating energy demand. The two-pit solution has the lowest OPEX in both climate scenarios. The difference between Sweden and Spain shows that climate has a strong effect on operating cost, especially for alternatives with high heating demand.

5.4 Operational performance

Figure 17 shows the maintenance and safety results for the three design alternatives. The two-pit solution received the lowest scores, with 3.0 for maintenance and 2.5 for safety. The extended basement solution performed better, with a maintenance score of 3.9 and a safety score of 3.5. The full basement solution received the highest scores, with 4.6 for maintenance and 4.5 for safety.

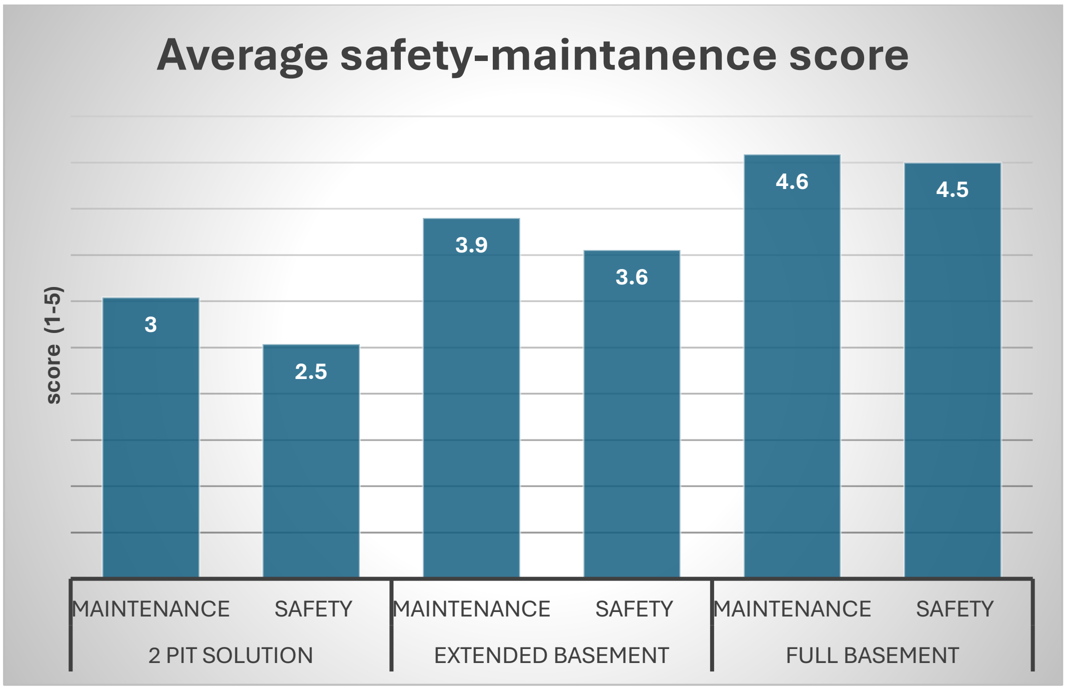

Figure 17: Maintenance accessibility and safety scores for the three design alternatives (scale 1–5).

The results indicate that operational performance improves as the basement configuration becomes more continuous and accessible. The full basement solution provides the best conditions for both maintenance and safety, while the two-pit solution performs the weakest due to its more limited and fragmented lower-level spaces.

Figure 18 shows the general quality/comfort score. The same trend is observed: the two-pit solution has the lowest score at 2.76, the extended basement solution scores 3.65, and the full basement solution achieves the highest score at 4.18.

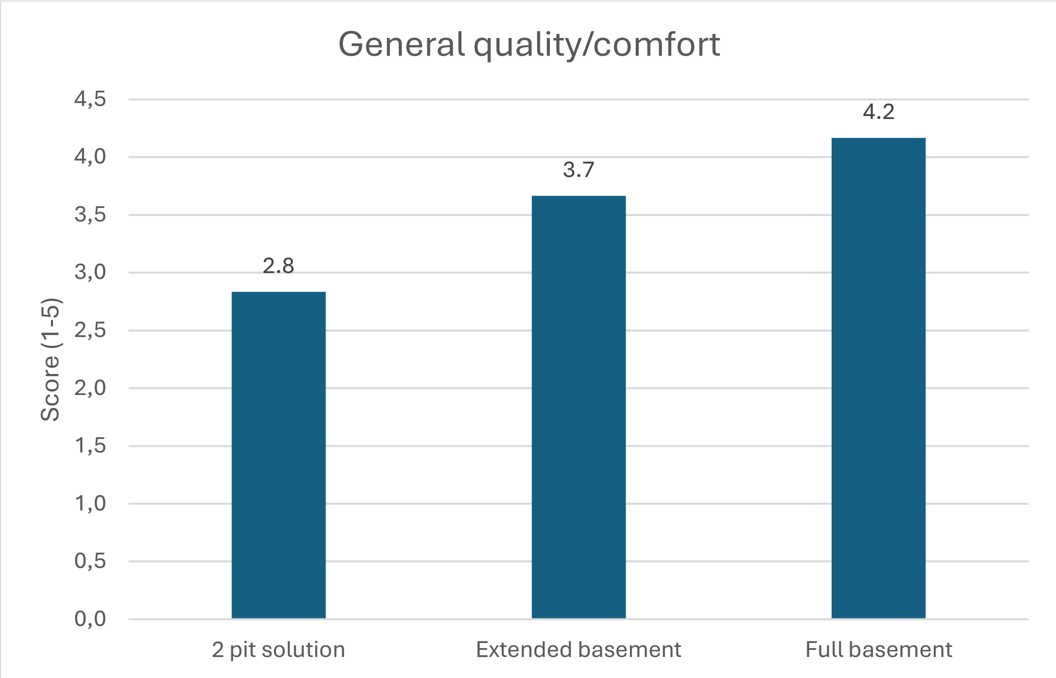

Figure 18: General quality and comfort scores for the three design alternatives (scale 1–5).

Overall, the operational assessment shows that the full basement solution performs best from an operational perspective, followed by the extended basement solution and the two-pit solution. This suggests that larger and more continuous basement areas improve perceived maintenance accessibility, safety, and working conditions.

5.5 Sensitivity Analysis of Heating Demand (Full Basement Design)

As the full basement configuration showed high heating energy demand when compared with others, a sensitivity analysis was conducted to assess how extensively the key input parameters affect the calculated results. The main aim of this analysis is to evaluate the robustness of the heating energy demand calculation and ~~d~~to identify which assumptions have the greatest influence on the annual heating energy demand.

This sensitivity analysis was done for the full basement design under the Swedish climate scenario, since this case produced the highest annual heating demand (23,046 MWh/yr). Four input parameters were considered on the basis of the calculation model.

- Recovered process heat from the Yankee hood exhaust system
- Winter air mass flow rate
- Outdoor design temperature
- Winter operating hours

Each parameter was varied individually while keeping all other input parameters constant at their base-case values. The variation ranges were chosen to reflect realistic uncertain~~i~~ty in early- stage design assumptions and are presented in Table 14.

Table 14: Sensitivity analysis input parameters and variation ranges for full basement design, Sweden scenario.

Parameter	Justification	Base Value	Variation Range
Recovered process heat	Yankee hood exhaust recovery may vary slightly under different operating conditions, though process is kept nominally constant	3,650 kW	±10% of base value
Winter air mass flow rate	Directly multiplied in heating load formula; varies between winter and summer design values across configurations.	237.9 kg/s	150 – 280 kg/s
Outdoor design temperature	Climate data varies by source and future conditions; defines the temperature difference driving ventilation heat loss	−11.3°C	−20°C to −4°C
Winter operating hours	Actual heating season duration depends on planned production shutdowns and seasonal maintenance periods	6,000 h/year	5,000 – 7,000 h/year

The results of the sensitivity analysis are presented in Figures 19 and 20. Figure 19 shows the tornado chart, which shows the deviation in the annual heating energy demand in Millions kWh/yr relative to the base case of each parameter. Bars extending to the left part represent scenarios where the parameter leads to a lower heating demand than the base case. While the bars extending to the right reflect where the parameter leads to a higher heating demand.

Figure 20 presents the maximum percentage deviation from the base case of each parameter, ranked from most to least influential.

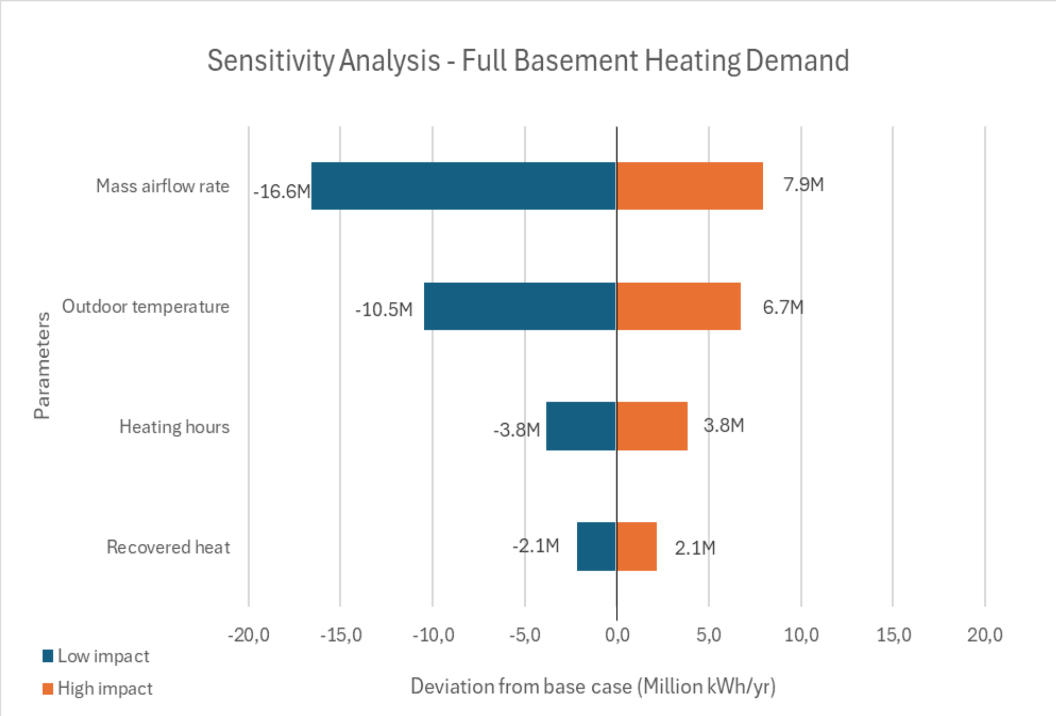

Figure 19: Tornado chart showing deviation from base case annual heating demand for each sensitivity parameter — full basement, Sweden scenario (MWh/year)

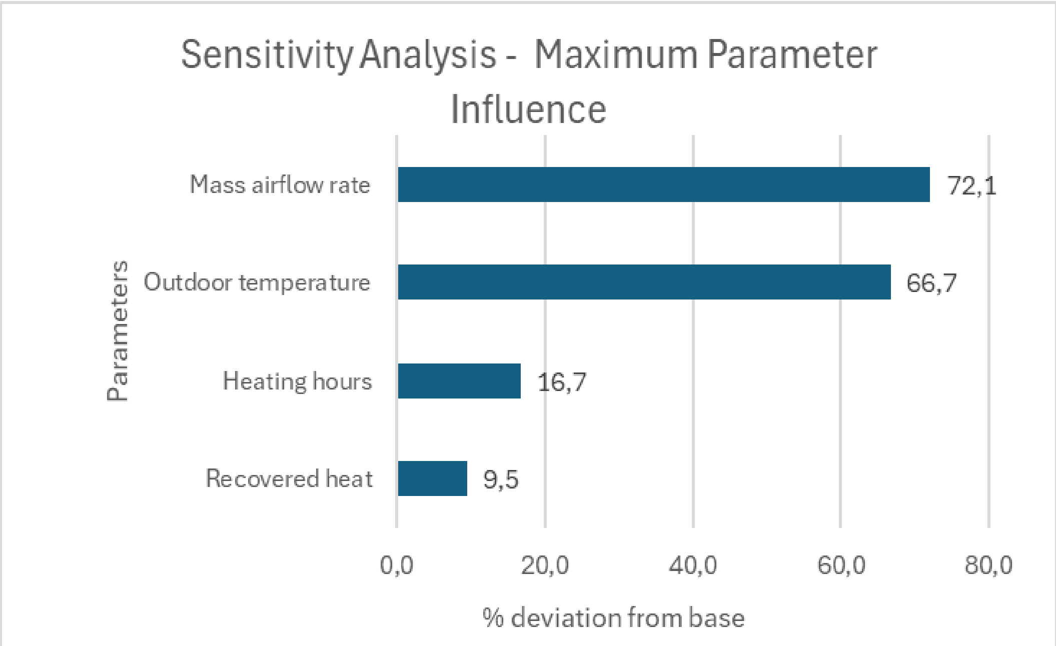

Figure 20 : Maximum percentage deviation from base case annual heating demand by sensitivity parameter.

The sensitivity analysis shows that mass airflow rate is the most influential parameter, with a maximum deviation of 72.1% from the base case. This is due to its direct proportional relationship with the ventilation heating load. Since the full basement has the largest ventilated volume, it requires a higher airflow rate, which increases the sensitivity of heating demand.

Outdoor design temperature is the second most influential parameter, with a maximum deviation of 66.7%. Colder outdoor conditions increase the temperature difference and heating demand, while milder conditions reduce it. Heating operating hours show moderate sensitivity (16.7%) because annual heating demand changes linearly with operating time. Recovered process heat has the smallest influence (9.5%), supporting the assumption that heat recovery remains relatively stable due to the constant tissue production process.

6. Comparison & Discussions

The results obtained from applying the evaluation framework to the Valmet case study show that there is no single design alternative that performs best across all performance dimensions. Each design shows strengths in certain areas while showing limitations in others. This chapter synthesises the individual KPI results presented in Chapter 5 into a cross-dimensional comparison, discusses the trade-offs between design alternatives and climate scenarios, and reflects on the implications for decision making at the early design stage.

Table 15 provides a summary of the relative performance of the 3 designs across the four dimensions evaluated in this study. Performance is expressed as direction ranking with terms ´best´, ´mid´, and ´worst.´

Table 15: Relative performance ranking of the three design alternatives across all KPI dimensions.

KPI	Two-pit	Extended basement	Full basement
Heating energy	Best	Mid	Worst
Ventilation energy	Best	Worst	Mid
Embodied carbon	Best	Mid	Worst
CAPEX	Mid	Best	Worst
OPEX	Best	Mid	Worst
Maintenance score	Worst	Mid	Best
Safety score	Worst	Mid	Best

The ranking reveals a clear tension in the results: the two-pit solution dominates on energy, carbon and operating cost, while the full basement solution leads on all operational indicators. The extended basement solution holds a middle position in nearly every dimension, without leading in any single category but without being last at any. There is no universally optimal solution, and the preferred alternative depends on the priorities of the investor and the specific project context. A project where long-term operational safety and maintenance accessibility are critical may favour the full basement, while an energy-driven project may favour the two-pit solution. The extended basement emerges as the most robust choice under uncertainty, offering acceptable performance across all dimensions without a dominant weakness.

The largest difference between the three design alternatives is observed in heating energy demand. The full basement solution requires substantially more heating energy in both climate scenarios. In Sweden, the full basement requires 23,046 MWh/year, compared with 6,592 MWh/year for the two-pit solution and 7,081 MWh/year for the extended basement solution. In Spain, the full basement requires 4,852 MWh/year, while the two-pit solution shows a heat surplus, and the extended basement requires only 439 MWh/year.

This higher heating demand is mainly caused by the larger ventilated volume and higher winter airflow rate of the full basement design. The full basement has a total ventilated volume of 112,802 m^3 and a winter mass airflow rate of 237.9 kg/s. By comparison, the two-pit solution has a winter airflow rate of 170.5 kg/s, while the extended basement has 153.4 kg/s.

Since heating demand is strongly influenced by the amount of cold outdoor air that must be heated during winter, the larger volume and higher airflow rate make the full basement solution significantly more energy intensive. In the Swedish scenario, the full basement requires approximately 3 times more heating energy than the two-pit solution.

The sensitivity analysis shows that mass airflow rate and outdoor design temperature are the most influential parameters, with maximum deviations of 72.1% and 66.7%, respectively. Heating operating hours had a moderate effect (16.7%) and recovered process heat had the lowest influence (9.5%). Even under the most favourable tested assumptions, the full basement still had a substantially higher heating demand than the two-pit solution (6,592 MWh/year) and the extended basement solution (7,081 MWh/year). This confirms that its high heating demand is not caused by conservative assumptions, but by its larger volume and higher ventilation airflow requirement.

Ventilation energy shows a different trend from heating energy. Although the full basement has the largest building volume, it does not have the highest fan electricity demand. The full basement requires 2,490 MWh/year, while the extended basement requires 2,968 MWh/year. This is because fan electricity demand depends mainly on the installed fan power and ventilation system design, not only on the size of the building. The extended basement's higher installed fan power reflects its more distributed ventilation system design, which uses a larger number of smaller supply and exhaust units spread across a layout. In contrast, the full basement uses fewer but larger centralised units, resulting in lower total installed power despite its greater building volume. Therefore, a larger hall volume does not automatically lead to higher ventilation electricity use.

Embodied carbon follows the same pattern as the structural material quantities. The full basement has the highest embodied carbon, at approximately 2,025 tCO_2e, followed by the extended basement at around 1,587 tCO_2e, and the two-pit solution at about 1,098 tCO_2e. The difference between the Swedish and Spanish results is small and is mainly caused by the different national emission factors used in the calculation. The Swedish emission factors are 199.16 kg CO_2e/m^3 for concrete, 0.69 kg CO_2e/kg for reinforcement steel, and 2.52 kg CO_2e/kg for structural steel. For Spain, the corresponding values are 221.4 kg CO_2e/m^3, 0.509 kg CO_2e/kg, and 2.56 kg CO_2e/kg respectively. The concrete emission factor is notably higher in Spain, which contributes to slightly higher total embodied carbon in the Spanish cases despite reinforcement steel having a lower emission factor than in Sweden.

This shows that the basement configuration has a stronger influence on embodied carbon than the climate scenario. Since the amount of concrete and steel is mainly determined during the early design stage, early decisions about structural layout have a major impact on the environmental performance of the building.

Economic performance shows that CAPEX is not determined by volume alone. Although the two-pit solution has the smallest basement extent, it does not have the lowest construction cost. The CAPEX results can be better understood by examining the structural assumptions underlying each design alternative. The full basement solution is constructed with a slab-on-grade foundation, meaning it sits at ground level without requiring deep excavation. This directly explains its significantly lower groundwork cost under good ground conditions (6.3 MSEK) compared to the extended basement (14.2 MSEK) and two-pit solution (14.9 MSEK), where basements are located below ground level and require active excavation. Under piling conditions, the same logic applies; the slab-on-grade foundation of the full basement distributes loads broadly across its base, reducing the number of piles required (18 MSEK) compared to the extended basement (31.8 MSEK) and two-pit solution (33.9 MSEK), where piling is concentrated under the ground floor slab only, excluding the basement areas. A detailed breakdown can be seen in Appendix 2.

The higher civil construction cost of the two-pit solution relative to the extended basement is partly related to its more complex below-ground configuration, which requires excavation across multiple separate pit zones rather than a single continuous basement volume. This complexity adds to both construction effort and groundwork requirements, causing the two-pit solution to consistently sit above the extended basement in total CAPEX across all four ground conditions, despite being structurally less complex than the full basement. The higher civil construction cost of the two-pit solution (400 MSEK) relative to the extended basement (380 MSEK) is not fully explained by material quantities, as the two-pit solution has the lowest concrete and steel volumes in this thesis. This suggests that the layout-based cost estimates from the reference projects incorporate additional cost factors beyond structural material quantities alone.

The full basement has the highest civil construction cost (495 MSEK) among the three alternatives. However, its slab-on-grade foundation requires minimal groundwork, which partially offsets this premium. This offset becomes particularly significant under poor ground conditions, where the extended basement and two-pit solution face sharply rising excavation and piling costs while the full basement groundwork cost remains comparatively low.

OPEX follows the total energy demand more directly. The two-pit solution has the lowest annual OPEX in both Sweden and Spain, while the full basement has the highest. In Sweden, the difference between the two-pit and full basement solutions is approximately 1.56 million €/year. However, these OPEX results are based on an electric heating scenario. In practice, heat pumps, district heating, or recovered process heat could reduce the heating cost. This would reduce the size of the OPEX difference, but the full basement would remain the most expensive option to operate because of its higher heating demand.

Operational performance is the main area where the full basement solution performs best. It received the highest scores for maintenance accessibility (4.6), safety (4.5), and general quality/comfort (4.2). The extended basement showed moderate performance, while the two-pit solution received the lowest scores, especially for safety (2.5), which is below the acceptable score of 3.0.

This difference is mainly explained by the layout of each design. The two-pit solution creates two separate lower-level areas, which limit movement, visibility, and access. This can make maintenance work more difficult and may increase safety concerns in an industrial environment with heavy equipment and continuous operation. In contrast, the full basement provides a continuous and open lower-level space. This improves movement, access routes, visibility, and working conditions. As a result, it is perceived as safer and easier to maintain.

6.1 Trade-Offs Between Performance Dimensions

The comparison reveals a clear trade-off between operational performance and resource efficiency.

The full basement solution achieved the highest maintenance and safety scores, reflecting the benefits of a large and continuous basement area that improves access to equipment and working conditions. However, this operational advantage comes at a high cost. The full basement required the greatest quantities of concrete and steel, resulting in the highest embodied carbon emissions and capital cost. In addition, its large, enclosed volume led to substantially higher heating demand, especially in the Swedish climate.

The two-pit solution showed the opposite performance profile. It required the least structural material, resulting in the lowest embodied carbon and lowest operating cost. However, its fragmented basement arrangement reduced accessibility and led to the lowest safety and maintenance scores.

The extended basement solution represented a compromise between these extremes. It provided improved operational performance compared to the two-pit design while maintaining significantly lower CAPEX and environmental impact than the full basement alternative.

These findings demonstrate that design decisions affecting basement extent involve inherent trade-offs. Increasing the basement size improves operational functionality but also increases material consumption, construction cost, and energy demand.

6.2 Influence of Climate Scenario

Climate conditions had a significant effect on heating demand and OPEX, but did not change the relative ranking of the design alternatives.

In Sweden, the long heating season amplified the impact of building volume on annual energy demand. The full basement solution exhibited particularly high heating demand, more than twice that of the other alternatives. In Spain, heating demand was substantially lower for all designs, and the two-pit solution even showed a small heat surplus after accounting for recovered process heat.

Despite these differences in absolute values, the relative performance of the alternatives remained consistent. The two-pit solution had the lowest energy use and OPEX in both climates, while the full basement remained the most energy-intensive and costly to operate.

This suggests that climate strongly affects the magnitude of energy and cost impacts, but the influence of design configuration is robust across different geographic contexts.

6.3 Design Implications for Early-Stage Decision-Making

The results provide practical guidance for early-stage industrial hall design.

Table 16: Design alternative recommendations by project priority.

Project priority	Most suitable design	Reason
Minimize energy use	Two-pit solution	Lowest total annual energy demand in both Sweden and Spain
Minimize embodied carbon	Two-pit solution	Lowest concrete and steel quantities
Minimize operating cost	Two-pit solution	Lowest annual OPEX in both climate scenarios
Minimize initial construction cost	Extended basement	Lowest CAPEX among the three alternatives
Improve maintenance accessibility	Full basement	Highest maintenance accessibility score
Improve safety	Full basement	Highest safety score
Achieve balanced overall performance	Extended basement	Avoids the main weaknesses of both two-pit and full basement solutions

7. Framework Generalizability and Adaptation to Other Industrial Contexts

The framework developed in this thesis was applied to a specific case study: a tissue machine hall designed by Valmet. Therefore, the quantitative results presented in Chapter 5 are specific to this case. However, the general structure of the framework can be applied to other types of industrial halls.

The framework can be understood in two parts. The first part is the overall evaluation structure. This includes the four performance dimensions: energy, environmental, economic, and operational performance. It also includes the KPI structure and the method used to compare different design alternatives. This part is not specific to the tissue machine hall and can be used for other industrial buildings, such as steel fabrication plants, food processing facilities, or automotive assembly halls.

The second part is the set of input values used in the calculations. These include ventilation rates, operating hours, process heat recovery, material quantities, emission factors, and cost data. These values are specific to each project and must be adjusted when the framework is applied to a different industrial context. Therefore, adapting the framework does not require changing the overall method, but it does require replacing the input data with values that match the new project.

The adaptation process can be carried out in three main steps. First, the boundary conditions of the new hall should be defined. This includes internal heat loads, occupancy patterns, and ventilation requirements related to the production process. The energy KPIs used in this thesis can also be applied to other large industrial halls, if the correct operational data are used.

Second, the environmental and cost factors should be updated according to the location of the project. In this thesis, Swedish and Spanish emission factors were used for the embodied carbon calculations. For projects in other countries, national databases or project-specific environmental product declarations should be used instead. Similarly, construction and operating cost data should be taken from local market sources.

Overall, the framework should be seen as a decision-support method rather than a fixed calculation model. Its value is not only in the specific results produced for the case study, but in the structured way it compares design alternatives across several performance dimensions. By keeping the evaluation structure separate from the project-specific input data, the framework can be adapted to different industrial building projects with limited changes.

8. Conclusion

This thesis developed and applied an integrated decision-support framework for evaluating industrial machine hall designs during the early design stage. By combining energy, environmental, economic, and operational performance dimensions through quantifiable KPIs, the framework enables a systematic and transparent comparison of design alternatives, moving beyond experience-based judgment toward evidence-based decision-making.

The framework was applied to a real-world case study provided by Valmet, comparing three tissue machine hall design concepts: the two-pit solution, the extended basement, and the full basement, across two climate scenarios (Sweden and Spain). The results demonstrate that no single design alternative is universally optimal. Instead, each concept exhibits distinct strengths and trade-offs depending on the performance dimension considered.

The two-pit solution consistently delivered the best performance in energy use, embodied carbon, and operating cost, making it the most resource-efficient alternative. However, its fragmented basement layout resulted in the lowest safety and maintenance accessibility scores, with the safety score falling below the defined acceptable threshold. The full basement solution showed the opposite profile: it achieved the highest operational scores but at a significantly higher material, construction, and energy cost. In the Swedish climate, the annual heating demand was approximately 3 times higher than that of the two-pit solution. The extended basement emerged as the most balanced alternative, holding a middle position across all dimensions without leading or lagging in any single category, making it the most robust choice under conditions of uncertainty.

Climate scenario analysis confirmed that while the absolute magnitude of energy and cost impacts differs substantially between Sweden and Spain, the relative ranking of the three alternatives remained consistent across both contexts.

In answering the main research question, this thesis demonstrates that a KPI-based, multi-dimensional framework can be successfully developed and applied to optimize industrial hall design at the early stage. The framework is not prescriptive; it does not recommend a single solution but rather supports informed decision-making by making performance trade-offs explicit and quantifiable. The appropriate design choice ultimately depends on the project's priorities: energy and cost efficiency, operational safety, environmental impact, or balanced performance

Although the framework was developed and demonstrated using a tissue machine hall designed by Valmet, its core structure is transferable to other industrial building typologies. The four-dimensional evaluation logic and KPI framework remain unchanged, while context-specific input parameters such as process loads, emission factors, and cost benchmarks can be recalibrated for new applications. This makes the framework a broadly applicable decision-support tool for comparing early-stage industrial building design alternatives across energy, environmental, economic, and operational dimensions.

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Appendix 1

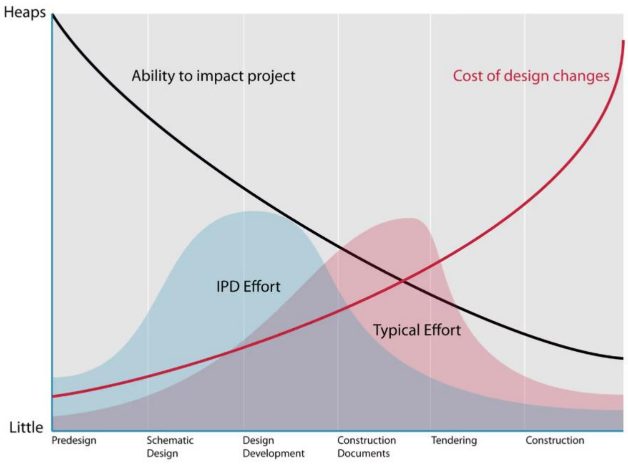

Figure 21: The MacLeamy Curve illustrating the relationship between the ability to influence design outcomes and the cost of change over project stages. Adapted from MacLeamy (2004).

Table 17: Input parameters for heating demand calculation by design and season

Case	Country	Season	Air change rate	Mass inflow	Fan power	Heat recovery output
2 Pit basement	Spain	Winter	6.7 ACH	170.5 kg/s	265.3 kW	4,270 kW
	Spain	Summer	7.1 ACH	181.0 kg/s	265.3 kW	0 kW
	Sweden	Winter	6.7 ACH	170.5 kg/s	265.3 kW	4,270 kW
	Sweden	Summer	7.1 ACH	181.0 kg/s	265.3 kW	0 kW
Extended basement	Sweden	Winter	4.0 ACH	153.4 kg/s	338.8 kW	3,650 kW
	Sweden	Summer	5.0 ACH	198.6 kg/s	338.8 kW	0 kW
	Spain	Winter	4.0 ACH	153.4 kg/s	338.8 kW	3,650 kW
	Spain	Summer	5.0 ACH	198.6 kg/s	338.8 kW	0 kW
Full basement	Spain	Winter	6.4 ACH	237.9 kg/s	284.2 kW	4,270 kW
	Spain	Summer	6.4 ACH	237.9 kg/s	284.2 kW	0 kW
	Sweden	Winter	6.4 ACH	237.9 kg/s	284.2 kW	3,650 kW
	Sweden	Summer	6.4 ACH	237.9 kg/s	284.2 kW	0 kW

Table 18: Heating energy demand calculation summary

Item	Unit	2-pit Sweden	2-pit Spain	Extended Sweden	Extended Sweden	Full basement Sweden	Full basement Spain
Indoor setpoint temperature	°C	20	20	20	20	20	20
Outdoor design / seasonal temp	°C	-11.3	-4.6	-11.3	-4.6	-11.3	-4.6
Mass inflow (m)	kg/s	170.5	170.5	153.4	153.4	237.9	237.9
Air change rate	ACH	6.7	6.7	4	4	6.4	6.4
Specific heat capacity (Cp)	kJ/kg.K	1.006	1.006	1.006	1.006	1.006	1.006
Heating energy demand	kW	5368.67	4219.46	4830.22	3796.28	7490.94	5887.45
Heat recovery output	kW	4270	4270	3650	3650	3650	4270
Net Heating energy demand	kW	1098.67	-50.5342	1180.22	146.28	3840.94	1617.45
Operating hours	h/yr	6000	2500	6000	2500	6000	2500
Heating demand	kWh/yr	6592019	126335.5	7081371.12	365704.6	23045685.7	4043635

Table 19: Installed power details for 2 pit solution design

Section / Application	RDC [kW]	Quantity	Subtotal [kW]
Supply air wall units	5.5	24	132
Supply air units (Room Vent)	30	1	30
Supply air units (basement/mezzanine)	30	2	60
Exhaust air units (Roof)	15	6	90
Heat recovery fan	30	1	30
Heating of wet end roof	30	1	30
Exhaust air from bale pulpers	3	1	3
Ventilation for QCS	4	1	4
Total installed power (kW)			379

Table 20: Installed power details for extended basement design

Application	Motor [kW]	Quantity	Subtotal
Supply air wall units	5.5	36	198
Supply air units	30	3	90
Exhaust air units	18.5	8	148
Heating of wet end roof	22	1	22
Exhaust air from bale pulpers	5.5	2	11
Transformer room exhaust	15	1	15
Total Installed Power (kW)			484

Table 21: Installed power details for full basement design

Application	Motor [kW]	Quantity	Subtotal
Supply air mancoolers	22	13	286
Exhaust air units	15	7	105
Ventilation of wet end roof	15	1	15
Total Installed power (kW)			406

Table 22: Scope of groundwork for each design alternative

Alternative	Good ground conditions	Good ground conditions, including rock	Poor ground conditions, mass replacement	Poor ground conditions, piling
Full basement	Topsoil excavation	Topsoil excavation	Topsoil excavation, 10 m of excavation, fill material 8 m of lightweight fill and 1 m of crushed stone fill.	Topsoil excavation, 0.5 m excavation and fill material 0.5 m of crushed stone fill. Piling c/c 6 m, L = 10 m
Extended basement	Topsoil excavation and basement excavation.	Topsoil excavation and rock excavation for basement.	Topsoil excavation, 10 m of excavation, fill material 8 m of lightweight fill and 1 m of crushed stone fill.	Topsoil excavation, 10 m of excavation, fill material 8 m of lightweight fill and 1 m of crushed stone fill for basement. Piling c/c 6 m, L = 10 m limited to the ground floor slab, excluding areas.
Two-pit solution	Topsoil excavation and basement excavation.	Topsoil excavation and rock excavation for basement.	Topsoil excavation, 10 m of excavation, fill material 8 m of lightweight fill and 1 m of crushed stone fill.	Topsoil excavation, 10 m of excavation, fill material 8 m of lightweight fill and 1 m of crushed stone fill for basement. Piling c/c 6 m, L = 10 m limited to the ground floor slab, excluding basement areas.

Table 23: Indicative cost estimate for groundwork

Alternative	Good ground conditions	Good ground conditions, including rock	Poor ground conditions, mass replacement	Poor ground conditions, piling
Full basement	6 300 000 kr	6 300 000 kr	120 400 000 kr	18 000 000 kr
Extended basement	14 200 000 kr	21 700 000 kr	103 400 000 kr	31 800 000 kr
Two-pit solution	14 900 000 kr	22 000 000 kr	123 400 000 kr	33 900 000 kr

This table presents the indicative costs for the groundwork described in Table 23. Each cell in this table corresponds to the respective cell in Table 22.

Table 24: summary of the combined costs for groundwork and the building based on the figures presented in results chapter

Machine hall type	Good ground conditions	Good ground conditions, including rock	Poor ground conditions, mass replacement	Poor ground conditions, piling
Full basement	501 300 000 kr	501 300 000 kr	615 400 000 kr	513 000 000 kr
Extended basement	394 200 000 kr	401 700 000 kr	483 400 000 kr	411 800 000 kr
Two-pit solution	414 900 000 kr	422 000 000 kr	523 400 000 kr	433 900 000 kr

Table 25: Embodied carbon emissions by material and design alternative, Sweden scenario (tCO_2e)

Design Type	Concrete Emission	Reinforcement Steel Emission	Structural Steel emission	Total Emission
2 pit	812,15	276,13	94,73	1088,29
Extended	1146,59	432,46	98,09	1579,05
Full basement	1444,29	575,95	231,47	2020,25

Table 26: Embodied carbon emissions by material and design alternative, Spain scenario (tCO_2e)

Design Type	Concrete Emission	Reinforcement Steel Emission	Structural Steel emission	Total Emission
2 pit	902,85	203,70	96,24	1106,54
Extended	1274,63	319,02	99,65	1593,65
Full basement	1605,58	424,87	235,15	2030,45

Appendix 2

Table 27: Individual respondent scores for maintenance accessibility and safety KPIs by design alternative. Maintenance score represents the average of Q1–Q5 and safety score represents the average of Q6–Q8 for each respondent.

Respondent	2 pit Solution		Extended Basement		Full Basement	
	Maintenance	Safety	Maintenance	Safety	Maintenance	Safety
R1	3.80	4.00	3.60	4.00	4.60	4.00
R2	3.00	3.00	4.60	4.67	5.00	5.00
R3	3.00	3.33	3.80	4.00	5.00	5.00
R4	3.60	2.67	4.20	3.67	4.80	5.00
R5	3.40	2.33	4.20	4.00	4.80	5.00
R6	3.00	2.67	4.20	4.00	4.80	4.67
R7	2.00	1.33	3.40	3.33	5.00	4.67
R8	3.00	2.67	4.00	3.67	5.00	5.00
R9	3.00	2.33	3.20	3.00	4.20	5.00
R10	3.20	1.33	4.00	3.33	4.20	4.00
R11	3.20	2.33	3.60	3.00	4.00	3.33
R12	2.80	2.67	4.00	3.00	4.40	4.00
R13	3.80	3.00	4.40	4.00	4.80	5.00
R14	2.00	2.00	3.00	3.00	5.00	5.00
R15	2.00	2.00	3.20	2.67	4.00	4.00
R16	3.00	3.00	5.00	4.00	5.00	5.00
R17	3.20	2.00	3.40	2.67	4.00	3.33
R18	3.80	3.00	4.40	4.00	4.00	4.00

Table 28: Overall KPI scores for maintenance accessibility and safety by design alternative. calculated as the average across all 18 respondents.

	2 pit Solution		Extended Basement		Full Basement	
	Maintenance	Safety	Maintenance	Safety	Maintenance	Safety
Average	3.04	2.54	3.90	3.56	4.59	4.50