



**Vaasan yliopisto**  
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**Simplifying Modular Life Cycle Assessment (LCA) for  
Metalworking Assembly Lines: A Framework for Efficiency**

*School of Technology and Innovations  
Master's thesis  
Master of Science in Industrial Management*

*Vaasa 2025*

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**UNIVERSITY OF VAASA****School of Technology and Innovations**

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**Title of the thesis:** Simplifying Modular Life Cycle Assessment (LCA) for Metalworking Assembly Lines: A Framework for Efficiency.  
**Degree:** Master of Science in Industrial Management  
**Discipline:** Industrial Management  
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**Year:** 2025      **Pages:** 73

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**ABSTRACT:**

This thesis presents a framework to simplify Life Cycle Assessment (LCA) for modular metalworking assembly lines by integrating parameterization techniques within a customized Excel-based tool. Traditional LCA approaches often face challenges when applied to modular production environments due to the dynamic nature of configurations, component variability, and the complexity of input data management. In response, this study proposes a streamlined, transparent methodology that enables rapid environmental impact evaluations by leveraging weight-based, time-based, and distance-based parameters.

The research begins by reviewing key developments in LCA, with particular attention to simplification methods, European Union climate policies, and the evolving role of modularization in manufacturing. The framework design is supported by existing literature and guided by recognized standards and regulations, including ISO 14040 and 14044, Environmental Product Declarations (EPD), and the Product Environmental Footprint (PEF) methodology.

A case application is conducted using a hypothetical modular machinery example, allowing the developed Excel tool to be tested for consistency, adaptability, and usability. The tool will provide the users inputs in drop-down-based structure, demonstrate automated calculations, and visualization sheets will be shared so that emission outputs can be interpreted. Results from two distinct customer orders demonstrate how the framework can capture and compare environmental impacts based on individual module configurations. Additionally, emission insights across modules are explored to identify optimization opportunities, including the use of alternative materials, transport strategies, and energy-saving techniques.

The findings support the feasibility of applying modular LCA frameworks in industry, offering flexibility, transparency, and integration potential with ERP or PLM systems. The study concludes by acknowledging current limitations and recommending future development, such as expanding the tool to include full life cycle phases and broader impact categories. This work contributes to a practical, scalable solution for advancing environmental assessments in modern modular manufacturing.

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**KEYWORDS:** Life Cycle Assessment (LCA), Modular Manufacturing, Parameterization, Environmental Impact, Excel-Based LCA, Metalworking Industry, Sustainability Assessment, Product Environmental Footprint (PEF), Simplified LCA Framework, Green Manufacturing

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# **1 Introduction**

In this chapter, readers will be provided with a comprehensive introduction to the background and context of the thesis, including an in-depth discussion of the identified research gap, research questions, and the objectives that guide the study. Furthermore, this chapter defines key terms and concepts essential for understanding the subject matter. It also outlines the limitations of the research, providing transparency on the scope and boundaries of the study. Additionally, the structure of the thesis is presented, accompanied by a thematic map and chapter outline that visually and descriptively organize the main themes and subtopics explored throughout the research. The thesis employs artificial intelligence tools to support grammatical refinement and to enhance the academic clarity and consistency of writing.

## **1.1 Background of study**

Sustainability has become a critical concern in industrial manufacturing, driven by increasing pressure on companies to reduce their environmental footprint and comply with evolving regulations. Life Cycle Assessment (LCA) has emerged as one of the most widely accepted tools for quantifying the environmental impacts of products and processes across their life cycle (ISO, 2006; European Commission, 2014; Zhou et al., 2023; Wu et al., 2023). It supports in increasing environmental transparency, informed decisions in sustainability, and playing a vital role in corporate reporting and public communication (Santero & Hendry, 2016).

Even with multiple positive aspects, traditional LCA methods are usually data-oriented, prolonged, and difficult measure dynamic manufacturing environments for example modular production systems. These systems are categorized by repeated reconfigurations and product variability which requires real-time, flexible assessment tools that is struggled to be supported by traditional static LCA models (Nuss & Eckelman, 2014; Hatim et al., 2023). Most commonly used software like OpenLCA and Ecoinvent, while methodologically vigorous, requires vast data input and technical expertise, which can regulate their feasibility in

swiftly evolving industrial settings (Wernet et al., 2016; Weidema et al., 2013; Mattila et al., 2012). Therefore, researchers and practitioners are progressively searching for streamlined and parameterized frameworks that will bring a balanced methodological precision along with operational usability (Mattila et al., 2012; Reap et al., 2008).

Specifically in the metalworking industry, Modular assembly lines are portrayed as regular reconfigurations and high variability in both product design and production processes. This adaptability, although benefits customization and productivity, complicates the application of traditional LCA methods, that usually depends on static models and standardized datasets. All new product variant shall go through tailored assessments, which will raise the workload and minimize the scalability of conventional LCA measures. Moreover, the metalworking industry is familiar for its major energy consumption and use of resource-intensive materials, which will make environmental evaluation a significant concern. Therefore, streamlined and flexible LCA approaches are necessary to provide immediate support in decision-making and retain environmental accountability (Güven et al., 2023; Nuss & Eckelman, 2014; Reap et al., 2008).

This study concerns the recommended framework into a representative modular metalworking assembly line that indicates general characteristics and operational practices in the industry. The demonstration emphasizes on usual configurations which is typical in such environments, which focuses on generalization of the utility of framework beyond any particular company. The primary focus is to consider the feasibility of applying Excel-based LCA models for modular systems in metalworking by highlighting accessibility, customization, and marginal technical overhead. These models will integrate parameter-driven inputs such as material categorization, energy consumption, and machine processes, thus authorizing earlier, frequent assessments through variable configurations. This approach supports practical, real-time sustainability evaluation in such a way that it will maintain methodological reliability and operational significance.

Modular systems in metalworking like robotic arms, cutting heads, and control modules—not only present design flexibility but also complications in environmental evaluation. Traditional LCA models are rigid and usually ineffective once applied to reconfigurable production systems. As Ribeiro et al. (2023) and Han et al. (2022) note, traditional LCAs struggle with modular variability and requirements of entire recalculations for each configuration.

Current methods offer parameterization to update assessments and not sacrificing accuracy. Favi et al. (2021) and Bey et al. (2020) indicates how module-based emission factors and average configuration values can support fast, frequent environmental impact calculations. These studies stimulated the development of a simplified, Excel-based LCA tool in this thesis and the primary goal is to bring balance in methodological clarity with adaptability for modular systems.

## **1.2 Problem Statement**

Traditional LCA tools such as OpenLCA and Ecoinvent depends on static input-output models that needs a greatly thorough datasets, and frequent reconfigurations in modular production lines are not easily adaptable. Inefficiencies in data handling, result calculation, and system responsiveness are generated from these limitations (Santero & Hendry, 2016; Norgate et al., 2007). Though LCA shares a coordinated approach to understanding environmental impacts, its application in modular manufacturing systems is still limited because of the lacks in scalability and adaptability. Traditional LCA models are usually static, tailored to fixed product designs, and dynamic nature of modular systems are not easily adapted. Furthermore, parameterization strategy offered in recent studies is not widely implemented yet in practice in spite of its potential to extend modular LCA flexibility along with minimizing calculation complexity (Moins et al., 2024). Companies those are engaged in customized machinery production and modular assembly lines have obstacles in applying full-scale LCAs to each distinctive product variation.

Challenges in using LCA to modular manufacturing systems appear usually from the rigidity and resource intensity of current assessment models. Countless traditional tools are not sufficient to adapt the flexibility and frequent amendments in typical of modular product lines. Consequently, every new product may require an individual LCA process and that results in time-consuming and expensive methods. Additionally, failure of current frameworks to scale effectively through numerous configurations, restricting the practicality in actual production environments. Another vital concern is the ongoing difficulty of balancing the accuracy requirements, data-rich assessments with the necessity for economical decision-making in time. These cause reduction the usability of LCA in faster settings in which instant environmental evaluation is vital for innovation driven by sustainability.

The objective of this research is to identify these obstacles by creating a modular and scalable LCA framework that extends the flexibility and efficiency of environmental impact assessments. While the purpose of this framework is not to replace advanced LCA software, it offers a simpler substitution for modular manufacturing environments where simplicity and adaptability are required. The primary objective of the proposed framework is to minimize the complications of data input and model generation using a parameter-driven approach which allows companies to accomplish assessments across varying configurations repeatedly without requiring a complete methodological reset for each product variation. This method is basically beneficial in modular assembly line settings where there are frequent customization and critical rapid responsiveness. By integrating streamlined processes such as attribute-based modelling and automated calculation templates—potentially implemented in accessible platforms like Excel—the framework pursues to create integration between theoretical robustness and real-world usability (Moins et al., 2024; Senseney et al., 2023; Reap et al., 2008).

### **1.3 Research Objectives**

The core objective of this thesis is to obtain a simplified as well as modular Life Cycle Assessment (LCA) framework. It is specifically designed for use in metalworking assembly lines, where production flexibility and configuration variability are high. The purpose is to

reduce the complexity, and resource. It demands typically associated with traditional LCA processes by introducing a parameterized modelling approach. This method involves structuring environmental calculations around measurable product attributes like material type, weight, and energy consumption. It results in assessments being efficiently repeated across multiple product variants without rebuilding the model every time. Excel-based implementation will be explored as a user-friendly platform. It will provide customization, scalability, and cost effectiveness and support updates rapidly and scenario testing.

A critical aspect of this research involves identifying and addressing the shortcomings of conventional LCA systems. Especially their lack of adaptability in dynamic manufacturing environments. The study demonstrates how modularization and simplification strategies can maintain sufficient accuracy. It also allows faster decision-making processes. This will be achieved by validating the proposed framework by data obtained from a case application on an average modular metalworking assembly line. The balance between environmental transparency and operational feasibility will be focused on the evaluation. Furthermore, the thesis proposes that future studies explore whether the developed LCA framework can be adapted beyond the metal sector. It also offers a transferable model for other industries facing similar sustainability and customization demands (Zhang, 2023; Reap et al., 2008; Nuss & Eckelman, 2014).

#### **1.4 Research Questions**

The core objective is to determine how can Life Cycle Assessment (LCA) calculations be streamlined for modular products and maintain accuracy and adaptability across varying configurations. This fundamental research question is deep-rooted in the operational complexities of modular manufacturing environments. Especially within the metalworking sector, where repeated reconfigurations and miscellaneous product assemblies generate crucial challenges for traditional LCA tools (Moins et al., 2024). These procedures usually need individual assessments for every product variant. This makes them inefficient and inappropriate for the dynamic nature of modular production.

This thesis investigates the expansion of a flexible and scalable LCA framework that integrates parameterization strategies. It allows the benefits of measurable product attributes like material inputs, energy consumption, and production time, as proxies for environmental impact metrics (Mayanti et al., 2024). Inserting these calculations into modular templates within platforms like Excel, the framework focuses on minimizing recurring modeling. It also enables immediate assessments through numerous configurations. This method supports realistic environmental decision-making on the production floor by not compromising the consistency of the results. Moreover, the research reflects the ability of this model transferring to other industries. Especially where similar customization and operational complexity exist.

## **1.5 Scope and Limitations**

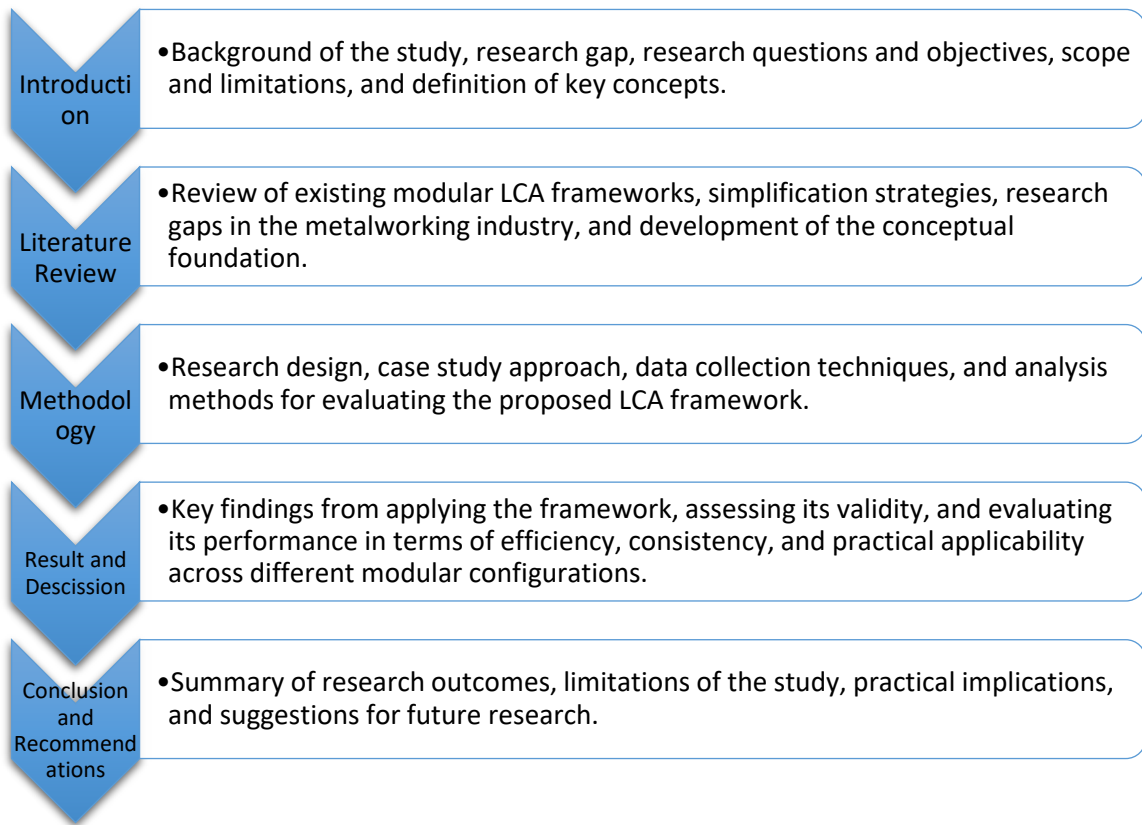
This research focuses on modular manufacturing systems within the metalworking industry, using a representative case of an average modular assembly line due to its relevance and high degree of modularity. The scope is constrained to cradle-to-gate boundaries, covering the environmental impacts from raw material extraction, component processing, and assembly stages up to the point where the product exits the manufacturing facility. This boundary is selected to align with industry practices and data availability, while also emphasizing the production-phase impacts, which are often the most controllable and measurable by the manufacturer. Excluding use-phase and end-of-life considerations allows for a focused analysis that avoids assumptions about highly variable customer behaviours and disposal practices.

The study will rely primarily on operational data gathered from standard modular manufacturing operations, such as material inputs, energy usage, and waste generation. It will also incorporate supplier data and secondary sources like Ecoinvent to fill critical data gaps. However, limitations are expected due to data access restrictions, potential inconsistencies in supplier reporting, and the generalization necessary for parameter-driven modelling. The simplification required to create a flexible and scalable LCA framework may involve trade-offs in precision and completeness. These limitations could influence the

framework's applicability to other sectors or companies with different production conditions. Nevertheless, careful boundary definition, transparent documentation of assumptions, and validation against real-world case inputs will help maintain the reliability and practical value of the proposed framework (Mondello et al., 2023; Reap et al., 2008).

## **1.6 Thesis structure**

This thesis is organized into six core chapters that follow a logical sequence from establishing the research context to drawing final conclusions and proposing future directions. The structure is designed to guide the reader through a coherent progression of ideas, beginning with the identification of the problem and theoretical foundation, followed by the design and execution of the research, and concluding with the interpretation of findings. Each chapter builds upon the previous one and contributes to answering the central research question, supporting the research objectives, and validating the proposed framework for simplifying LCA in modular manufacturing environments.



**Figure 1:** Overview of the thesis structure, highlighting the thematic focus and content of each chapter from introduction to conclusion.

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## **2 Literature Review**

This chapter presents a comprehensive literature review, beginning with an overview of the principles and importance of Life Cycle Assessment (LCA). It outlines the limitations of traditional LCA in modular assembly lines and examines current approaches to simplifying LCA, including parameterization and modular frameworks. The application of LCA in the metalworking sector is investigated and various LCA tools and databases applied in environmental impact calculations are evaluated. Furthermore, the progression of EU climate policies and their influence on industry practices are also considered, especially within modular and metal-based manufacturing. The chapter is concluded by determining unresolved issues and research gaps. It utilizes streamlined LCA frameworks to modular production systems.

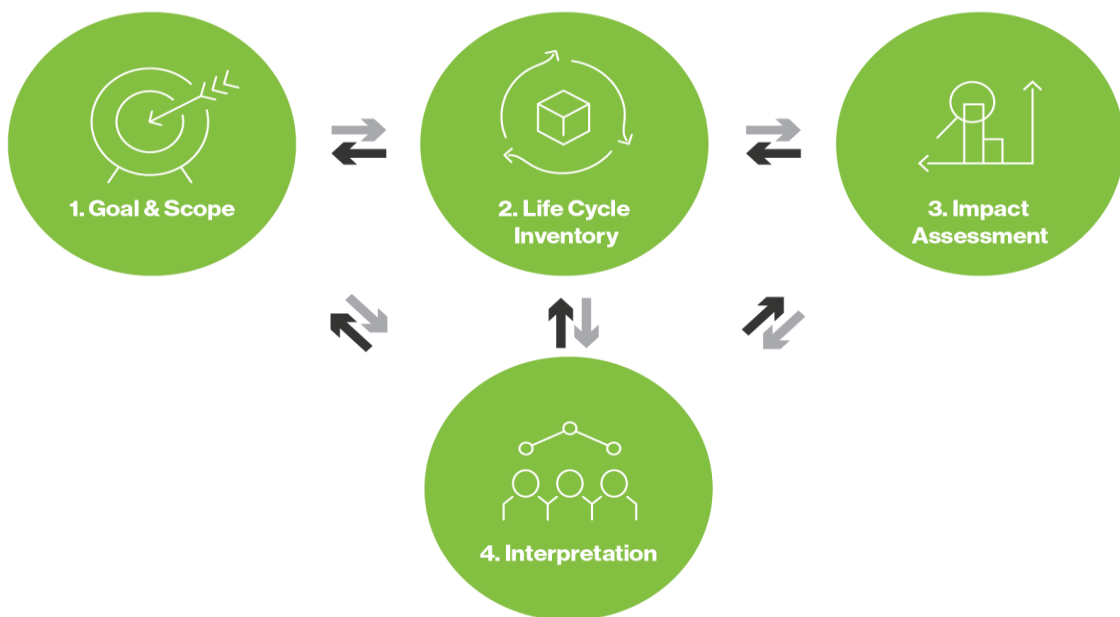
### **2.1 Introduction to LCA and Its Importance**

Life Cycle Assessment (LCA) is a consistent methodology. It evaluates the environmental impact of products, methods, or systems throughout their life cycle (ISO 14040/14044). It helps organizations measure sustainability performance. Data-driven decisions are also conducted. As per Hauschild et al. (2018), LCA is instrumental for sustainability assessment in industries focusing on minimizing their environmental footprint. The harmonization of LCA methodologies is significant. Since it emphasized by Guinee et al. (2011), who highlighted the requirement for a reliable framework to evaluate various industrial processes.

In manufacturing, LCA has a crucial part in reviewing environmental burdens from raw material extraction to end-of-life disposal. Studies like Norgate et al. (2007) and Rodrigues et al. (2016) provide intuition into LCA applications in metal industries. It determines traditional LCA models struggle with modular and customizable production systems.

LCA contains four key stages: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. These four phases form the backbone of any LCA study:

- **Goal and Scope Definition:** Establishes the purpose, system boundaries, and assumptions of the study.
- **Life Cycle Inventory (LCI):** Involves data collection on all relevant inputs (energy, materials) and outputs (emissions, waste) associated with the product or process.
- **Life Cycle Impact Assessment (LCIA):** Translates the inventory data into environmental impacts, such as global warming potential or resource depletion.
- **Interpretation:** Evaluates the results, identifies key findings, and draws conclusions and recommendations.



**Image 1:** The Four Phases of Life Cycle Assessment [LCA]

Source: Rochester Institute of Technology (n.d.).

The significant definitions related to the thesis:

- **Life Cycle Assessment (LCA):** LCA is a continuous workflow of evaluating the environmental impacts of a product from collecting the raw material to disposal of that (ISO, 2006; Reap et al., 2008).
- **Environmental Product Declarations (EPD):** Certified documents grounded in LCA which are used for transparent environmental communication (Senseney et al., 2023).
- **Cradle-to-Gate:** The boundary that indicates LCA mode which cover the process from collecting the raw material of the product until the product leaves the plant. (Mondello et al., 2023).
- **Modular Assembly Line:** Modular assembly line indicates the procedure where modules can be switchable according to the demand of the customer (Hatim et al., 2023; Zhou et al., 2023).
- **Parameterization:** Product specific parameter: such as weight, material, distance, can be automate environmental effect calculation by this parameterization system. (Moins et al., 2024; Mayanti et al., 2024).

LCA is considered as the way of evaluating the environmental effect of goods, production process and the system across the entire life cycle of that product (ISO 14040/14044). LCA assists companies to take decisions that are data driven and can improve their performance in a sustainable way. Hauschild et al. (2018) stated that LCA can be used as a major tool for sustainability assessment in industries, which are willing to decrease their carbon footprint. According to Guinee et al. (2011), the coordination of LCA is vital, and also emphasized the necessity for a reliable framework that can make comparison in various industrial procedures.

LCA plays a vital role in manufacturing by calculating environmental impacts that comes from raw material collection to final disposal. Norgate et al. (2007) and Rodrigues et al. (2016) provided their perspective about LCA applications in metal industries. That reflects

the struggle with modular, customizable, simplified production systems in traditional LCA Model.

Traditional LCA applications demand more flexibility for modular assembly lines which is a major concern in this thesis and the complexity of LCA implementation varies in different industries. Sectors like automation and construction have accepted structured LCA models (Finnveden et al., 2009) but modular industries are still having difficulties in standardization and repeatability (Weidema et al., 2013). According to Hellweg & Milà i Canals (2014), the degree of flexibility in LCA method is crucial, mostly in industries that produce products that are customizable.

## **2.2 Challenges of Traditional LCA in Modular Assembly Lines**

Traditional LCA is designed for standardized production models which makes it more time-consuming, expensive, and lacks in flexibility when applied to modular systems. Modular assembly lines, which permit product customization, introduce additional complexities in assessing environmental impacts (Suh, 2016).

The study by Lawani and Reed (2018) compares traditional and modular approaches, highlighting inefficiencies in current LCA models when applied to modular configurations. Correspondingly, Liu et al. (2020) states that the lacking in flexibility in standard LCA frameworks when dealing with product variability.

Data Management is one of the biggest limitations of traditional LCA. Modular production results in several design variations, which require individual LCAs for each configuration. This topic is described in Zhang et al. (2017), who focuses on the burden of data-intensive calculations in modular LCA models. The lack in standardization though modular industries is highlighted by Vernay et al. (2015). He claims that the lack in uniform guidelines leads obstacles in comparing environmental impacts through multiple modular systems.

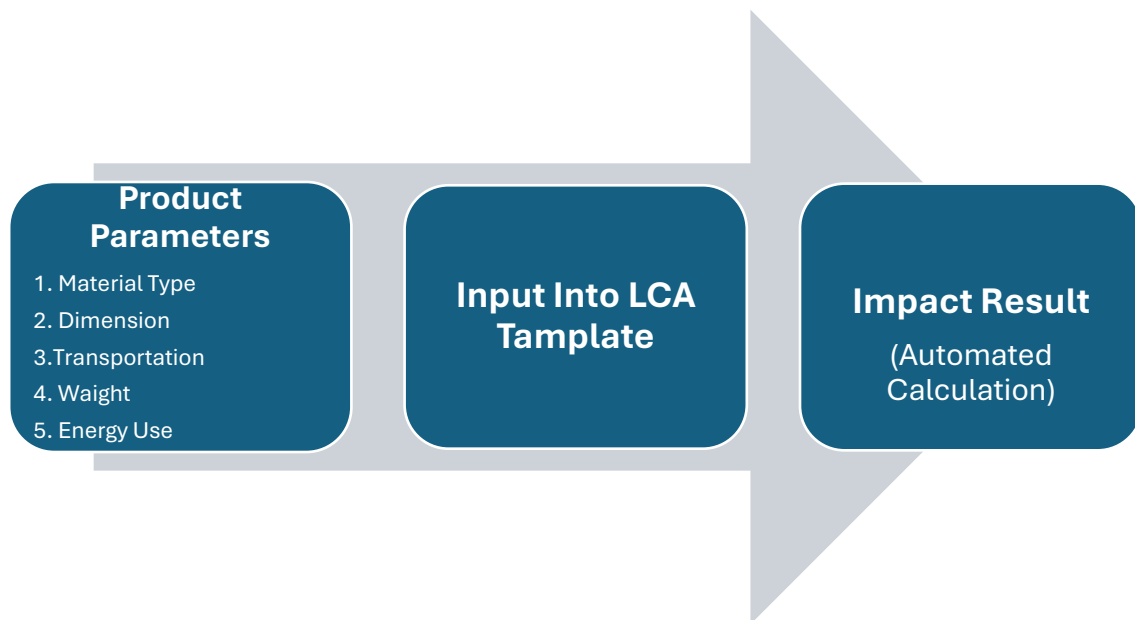
Modular production effects higher complexity in supply chain management. It requires dynamic LCA adjustments. Studies like Lenzen et al. (2010) suggest new approaches for streamlining data processing to better combine with modular manufacturing.

Data uncertainty and reliability are other crucial concerns. LCA results can vary significantly based on assumptions, data input quality and system limitations which is highlighted by Reap et al. (2008). This uncertainty is further multiplied because of high product variation and different supply chain actors in modular manufacturing (Mattila et al., 2012).

## 2.3 Existing Approaches to Simplifying LCA

Increasing product complexity and the requirement for instant sustainability assessments have headed to generalization techniques in LCA. Simplification helps in minimizing data intensity and enhance adaptability especially in modular manufacturing.

### 2.3.1 Parameterization in LCA



**Figure 2:** Flow of Parameterized LCA for Modular Configurations

Figure 2 demonstrates how product-specific parameters like weight, material type, or energy consumption are used as input into a predefined LCA format. The purpose is to automate environmental impact determinations. This method minimizes complexity. It also maintains consistency in sustainability assessment.

Identifying the inefficiencies of traditional LCA, parameterized LCA has been presented as a method to conduct impact estimations which is automated. It is based on product attributes such as weight, material, and energy consumption. As per Reap et al. (2008), parameterization significantly minimizes time for calculation maintaining accuracy. The effectiveness of parameterized models in reducing complexity is reflected in Research such as Mattila et al. (2012) and Yang et al. (2018). These studies illustrate the way parameterization can develop sustainability evaluations in industries with high product variability. Parameterization explored which is through machine learning and predictive modeling (Sousa et al., 2019) in modular system. These models allow automatic impact estimations based on historical data and product characteristics, offering real-time LCA analysis for modular production lines.

### **2.3.2 Other Simplification Methods**

Other simplification methods contain simplified LCA, which highlight vital environmental factors, and hybrid LCA models, which integrate both full and simplified assessments. As per to Hellweg and Milà i Canals (2014), the most crucial environmental impacts is focused in simplified LCA whereas minimizing data collection attempts. Finnveden et al. (2009) also highlight how hybrid LCA models can enhance efficiency and preserve result accuracy at the same time.

Furthermore, many research advocate for modular LCA frameworks, where pre-defined environmental impact factors are used focusing material type and process selection (Duflou et al., 2012). This approach enables instant sustainability assessments for varying products in different configurations.

## 2.4 LCA in Metalworking and Modular Manufacturing

Current literature focuses on the benefits of modular LCA frameworks. It highlights their effectiveness in reducing complexity maintaining transparency and robustness in environmental assessments (Beemsterboer et al., 2020; Chen et al., 2014). Consistent with these trends, the developed methodology supports streamlined, iterative environmental evaluations suitable for initial stage product design decision-making. It is crucial for achieving optimal sustainability outcomes (Tatipala et al., 2020).

Metalworking industries encounter distinguishing challenges in applying LCA because of their high energy consumption, material waste generation along with process variability. Processes such as welding, machining, and casting need significant energy inputs. It also influences the overall environmental impact of manufacturing. These processes contribute heavily to greenhouse gas emissions. It makes LCA essential in detecting ways to reduce carbon footprints. This will optimize material efficiency also. Moreover, energy-intensive processes such as smelting and heat treatment further complicate sustainability assessments. Because they differentiate relying on the metal categorization and production scale.

There is another vital concern in metalworking industries, and it is material waste generation. Significant amounts of metal scraps, chips, and offcuts are produced during machining and forming processes. It necessitates widespread waste management strategies. LCA assessments should be responsible for material recovery, recycling efficiency, and the environmental impact of scrap disposal (Rodriguez & Taylor, 2020). Effective material flow analysis within LCA can support industries in transitioning through circular economic approach. Waste materials are reintroduced into the production cycle instead of being discarded.

Variability is another critical challenge in metalworking LCA. Various combinations of metals, coatings, and processing techniques alter LCA calculations, making standardization complex (Wang et al., 2022). For instance, the energy consumption and emissions profile of aluminum extrusion contrasts substantially from steel forging. It requires tailored LCA

methods. The introduction of additive manufacturing (AM) has more diversified the industry. It offers new prospects for sustainable metal production. While AM reduces material waste compared to subtractive machining, its energy demands are often higher, leading to trade-offs that must be accounted for in LCA assessments. Several case studies focusing on steel, aluminum, and additive manufacturing LCA provide insights into sustainability improvements within the metal industry, focusing on the requirements for industry-specific impact assessment models.

However, current LCA frameworks have a deficit in adaptability to modular manufacturing processes. It necessitates new initiatives that account for variability and scalability in metalworking industries. Modular manufacturing introduces dynamic product configurations. It requires flexible LCA methodologies suitable for adapting real-time adjustments in production parameters. The integration of digital twin technology and AI-driven impact forecasting presents a potential solution. It is to allow manufacturers to simulate various production scenarios. It also optimizes environmental performance in modular metalworking systems.

## **2.5 Tools and Databases for LCA Calculations**

Different LCA tools exist to enable environmental impact assessment and consist of OpenLCA, GaBi, and Ecoinvent databases. As per Wernet et al. (2016). The Ecoinvent database is one of the most comprehensive life cycle inventory databases. It supports robust environmental assessments.

In Hauschild et al. (2018), the significance of database selection is highlighted. He demonstrates how different LCA databases can lead to varied results. As Weidema et al. (2013) argue, ensuring database consistency is crucial for consistent modular LCA applications.

The role of regional and industry-specific databases is achieving prominence. For instance, Nemecek et al. (2014) highlights how sector-specific life cycle inventory databases can improve the accuracy of LCA calculations. The process is accounting for local energy mixes,

production methods, and environmental regulations. Moreover, projects like the European Commission's Product Environmental Footprint (PEF) initiative have introduced harmonized database methodologies. The intention is to initiate cross-industry comparability that can be enhanced (Finkbeiner et al., 2014).

Multiple studies have shown automatic data integration systems in LCA software to improve efficiency. Mutel et al. (2017) discuss the development of Brightway2. It is an open-source framework for LCA modeling and allows dynamic data integration with real-time impact assessment. The requirement for interoperability between LCA tools and enterprise resource planning (ERP) systems are focused on Ciroth et al. (2016). This facilitates real-time environmental performance tracking in manufacturing.

Selecting the appropriate LCA database and computational tool is crucial for ensuring accuracy and scalability in assessments which has given the complexity of modular manufacturing. As per Steubing et al. (2016) underscores the need for customized database configurations to accommodate modular product variations, a necessary aspect of this particular research.

## **2.6 Evolution of EU Climate Policy and Its Impact on LCA and Modular Metalworking**

Over the past two decades, European Union climate policy has evolved significantly and established a regulatory environment that increasingly prioritizes sustainability, circular economic methods, and low-carbon production systems. Key milestones consist of the introduction of the EU Emissions Trading Scheme (ETS) in 2005, the development of the Product Environmental Footprint (PEF) methodology, and the more recent Carbon Border Adjustment Mechanism (CBAM) presented under the EU Green Deal (European Commission, 2014). Primary objective of these policy frameworks is to standardize environmental performance metrics through member states and not only industries but also promotion of competitive sustainability methods.

These policies have direct implications in the context of metalworking. The metal industry is always a significant contributor to industrial greenhouse gas (GHG) emissions, which is increasing pressure to adopt cleaner production technologies and document environmental performance through standardized methods like LCA and Environmental Product Declarations (EPD). LCA serves as an elementary tool in meeting these regulatory requirements that offers a well-structured approach to measure impacts across the value chain (Zhou et al., 2023). EPDs, which are grounded in LCA methodology, enable manufacturers to disclose environmental data transparently and support public procurement and labeling programs (Senseney et al., 2023).

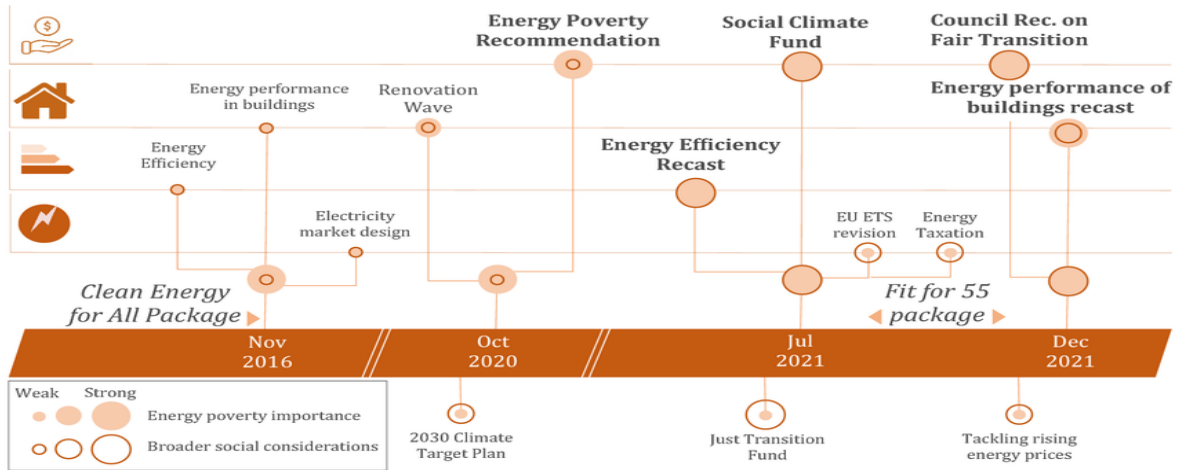
The primary objective of the introduction of the PEF by the European Commission was to unify LCA calculations across the EU minimizing inconsistencies in environmental claims. It has applications in the metal sector. It also reinforces the significance of methodological consistency and transparency (Mondello et al., 2023). The CBAM policy identifies the risk of carbon leakage by imposing carbon pricing on imported goods with high embedded emissions consisting of steel and aluminum therefore pushing the metal sector toward greener practices.

Manufacturers are increasingly turning to modularization and digital tools to improve efficiency and maintain compliance in response to those regulations. Modular production systems allow for adaptive and low-waste manufacturing strategies, which align well with EU sustainability objectives. Incorporating LCA into modular production allows companies to meet environmental requirements without harming operational flexibility (Hatim et al., 2023). Furthermore, digital platforms—such as parameterized LCA templates and Excel-based model enhance repeatability and responsiveness in modular settings, supporting both regulatory reporting and internal decision-making.

	(1990-1997) aimed at 2000	(1998-2006) aimed at 2010 (or 2008-12)	(2007-2010) Aimed at 2020
<b>GHGS</b>	No European Policy (discussion on CO2 tax which was not adopted) → Mainly national policy	EU ETS (2003)	EU ETS review (2008, 2009) (One EU-wide ETS target / including aviation) Effort Sharing Decision (National non-ETS Targets) Fluorinated Gases Regulation review Further Implementation
<b>RES</b>	ALTENER	Fluorinated Gases Regulation Mobile Air-Conditioning Systems Directive Voluntary agreement with car manufacturers (1998/ 1999) Renewable Electricity Directives (2001) Biofuels Directives	Mandatory standards for cars and vans Renewable Energy Directive (Red) & Fuel Quality Directive
<b>EEff</b>	SAVE	Energy Services Directive Combined Heat & Power Directive Eco-design of Energy Using Product Directive Energy Labelling Framework Directive Energy Performance of Buildings Directive	Energy Efficiency Directive (EED) Further Implementation Energy Labelling Framework Directive Review Energy Performance of Buildings Directive Review

**Figure 3:** Chronological development of EU climate and environmental policies from 1990 to 2010. Adapted from Climate Policy Info Hub (n.d.).

Figure 3 reflects a timeline of key EU policy developments that is related to climate change and energy efficiency between 1990 and 2010, consisting of the introduction of the EU ETS, the Renewable Energy Directive, and the Energy Efficiency Framework. These foundational policies laid the groundwork for the broader sustainability approaches that followed in the following decade.



**Figure 4:** Timeline of major EU legislative actions from 2016 to 2021 addressing climate transition and energy poverty. Adapted from European Commission (2023).

Figure 4 illustrates more current developments, including the Fit for 55 package, energy performance reforms, and social climate funding mechanisms. The progressive evolution of EU environmental policy frameworks over time is highlighted in Figure 4 and Figure 5. The combination among these evolving EU policies, combined with rising consumer and stakeholder expectations, has made LCA not only a scientific method, but also a strategic necessity. To remain competitive and compliant in this increasingly regulated global market, the metalworking sector must amend by embedding LCA into modular systems.

## 2.7 Unresolved Issues and Future Considerations

In spite of having significant advancements in Life Cycle Assessment (LCA) methodologies, many research gaps persist, particularly in the context of modular assembly lines and simplified LCA approaches. One of the key challenges is lacking in standardization in streamlined LCA methods, making it difficult to compare results across different industries (Beemsterboer et al., 2022). The accuracy and transparency of simplified LCA models remain an issue, as simplifications often lead to data loss and reduced precision, which may compromise decision-making processes (Santero & Hendry, 2016).

Another critical research gap is the restricted integration of automation along with AI-driven tools in LCA. As per recent advancement, machine learning algorithms and computational LCA models could streamline impact assessments by predicting environmental outcomes based on existing datasets (Chen & Chien, 2004). Nonetheless, due to challenges in data availability, widespread adoption of AI-driven LCA tools remains limited, model validation, and industry acceptance. Further research is required to explore how neural networks and automated data integration can enhance the efficiency and reliability of LCA in modular manufacturing settings.

Moreover, parameterized LCA models have appeared as a promising approach to simplifying LCA for modular assembly lines that allow manufacturers to reuse environmental impact factors for similar product configurations. While parameterization reduces computational effort, there is a requirement for more empirical validation and industry case studies to determine best practices for its implementation (Kamalakkannan & Kulatunga, 2020).

Finally, with increasing emphasis on the harmonization of LCA methodologies across industries. Regulatory frameworks are evolving. But the application of Cradle-to-Gate versus Cradle-to-Cradle approaches in modular manufacturing is underexplored, and further studies are needed to determine how different system limits influence sustainability assessments (Graedel et al., 2011).

This literature review highlights the challenges, advancements, and research gaps to streamline LCA for modular assembly lines. Meanwhile, significant progress has been conducted in streamlining impact assessments through parameterized models, automation, and hybrid LCA approaches. Further research is required to increase data integration, standardization, and regulatory compliance. Identifying these gaps will be crucial for improving the efficiency and applicability of LCA methodologies in modular manufacturing, ultimately supporting sustainable industrial practices.

### **3 Research Methodology and Data Collection**

This chapter portrays the research methodology used to elaborate and validate a modular Excel-based LCA framework tailored for determining environmental impacts in sheet metal manufacturing. The research design approach, scope, data sources, tool architecture, and limitations are outlined. The modular methodology is justified in recognized LCA standards and informed by existing literature, allowing for flexible application in both industry and academic perceptions.

#### **3.1 Framework Overview**

This chapter elaborates the methodology utilized to create a modular, Excel-based Life Cycle Assessment (LCA) framework designed to evaluate the environmental impacts associated with sheet metal manufacturing systems. The framework utilizes modularity and parameterization, allowing users to adapt input variables like material selection, energy usage, transportation distances, and waste outputs at the individual module level. This modular approach significantly streamlines and accelerates LCA analysis, particularly beneficial in environments involving extensive product variability and customization (Majstorovic et al., 2023).

The system boundaries implemented in this study is cradle-to-gate, covering all processes from raw material extraction through manufacturing, assembly, and transportation, explicitly excluding the product's use-phase and end-of-life treatment. This method aligns with ISO 14040 and ISO 14044 standards, emphasizing lifecycle stages with the most significant potential for emission reduction. Emission factors used within the framework mostly derive from the Ecoinvent 3.11 database which are nominated for its comprehensive, reliable, and geographically appropriate datasets (Ecoinvent, 2024).

### 3.2 Research Design

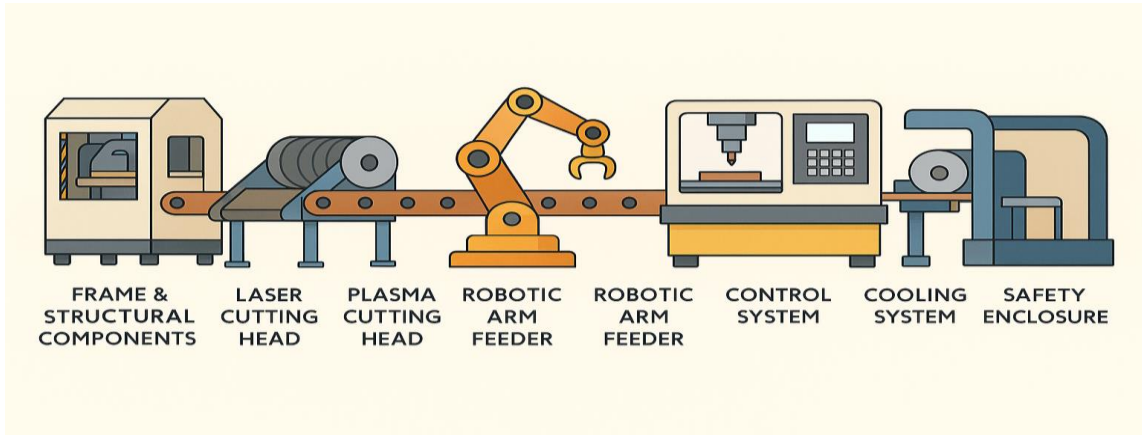
This research follows a Design Science Research (DSR) approach, which emphasizes iterative development, assessment, and refinement of practical solutions to difficult real-world issues. DSR is especially compatible to sustainability-related engineering challenges, as it combines theory-driven approaches with a vigorous concentration on usability, stakeholder relevance, and continuous feedback. In this context, DSR supports the creation of a flexible, Excel-based LCA framework focused on streamlining environmental assessments and enabling actionable insights during the early stages of product design, where environmental interventions can be most effective (Majstorovic et al., 2023).

The product system evaluated in this study is a modular sheet metal machine that reflect on the increasing trend toward modularity in industrial equipment design. The machine can be selectively configured to suit different customer specifications or functional objectives since the machine is composed of several interchangable components. These components include:

- Frame & Structural Components
- Laser Cutting Head
- Plasma Cutting Head
- Mechanical Cutter
- Coil Handling System
- Robotic Arm Feeder
- Control System
- Cooling System
- Safety Enclosure

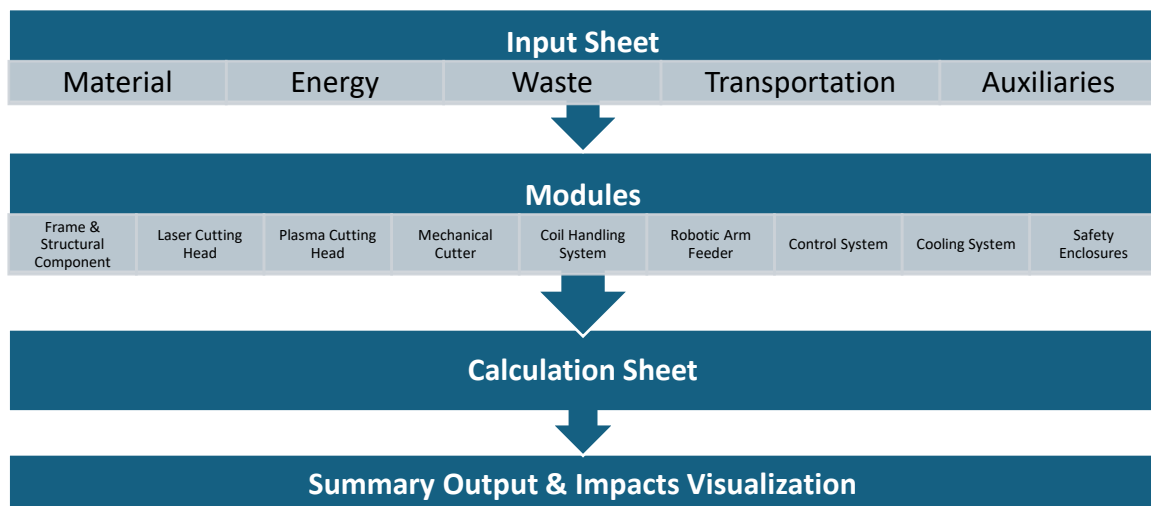
Each of these modules represents a self-contained functional unit with its own material composition, energy requirements, and manufacturing processes. In the context of LCA, this allows a granular approach toward impact analysis. Each module can be independently

evaluated and updated without recalculating the full system which offers a crucial advantage in terms of scalability and adaptability (Beemsterboer et al., 2020).



**Image 2:** Modular Assembly Line Schematic with Key Components

Image 2 demonstrates the layout of regular modular stations such as structural frames, robotic arms, and cutting heads. It complements the Excel tool's modular design logic and provides a visual understanding of how components are arranged in a typical metalworking assembly line.



**Figure 5:** Modular LCA Framework Visualization.

Figure 5 illustrates the Excel-based framework's architecture. It displays how material, energy, transport, waste data flow from the INPUT sheet into each module and are then processed through the CALCULATION sheet to generate a total environmental impact summary.

This modular structure enhances transparency and allows quick scenario modeling across machine configurations. The framework's flexibility means that users can easily add or remove elements—such as new materials or processes—without affecting the full system. This adaptability is especially useful in modular manufacturing environments and supports continuous improvement.

### **3.3 Data Collection**

Primary data collection from industrial partners or direct field measurements are not included in this study. Instead, input values for materials, energy use, and waste were derived from secondary data available in peer-reviewed literature. It has published technical standards, and LCA databases. The literature was preferred to guarantee relevance to modular sheet metal manufacturing. Vaski documents that are confidential and proprietary were not used. As a result, the framework depends entirely on transparent and publicly verifiable sources that maintain academic reproducibility.

Data integrated into emission factors and process-based environmental metrics sourced from the Ecoinvent database. It is justified by published LCA studies which is relevant to modular systems. For example, Mayanti et al. (2023) presented emission benchmarks for common steel slab modules under varying production conditions. On the other hand, Bey et al. (2020) contributed insights into average transport and energy profiles for modular unit assessments (Mayanti et al., 2023; Bey et al., 2020).

The input values used in the Excel model which includes module weight, material type, energy consumption, and operating parameters, were acquired from sources that are publicly available like technical documentation, peer-reviewed studies, and LCA databases.

Furthermore, selected operational data (e.g., for drilling, cutting, and welding modules) were shared through direct communication with Bening Mayanti. She had collected them during the OSME project (2022–2023). These merged sources ensured both scientific accuracy and realistic applicability in the case of modular manufacturing context.

### 3.4 Parameterization Process

The LCA framework utilizes a parameterization method that will streamline and scale impact assessments across different configurations. Rather than building full LCA models for every new product layout, this approach breaks down environmental impacts into component-level calculations that can be rapidly updated. The fundamental equation consists of weight-based, distance-based, and time-based parameterization:

- Weight-based: impact relies on the material mass.
- Distance-based: Transport distance influences emission.
- Time-based: amount of time accounts for the energy used over time in manufacturing processes (e.g., minutes spent welding, bending or cutting a module).

These parameterization types enable the Excel tool to be flexible and responsive to different product configurations. It also enables instant and frequent life cycle assessments. The following mathematical equations demonstrate the parameterized calculation methods applied in the Excel-based LCA tool:

- **Weight-based Emission Calculation:**

$$CO_2 \text{ Emission} = Weight \times EF$$

- **Distance-based Emission Calculation:**

$$CO_2 \text{ Emission} = Weight \times Transport \times Transport \text{ EF}$$

- **Time-based Emission Calculation:**

$$CO_2 \text{ Emission} = Time \times Energy \text{ Consumption Rate} \times EF \text{ for Electricity}$$

Where,

CO<sub>2</sub> Emission= Kg CO<sub>2</sub> eq / Kg

EF= Emission Factor [Kg CO<sub>2</sub> eq / Kg]

Weight= Total Mass of Material [Kg]

Transport= Total Transport Distance [KM]

Transport EF= Emission Factor from Transportation [Kg CO<sub>2</sub> eq / Kg]

EF for Electricity= Emission Factor from Electricity [Kg CO<sub>2</sub>/KWH]

Energy Consumption Rate= Energy Consumed per Minutes [KWH/Minutes]

Time= Total time required [Minutes]

This equation enables modular quantification by combining key measurable inputs—such as mass and material category—with established emission factors. This structure allows for immediate recalculations when modules are swapped or reconfigured.

Key input parameters considered in the framework include:

- Weight and material of each component have a direct impact on emission magnitude.
- Energy consumption during module fabrication or operational use, derived from literature or estimated based on equipment type and usage intensity.
- Transportation distance, standardized at 50 km for consistency with standard regional delivery profiles.
- Thermal efficiency factors applied particularly to modules. It involves heating or electric power which confirms that system-specific proficiency losses are indicated while determining emissions.

This method enables environmental evaluation to be both responsive and repeatable, supporting on-the-fly decision-making in modular design scenarios.

### **3.5 Goal and Scope Definition**

This section defines the overarching aim of the study, the specific unit of analysis, and the lifecycle stages included within the assessment boundaries. Clarifying these elements ensures methodological consistency and transparency in interpreting the environmental results that follow.

#### **3.5.1 Goal**

The goal of this study is to systematically evaluate the environmental impacts arising from the manufacturing of customizable sheet metal machines using a modular Life Cycle Assessment (LCA) framework. Implemented in Microsoft Excel, this framework is designed to offer a flexible, transparent, and scalable method for assessing emissions during the early phases of product development. By enabling configuration-specific analysis through parameterized modules, the tool aims to provide decision-makers with rapid and reliable insights into how various material choices, energy inputs, and structural layouts influence the overall carbon footprint. This supports a broader goal of integrating sustainability metrics into technical and procurement decisions, aligning with the industry trend of embedding environmental considerations into design and development workflows (Beemsterboer et al., 2020; Majstorovic et al., 2023).

#### **3.5.2 Functional Unit**

The functional unit for this analysis is defined as one complete modular sheet metal machine or one individual module and it relies on the scope of the evaluation. This dual-level functional unit provides a flexible basis for analyzing environmental impacts in both detailed and aggregated scenarios. When applied to a single module, the framework supports micro-level analysis that helps in optimizing specific subcomponents; when extended to the entire machine, it enables macro-level evaluations useful for overall process redesign

or comparative studies. Such a scalable functional unit structure aligns with modular LCA approaches discussed in recent literature, including studies focused on parameterized LCA systems for manufacturing (Beemsterboer et al., 2020), product system configuration (Schulz et al., 2012), and lifecycle modeling in component-based tool design (Majstorovic et al., 2023).

### **3.5.3 System Boundary**

The LCA conducted in this study adopts a cradle-to-gate system boundary. This includes all upstream and core processes associated with the production and assembly of modular sheet metal machines, such as raw material extraction, energy consumption, transportation, part manufacturing, and final in-factory assembly. It excludes downstream stages like the operational phase and end-of-life treatment. This boundary was chosen to maintain focus on stages most influenced by manufacturers and to align with recognized LCA practices, where early-phase environmental interventions are often most impactful. Literature confirms that cradle-to-gate assessments are both practical and effective when dealing with modular and reconfigurable systems (Beemsterboer et al., 2020).

## **3.6 Tool Overview:**

Excel Spreadsheet Tool: Served as the primary platform for modeling, where user input of module-specific values (weight, material type, process energy, etc.) was combined with emission factors to generate life cycle emissions. The full Excel-based framework used in this thesis is provided via a Google Drive link included in **Appendix B**.

## **3.7 Tool Architecture**

The Excel-based LCA framework is built around a structured layout that connects user inputs with standardized emission data to produce module-specific and system-wide impact calculations. The tool is composed of three core sheets:

**INPUT Sheet** – This user-facing sheet is designed for manual data entry specific to each machine module. It includes fields for specifying material types (e.g., steel, aluminum, plastics), component weights (kg), energy consumption (kWh), transport distances (km), and estimated waste ratios (%). The format uses structured rows and dropdown fields for consistency, minimizing data entry errors and supporting scenario analysis.

**FACTOR Sheet** – This backend database consolidates emission factors related to materials, energy sources, manufacturing processes, transport, and waste disposal. Most of the data are extracted from the Ecolnvent database and cross-referenced with academic publications and supervisor-validated values. Emission factors are categorized as easy reference and are formatted for direct linkage via Excel formulas (e.g., VLOOKUP or INDEX-MATCH) to support automated calculations.

This structure is categorized as:

- Material type (e.g., steel, aluminum, copper)
- Energy source (e.g., electricity, kWh per module)
- Transport mode (e.g., truck, 50 km per ton-km)
- Waste treatment (e.g., scrap steel per kg processed)

Each factor is expressed in terms of kg CO<sub>2</sub>-equivalent per unit (e.g., per kg of material, per kWh of electricity). This design allows traceable, modular environmental assessments tailored to individual component flows.

When a user enters data into the INPUT sheet (e.g., 12 kg of steel for a module), the tool automatically links it to the emission factor in the FACTOR sheet. The CALCULATION sheet then computes the corresponding emissions. This modular and automated process supports scenario testing, design optimization, and environmental reporting, while ensuring alignment with international standards and academic recommendations for streamlined LCA (Duflou et al., 2020).

**CALCULATION Sheet** – This is the computational core of the framework. It receives inputs from both the INPUT and FACTOR sheets and uses logical formulas to calculate the environmental impact of each module. These formulas include unit conversions, multiplication of quantities with emission factors, and summations across modules. The final outputs are aggregated at both the module level and the system level, enabling comparative assessment and reporting. This sheet also includes reference columns for diagnostics and verification, enhancing the transparency and traceability of the results.

**VISUALIZATION Sheet** – This output-oriented sheet aggregates the results from the CALCULATION sheet and presents them in a structured visual format. It includes summary graphs, comparison charts, and tabular breakdowns of emissions by module and by activity type (materials, energy, transport, waste). The goal is to enhance interpretability and allow users to quickly identify environmental hotspots and improve opportunities.

This structured Excel environment enables users to simulate numerous design scenarios quickly by adjusting parameters without reprogramming or rebuilding the model. All inventory data are manually entered in the INPUT sheet and automatically linked to the FACTOR sheet where they are matched with appropriate emission factors sourced from the EcoInvent database and literature-confirmed estimates. This configuration extends both traceability and flexibility as well as providing support module-level updates, scenario simulations, and audit-readiness (Majstorovic et al., 2023; Chen et al., 2014; Beemsterboer et al., 2020; Duflou et al., 2020). As per Duflou et al. (2020), individual manufacturing processes in sheet metal production like stamping, bending, or hybrid operations, have distinct environmental impacts and it depends on geometry, material, and processing strategy. Including module-specific inputs for energy and transport enables for better representation of these realistic variations, validating the framework's modular and process-driven structure (Duflou et al., 2020). This setup is particularly beneficial in industries where frequent redesign or product variability is usual. The transparency of this structure also enables traceable calculations that support internal assessment, academic scrutiny, or external reporting requirements.

Excel was selected over specified LCA software to make sure of higher accessibility, particularly for small- and medium-sized manufacturers. It may have a lack of resources for advanced tools. Furthermore, its compatibility with existing organizational workflows increases usability. It also motivates broader adoption of environmental impact modeling across non-expert clients (Chen et al., 2014; Beemsterboer et al., 2020).

### **3.8 Life Cycle Inventory (LCI)**

The modular LCA framework presented in this study is evaluated using a generic example of a modular sheet metal machine. As described in Section 3.2, this hypothetical case simulates a realistic modular industrial system composed of configurable units such as cutting heads, feeders, and control modules. While the case is conceptual, its configuration is informed by typical components, structures, and functions found in actual sheet metalworking systems. The purpose is to test the tool's flexibility, scalability, and applicability in a representative manufacturing scenario without relying on proprietary or company-specific data.

The LCI stage in this framework captures the key environmental input data necessary for emissions calculation at the module level. Each module in the system involves structural framing, control systems, or cutting mechanisms, requires its own unique set of LCI data. This ensures high granularity and precision in evaluating environmental performance.

#### **3.8.1 Materials and Auxiliaries**

The INPUT sheet supports entry of various material types including low-alloy steel, aluminum, copper, HDPE, and polycarbonate. It also includes auxiliary materials such as lubricating oils, packaging components (e.g., cardboard, shrink wrap), and fasteners, which are essential to the machine's function or distribution but are not primary structural elements. Users input the weight of each material per module (in kg), which is then linked to emission factors through lookup functions.

### **3.8.2 Energy Use**

Electricity consumption is measured in kilowatt hours per module and corresponds to the expected process energy demand, such as laser cutting or robotic feeding.

### **3.8.3 Waste Generation**

Waste is represented as a percentage of raw material lost during production. The Excel sheet supports user-defined waste rates, though default values range from 2–5% depending on the material type.

### **3.8.4 Transport**

Distance-based emissions are calculated using transport input data (default 50 km for internal movement), which can be modified per module. Freight emissions are based on ton-km multipliers.

### **3.8.5 Emission Factor Sources**

Most emission factors in this study are drawn from the Ecolnvent database, widely recognized for its regional relevance, consistency, and transparency. Where Ecolnvent data were missing or overly generic, supplementary values were sourced from peer-reviewed literature within a curated set of peer-reviewed LCA studies relevant to modular manufacturing and validated through expert feedback (Majstorovic et al., 2023; Chen et al., 2014).

## **3.9 Calculation Methodology**

To quantify the environmental impact of each module, a structured emission calculation model is employed. This model integrates the key LCI parameters—material mass, electricity use, transport distance, and waste ratio—into a clear and replicable formula. The use of standardized emission factors ensures transparency, comparability, and alignment with internationally recognized LCA practices. The modular setup also supports

quick recalculations when any single parameter changes, making it ideal for high-variability production environments.

- Total Emissions = Material Emissions + Manufacturing Emissions + Transport Emissions
- Material Emissions = Material Mass × Emission Factor for Material
- Manufacturing Emissions = Electricity Consumption × Emission Factor for Electricity
- Transport Emissions = Transport Distance × Emission Factor for Transport

(Note: Waste emissions are included as a separate sub-component. Waste Emissions = Material Mass × Waste Ratio × Emission Factor for Waste.)

A detailed example calculation using the Robotic Feeder Module is provided in **Appendix A** to illustrate how the framework integrates material, energy, transport, and waste parameters into the emissions calculation.

### 3.10 Limitations and Assumptions

Although the Excel-based LCA framework has been developed with flexibility and modularity in mind, several limitations and assumptions must be acknowledged to ensure accurate interpretation of results.

#### 3.10.1 Key Assumptions:

- **Cradle-to-gate boundary:** The framework excludes the product's use phase and end-of-life treatment, if these stages either fall outside the manufacturer's control or vary widely based on customer-specific usage scenarios.
- **Default transport distances:** Transport emissions are calculated using a default distance of 50 km for intra-factory movement or supplier-to-factory delivery unless modified by the user.
- **Material waste ratios:** Waste is applied as a fixed percentage (usually between 2–5%) across all modules and materials. This standardization simplifies calculations

but may not capture nuanced differences between material types or processing techniques.

- **Electricity mix:** The emission factor for electricity assumes a generalized medium-voltage supply, which may not reflect regional or supplier-specific variations unless customized.
- **Static emission factors:** Unless manually updated, the emission factors remain constant over time, which may limit the tool's responsiveness to changes in upstream production technologies or emission baselines.

### 3.10.2 Limitations:

- The framework does not model interactions between modules (e.g., shared energy consumption) or consider the influence of operational efficiency in assembly.
- It assumes that emissions increase at a constant rate as the amount of material increases. However, in real factories, this is not always true. For example, when companies produce in large batches, they often become more efficient and generate fewer emissions per unit. Also, setting up a machine may use the same amount of energy whether it's producing one piece or a hundred. This tool does not constitute those types of proficiency.
- While designed for modular manufacturing, the tool's flexibility is constrained by the structure of Excel itself while designed for modular manufacturing. It also may be less suitable for highly automated or real-time LCA applications.

The framework offers a practical and scalable method for conducting comparative, configuration-specific environmental assessments during the early design and manufacturing stages despite these above-mentioned shortcomings. Its modular design confirms traceability and adaptability. It also maintains ease of use, supports broader adoption of LCA in industrial decision-making (Beemsterboer et al., 2020; Majstorovic et al., 2023).

## 4 Results and Discussion

This chapter demonstrates the findings extracted from the developed Excel-based modular Life Cycle Assessment (LCA) tool. It is particularly designed to identify the complexities of conducting environmental assessments for modular metalworking assembly lines. Initially, it outlines the tool's functionality. Furthermore, it emphasises its adaptive structure capable of easily operating different product configurations. Two customer scenarios have been created to practically illustrate the tool's application and effectiveness. This chapter critically situates the developed tool within broader advancements in modular LCA practices. The chapter also demonstrates its potential to make environmental evaluations more feasible and scalable which results in modular metalworking industries where customer-specific product configurations are increasingly common.

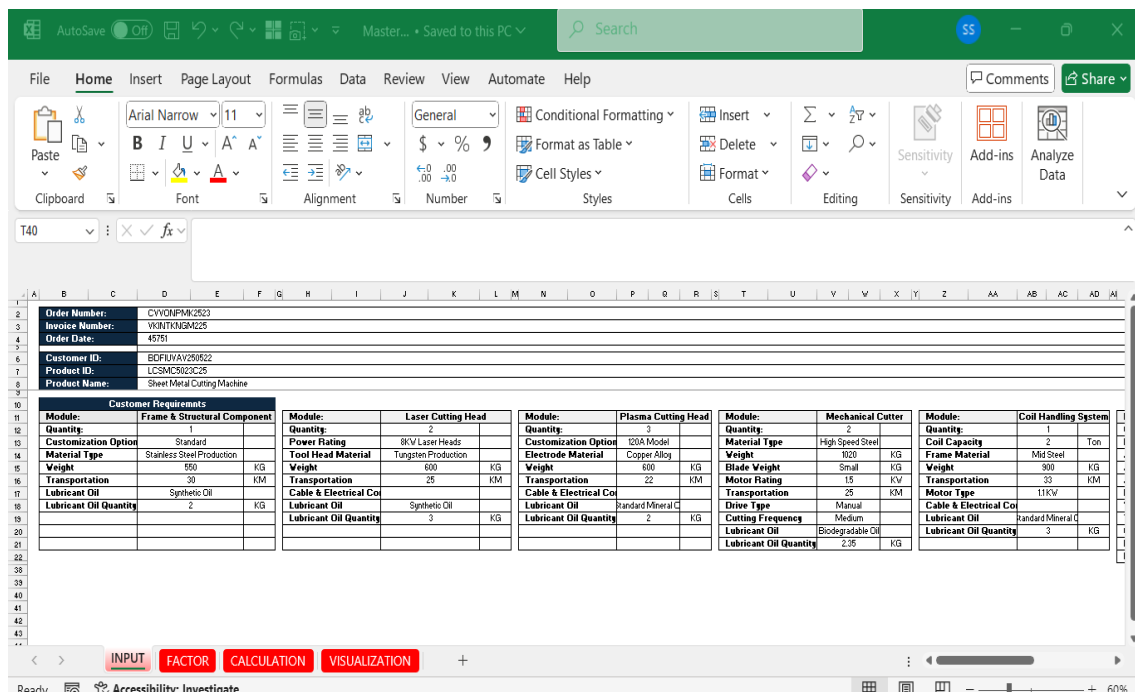
### 4.1 Demonstration of the Excel-Based LCA Tool

The Excel tool was designed to simplify LCA calculations for modular metalworking assembly lines. It integrates an intuitive interface where users can input data quickly and efficiently. Key sections of the tool include fields for entering customer order details (e.g., order number, customer ID, and invoice date), module selection from drop-down menus, weight and energy consumption inputs, and options for selecting the type of lubricant oil used in production.

Each selected module automatically pulls emission factors and material use parameters from a linked database located within the 'FACTOR' sheet, ensuring consistency and minimizing manual errors. Once the modules are selected, the tool instantly calculates cradle-to-gate greenhouse gas emissions by aggregating emissions from material production, energy usage, and auxiliary processes like packaging and cabling. The cardboard packaging emissions are applied universally across all module selections, reflecting real-world manufacturing practices where protective packaging is always required. In addition, cable electronic components are factored based on the module's weight, aligning with typical industrial scaling methods for material consumption. This streamlined automatic input

significantly reduces user workload and enhances the reliability of the assessment results by minimizing inconsistencies during data entry.

The 'Calculation' sheet consolidates these inputs and performs background calculations using embedded formulas, while the 'Visualization' sheet translates the output data into graphical representations for easy interpretation.



**Image 3:** Overview of the Excel Tool Main Interface showing customer order fields and input area

Image 3 shows the main input interface of the developed Excel-based LCA tool. At the top, users can enter essential customer order details such as Order Number, Invoice Number, Order Date, Customer ID, Product ID, and Product Name. This structured data capture ensures traceability and consistency across different orders. Below this section, the tool provides organized tables for individual module entries under "Customer Requirements." Each module, such as Frame & Structural Component, Laser Cutting Head, Plasma Cutting Head, Mechanical Cutter, and Coil Handling System, includes input fields for quantity, material type, customization options, weight, transportation distance, lubricant oil selection, and

lubricant oil quantity. The dropdown menus and direct input fields enable users to customize each module's environmental parameters quickly. This comprehensive setup supports modular calculations, where each module's emissions and material impacts are individually considered and automatically integrated into the overall cycle assessment.

Order Number:	CVVONPMK2523	
Invoice Number:	VKINTKNGM225	
Order Date:	45751	
Customer ID:	BDFIUAV250522	
Product ID:	LCSMC5023C25	
Product Name:	Sheet Metal Cutting Machine	
<b>Customer Requirements</b>		
<b>Module:</b>	<b>Frame &amp; Structural Component</b>	
Quantity:	1	
Customization Option:	Standard	
Material Type:	Stainless Steel Production	
Weight:	Steel Production	KG
Transportation:	Stainless Steel Production	KM
Lubricant Oil:	Aluminium Production	
Lubricant Oil Quantity:	2	KG
<b>Module:</b>	<b>Laser Cutting Head</b>	
Quantity:	2	
Power Rating:	8KW Laser Heads	
Tool Head Material:	Tungsten Production	
Weight:	600	KG
Transportation:	25	KM
<b>Cable &amp; Electrical Component</b>		
Lubricant Oil:	Synthetic Oil	
Lubricant Oil Quantity:	3	KG

**Image 4:** Module Selection Drop-Down Menus and input options

Image 4 shows how drop-down menus are embedded within the input sheet. Users can select predefined options for key parameters such as material type (e.g., Stainless Steel Production, Aluminum Production) and tool head material. The use of drop-down menus ensures standardized data entry, minimizes user errors, and allows quick customization for different product modules. This system enhances user experience and supports consistency across multiple customer orders in the environmental impact calculations.

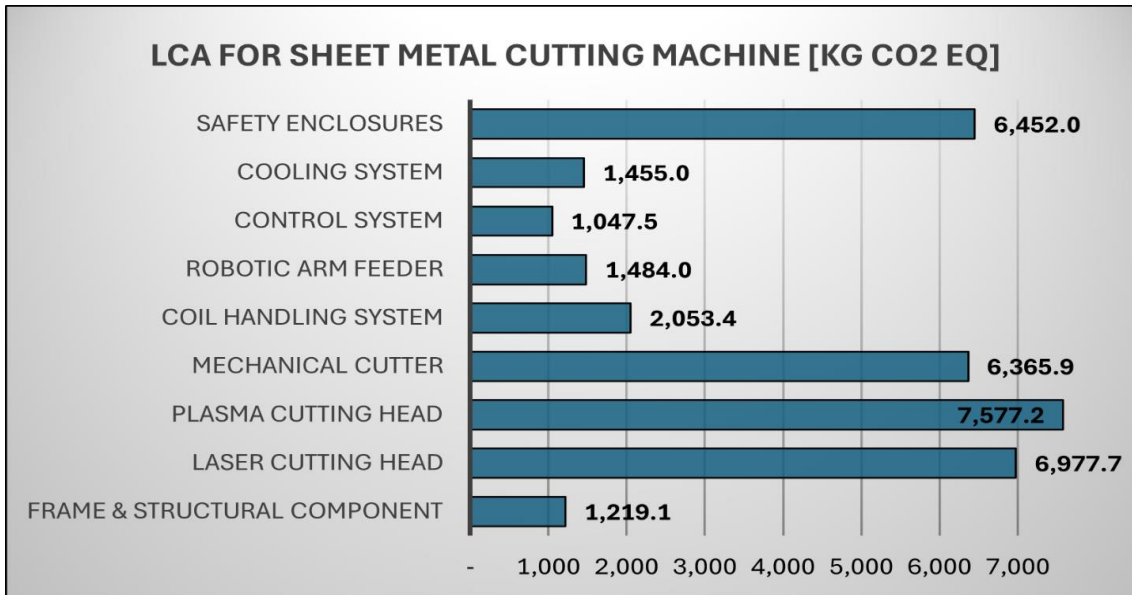
The screenshot shows an Excel spreadsheet titled "LCA Calculation Sheet Metal Cutting Machine". The spreadsheet is organized into four columns, each representing a different module of the machine. Each module has a table of energy consumption and material waste values, followed by an "Impact Calculation" table showing manufacturing, material, and transportation emissions. A formula bar at the top shows a complex IF statement for cell D11. The bottom of the spreadsheet has a navigation bar with "INPUT", "FACTOR", "CALCULATION", and "VISUALIZATION" tabs.

Module:	Frame & Structural Component	Module:	Laser Cutting Head	Module:	Plasma Cutting Head	Module:	Mechanical Cutter
Welding	955.25 KWH	Welding	1,047.60 KWH	Welding	1,050.30 KWH	Welding	1,999.20 KWH
Drilling	0.73 KWH	Drilling	0.83 KWH	Drilling	0.64 KWH	Drilling	0.77 KWH
Cutting	1.17 KWH	Cutting	1.03 KWH	Cutting	1.63 KWH	Cutting	1.07 KWH
Bending	0.70 KWH	Bending	- KWH	Bending	- KWH	Bending	- KWH
Material Waste	15.15 KG	Material Waste	19.40 KG	Material Waste	18.30 KG	Material Waste	22.63 KG
<b>Impact Calculation</b>		<b>Impact Calculation</b>		<b>Impact Calculation</b>		<b>Impact Calculation</b>	
Manufacturing	488.17 kg CO2 eq	Manufacturing	737.72 kg CO2 eq	Manufacturing	600.95 kg CO2 eq	Manufacturing	1,069.32 kg CO2 eq
Emission from material	3,382.50 kg CO2 eq	Emission from material	3,474.00 kg CO2 eq	Emission from material	2,448.00 kg CO2 eq	Emission from material	3,100.80 kg CO2 eq
Transportation	12.38 kg CO2 eq	Transportation	11.25 kg CO2 eq	Transportation	9.90 kg CO2 eq	Transportation	19.13 kg CO2 eq
<b>Total</b>	<b>3,883.04 kg CO2 eq</b>	<b>Total</b>	<b>8,445.94 kg CO2 eq</b>	<b>Total</b>	<b>9,176.55 kg CO2 eq</b>	<b>Total</b>	<b>8,378.50 kg CO2 eq</b>

**Image 5: Calculation Area Showing Automatic Impact Summation**

Image 5 displays the calculation sheet where the Excel-based LCA tool automatically aggregates energy consumption, material waste, and greenhouse gas emissions for each selected module. For example, for the Laser Cutting Head and Plasma Cutting Head, the sheet shows specific energy use for welding, drilling, and cutting operations, alongside material waste values. Below that, total emissions are calculated under three categories: manufacturing processes, emissions from materials, and transportation. These values are dynamically generated based on the user's inputs in the "INPUT" sheet and linked emission factors from the "FACTOR" sheet. This calculation view serves as the backbone of the tool's modular approach, consolidating detailed component-level data into a total carbon footprint per module, enabling fast, traceable, and transparent life cycle assessment.

After entering configuration data, the Excel tool computes carbon emissions on a per-module basis. Each module's emission is automatically calculated by multiplying its weight and material type by the corresponding emission factor. The results are then aggregated to provide a total carbon footprint for a specific product configuration.



**Image 6:** Illustrates the emission distribution across different module types based on the LCA calculations.

**Key observations drawn from the results include:**

- The Plasma Cutting Head emerged as the most emission-intensive module, producing approximately 7,577.2 kg CO<sub>2</sub>-eq. This is attributed to its energy-intensive operation and the nature of materials involved in its function.
- The Laser Cutting Head and Mechanical Cutter followed closely with 6,977.7 kg and 6,365.9 kg CO<sub>2</sub>-eq respectively, confirming the high environmental burden of precision cutting technologies.
- The Safety Enclosures, a non-cutting but substantial structural component, also contributed significantly at 6,452.0 kg CO<sub>2</sub>-eq, likely due to its material volume and weight.
- Mid-range emissions were observed from modules like the Coil Handling System (2,053.4 kg) and Robotic Arm Feeder (1,484.0 kg), highlighting their moderate impact relative to their function.
- Modules such as the Control System (1,047.5 kg) and Cooling System (1,455.0 kg) contributed the least among primary systems, consistent with their lower material demands and energy use.

This visual breakdown confirms that emissions vary significantly across module types, reinforcing the value of a parameterized approach in identifying environmental hotspots and informing design trade-offs.

These findings validate the effectiveness of the parameterized approach and support the use of modular analysis in industrial LCA frameworks focused on metalworking environments.

## 4.2 Example of Customer Cases

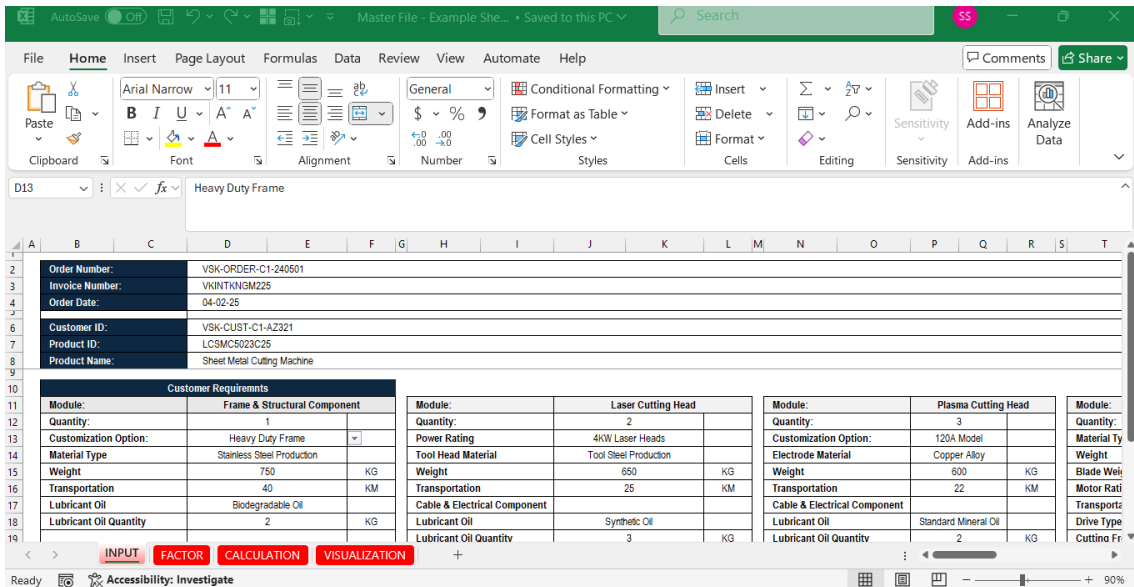
To demonstrate the flexibility and practical functionality of the tool, two hypothetical customer cases were created by placing orders in the Excel framework. These examples serve not only to showcase the tool's capacity to handle varying configurations and parameters but also to simulate how real-life product configurations can be evaluated in terms of their environmental impacts. By walking through distinct customer scenarios, the analysis offers a tangible representation of how emissions are calculated across different modules, providing visual and data-driven proof of how the tool streamlines the LCA process in a modular assembly line context.

	Customer 1	Customer 2
Order Number	VSK-ORDER-C1-240501	VSK-ORDER-C2-240502
Customer ID	VSK-CUST-C1-AZ321	VSK-CUST-C2-BX894
Module Selected	Frame & Structural Component, Laser Cutting Head	Laser Cutting Head, Plasma Cutting Head, Mechanical Cutter

<p>Input Details</p>	<ul style="list-style-type: none"> <li>❖ Frame: Stainless Steel, 750 kg, 40 km transport, 2 kg bio-oil</li> <li>❖ Laser Head: Tool Steel, 650 kg, 25 km transport, 3 kg synthetic oil</li> </ul>	<ul style="list-style-type: none"> <li>❖ Laser Head: Tungsten, synthetic oil</li> <li>❖ Plasma Head: Silver alloy, mineral oil</li> <li>❖ Cutter: High-speed steel, biodegradable oil</li> </ul>
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**Table 1:** Two hypothetical customer cases

### 4.2.1 Impact of Customer 1



**Image 7:** INPUT Sheet for Customer 1 showing selected modules and parameters

Image 7 shows the actual input fields filled in for Customer 1's order. The modules selected were Frame & Structural Component and Laser Cutting Head. These detailed entries provide the basis for the tool's lifecycle impact calculations, linking real-world variables like weight and transport distance to emission factors.

### Calculation Example: Total GHG Emissions for Laser Cutting Head

The table below summarizes the breakdown of total greenhouse gas (GHG) emissions associated with the Laser Cutting Head module selected by Customer 1. Each component contributing to the overall carbon footprint is itemized, including manufacturing energy, lubricant use, transport emissions, and packaging. As shown, manufacturing energy dominates the impact, while other factors such as transport and oil use contribute smaller amounts. Material emissions are excluded in this instance, as defined in the Excel tool for Tool Steel. This example clearly illustrates how the modular LCA tool quantifies environmental impact per module.

Component	Input Value	Emission Factor (kg CO <sub>2</sub> e/unit)	Total Emission (kg CO <sub>2</sub> e)
Manufacturing Energy	1,140.75 kWh	(Excel-calculated)	692.27
Material Emission	-	Tool Steel (excluded)	0.00
Transport Distance	25 km	0.1	12.19
Lubricant Oil	3 kg	1.2	3.60
Packaging	-	Fixed	1.00
<b>Total Emission</b>			<b>1,408.91</b>

**Table 2:** Total GHG Emissions for Laser Cutting Head

=(INPUT!AZ16\*IF(INPUT!AZ13="Mild Steel",FACTOR!AI17,IF(INPUT!AZ13="Aluminium",FACTOR!AI18)))+(INPUT!AZ16\*IF(INPUT!AZ14="Polycarbonate",FACTOR!AI19,IF(INPUT!AZ14="Acrylic",FACTOR!AI20,IF(INPUT!AZ14="Plastic Sheet",FACTOR!AI21))))

**LCA Calculation Sheet Metal Cutting Machine**

Module:	Frame & Structural Component	Module:	Laser Cutting Head	Module:	Plasma Cutting Head	Module:	
Welding	1,316.25 KWH	Welding	1,140.75 KWH	Welding	1,050.30 KWH	Welding	
Drilling	0.73 KWH	Drilling	0.83 KWH	Drilling	0.64 KWH	Drilling	
Cutting	1.17 KWH	Cutting	1.03 KWH	Cutting	1.63 KWH	Cutting	
Bending	0.70 KWH	Bending	- KWH	Bending	- KWH	Bending	
Material Waste	20.65 KG	Material Waste	17.65 KG	Material Waste	18.30 KG	Material Waste	
<b>Impact Calculation</b>		<b>Impact Calculation</b>		<b>Impact Calculation</b>		<b>Impact Calculation</b>	
Manufacturing	665.21 kg CO2 eq	Manufacturing	692.27 kg CO2 eq	Manufacturing	600.95 kg CO2 eq	Manufacturing	
Emission from material	4,612.50 kg CO2 eq	Emission from material	0.00 kg CO2 eq	Emission from material	2,448.00 kg CO2 eq	Emission from material	
Transportation	22.50 kg CO2 eq	Transportation	12.19 kg CO2 eq	Transportation	9.90 kg CO2 eq	Transportation	
<b>Total</b>	<b>5,300.21 kg CO2 eq</b>	<b>Total</b>	<b>1,408.91 kg CO2 eq</b>	<b>Total</b>	<b>9,176.55 kg CO2 eq</b>	<b>Total</b>	

**Image 8:** Calculation Sheet for Customer 1 showing module-level emissions

Image 8 presents automatic calculations based on the inputs from figure 5.4. It summarizes energy consumption, material waste, and emissions by category (manufacturing, material, and transport) for each module.

Overall CO2 Emission			
Name of the module	Overall CO2 Emission	Unit	
Frame & Structural Component	5,300.21	KG CO2 EQ	
Laser Cutting Head	1,408.91	KG CO2 EQ	
Plasma Cutting Head	9,176.55	KG CO2 EQ	
Mechanical Cutter	8,378.50	KG CO2 EQ	
Coil Handling System	3,041.42	KG CO2 EQ	
Robotic Arm Feeder	2,200.36	KG CO2 EQ	
Control System	1,618.20	KG CO2 EQ	
Cooling System	2,243.39	KG CO2 EQ	
Safety Enclosures	7,273.04	KG CO2 EQ	
<b>Total</b>	<b>40,640.59</b>	<b>KG CO2 EQ</b>	

**Table 3:** Table Showing Overall CO2 Emissions by Module for Customer 1

This table 3 presents the numerical CO2 emissions for each module selected by Customer 1. It clearly shows how much each module contributes to the total carbon footprint, offering an alternative to graphical charts for emissions comparison.

### 4.2.2 Impact of Customer 2

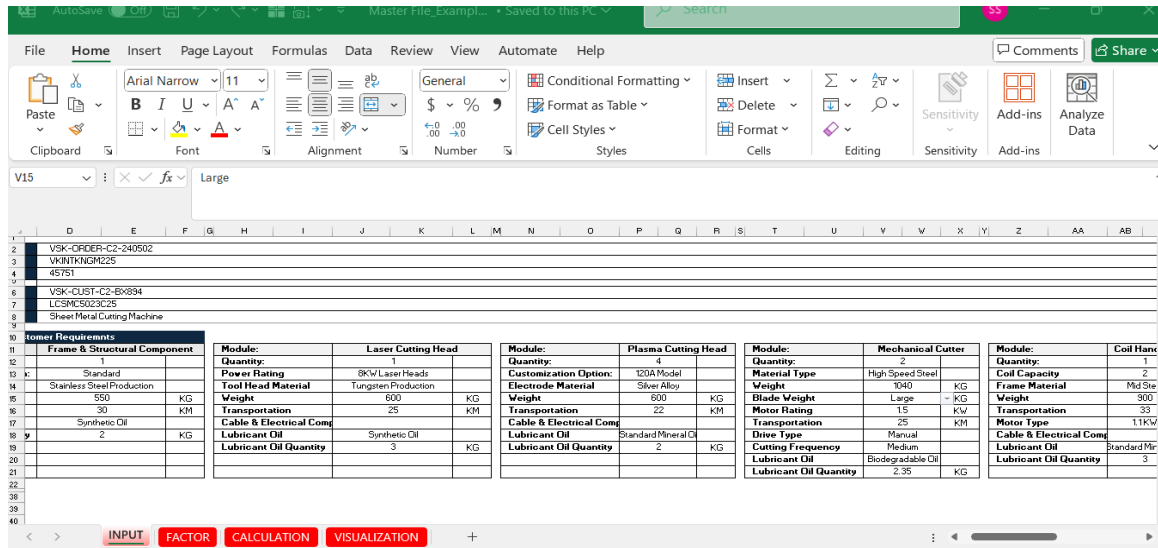


Image 9: INPUT Sheet for Customer 2

Image 9 shows the modules and specifications entered for Customer 2. The selections represent a more resource-intensive configuration compared to Customer 1.

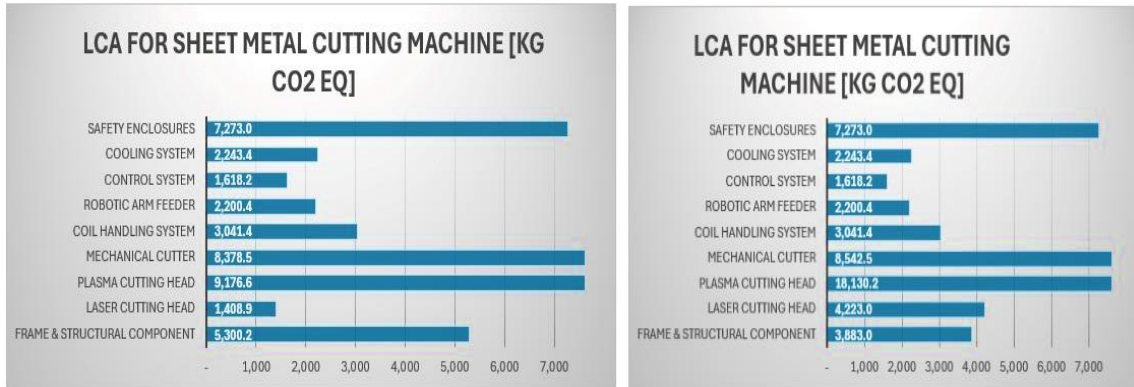
Overall CO2 Emission			
Name of the module	Overall CO2 Emission	Unit	
Frame & Structural Component	3,883.04	KG CO2 EQ	
Laser Cutting Head	4,222.97	KG CO2 EQ	
Plasma Cutting Head	18,130.19	KG CO2 EQ	
Mechanical Cutter	8,542.48	KG CO2 EQ	
Coil Handling System	3,041.42	KG CO2 EQ	
Robotic Arm Feeder	2,200.36	KG CO2 EQ	
Control System	1,618.20	KG CO2 EQ	
Cooling System	2,243.39	KG CO2 EQ	
Safety Enclosures	7,273.04	KG CO2 EQ	
<b>Total</b>	<b>51,155.10</b>	<b>KG CO2 EQ</b>	

**Table 4:** Table Showing Overall CO2 Emissions by Module for Customer 2

This table 4 summarizes the module-wise carbon dioxide emissions calculated for Customer 2. The emission values highlight the heavy contribution from the Plasma Cutting Head and Mechanical Cutter, showing the environmental intensity of Customer 2's configuration.

#### 4.2.3 Summary Comparison Between the Two Cases

Customer 1 selected a simpler configuration using two modules with moderate material inputs, resulting in relatively lower emissions. In contrast, Customer 2's setup included three heavier and more energy-intensive modules, particularly the Plasma Cutting Head, which produced significantly higher emissions. This comparison illustrates the process of module selection and material selection that affect environmental outcomes directly.



**Image 10:** Bar Chart Comparing Emission Contributions by Module of Customer 1(Left) and Customer 2(Right)

Image 10 relates the greenhouse gas emissions by module across both customer cases. It affirms that Customer 2's configuration leads to higher total emissions, especially from the Plasma Cutting Head and Mechanical Cutter. Identifying emission hotspots and comparing configuration impacts are supported by the value of modular analysis.

### 4.3 Discussion

The modular LCA methods conducted here respond to different persistent challenges observed in traditional LCA processes. Studies by Shafiee and Brennan (2022) and Willersinn et al. (2020) demonstrate that traditional LCA methods struggle with integrating high variability among products. Again, it is root-cause of time-consuming and resource-intensive analyses. The tool incorporates a parameterization strategy after the findings are identified. It results in recommendation of researchers such as Mair et al. (2020) and Zimmermann et al. (2017) so that operational efficiency can be extended without heavily compromising accuracy of analytics.

The efficiency of operating the Life Cycle Assessments (LCAs) in modular manufacturing process can be increased significantly by using excel-based tool. It allows clients to insert standardized parameters such as module type, weight, and energy consumption so that

cradle-to-gate emissions can be estimated automatically and the requirement of entire product systems from the initial stage can be minimized.

Adopting a modular LCA perspective associated with the current development identified by researchers like Cucurachi et al. (2018) and Lesage et al. (2018) advocating for modularization as well as the reuse of environmental information through similar product variations and that results in minimizing duplication of tasks. This approach significantly develops transparency, adaptability, and scalability. These attributes are crucial for industries that face instant product innovation cycles (Lo-lacono-Ferreira et al., 2017).

This framework presents significant progress. But it also comes with trade-offs. As per Arvidsson et al. (2017) and Laurent et al. (2020), granularity can be minimized through streamlined complex product systems into modular elements. It can affect the precision of determining impact and rely on average data and generalized emission factors in lieu of case-specific measurements. And it lead to uncertainties (Laurent et al., 2019).

#### **4.3.1 Benefits:**

- The tool has intuition and decreases in time required for frequent LCA tasks, associating fast scenario assessments (Gautam et al., 2020).
- The modular structure aids reusability of prior evaluated elements along with a method that is supported by research on parameterized LCAs in engineering process (Zimmermann et al., 2018).
- This method makes the production of Environmental Product Declarations (EPDs) faster particularly in industries with high customization like metalworking (Liu et al., 2019).
- This method supports instantly in the identification of emission hotspots at the module phase, and it is vital for continuous product design and material selection (Mousavi et al., 2021).

#### 4.3.2 Trade-Offs and Limitations:

- The model offers a simplified route. It is unable to analyze the high-resolution granularity of a comprehensive OpenLCA analysis (van der Harst & Potting, 2015).
- The emission consequences depend heavily on the embedded emission factor datasets. It may also simplify complex industrial processes (Lesage et al., 2018).
- Lifecycle emissions are calculated by the tool that assumes static transport and energy use. It may vary from real operational settings or region-specific variables (Favi et al., 2017).

#### 4.4 Implications for Industry

This framework shares strategic advantages to modular metalworking companies. It also streamlines the sustainability assessments and increasing responsiveness to environmental challenges. Allowing quicker estimations of environmental impacts, companies can react more swiftly to customer requests for transparency and eco-efficiency. It is a growing apprehension in industries with mass customization (Silva et al., 2021). The tool also advocates compliance with environmental standards such as ISO 14040 and ISO 14044, incorporation of defined lifecycle analysis practices (Li et al., 2020).

During the early design phases, this kind of modular tool can cooperate engineers in selecting more sustainable materials and configurations. It aligns with findings by Oberg et al. (2018) regarding design-integrated LCA strategies. The framework contributes to decreased time and cost expenditures by removing the frequent requirements to conduct entire and individual LCA studies for every product variant and is mentioned in modular product evaluation studies (Kraatz et al., 2020).

#### 4.5 Key Findings and Summary

The reasonable analysis supports the value of modular evaluation between Customer 1 and Customer 2. Customer 1's simplified configuration demonstrates minimum

environmental impact. On the other hand, Customer 2's higher emission outcome highlighted the significance of material and module selections. This demonstrates the ability of the framework to support environmental decision-making using instant and transparent comparisons.

In this section it is shown how the Excel-based modular LCA tool acts and presents results from two example customer cases. The framework focuses the benefits of using a simplified model and also acknowledge the trade-offs between speed and correctness. The framework presents a realistic approach of doing LCA calculation faster, easier, and more straightforward for modular assembly production lines.

## **5 Conclusion**

In this chapter, the thesis work concludes by summing up the main findings and assessing how the research objectives were met. It demonstrates indication on the key contributions to both academic knowledge along with industrial practice and discusses the limitations of the developed tool. Practical implications for modular manufacturing and recommendations for future research are also outlined. The chapter finishes with end remarks emphasizing the significance of simplified and accessible LCA tools for advancing sustainability in modular systems.

### **5.1 Summary of Main Findings**

This research developed an Excel-based modular Life Cycle Assessment (LCA) tool specifically constructed for modular metalworking assembly lines and identification of notable challenges of traditional LCA methods. Traditional LCA models usually face significant limitations and deal with the excessive variability with frequent reconfigurations characteristic of modular manufacturing environments. These conventional approaches often require separate, exhaustive assessments for each unique product variation. It causes inefficiencies, substantial time demands, and high resource consumption.

By applying a parameterized approach, this Excel-based tool drastically streamlined the complexity associated with environmental impact evaluations. Parameterization facilitates rapid and flexible calculations which has automatic impact estimations based on measurable product attributes such as material type, weight, and energy consumption, substantially minimizing time for calculation and requirements for resources without compromising accuracy. It was demonstrated how effective the tool was through two comprehensive customer case studies. Firstly, confirming its capability to provide rapid, reliable, and secondly transparent environmental impact assessments. Thereby increasing practical usability along with decision-making efficiency within modular manufacturing settings.

## **5.2 Achievement of Research Objectives**

The primary research objective—to simplify and accelerate the LCA process for modular manufacturing—was successfully accomplished through the development and application of a structured, parameter-driven Excel tool. The framework addressed challenges identified in modular assembly line contexts, such as the inefficiencies of conducting full-scale LCAs for every product variation. By integrating modularity and parameterization, the tool enabled automated environmental assessments that reduced both time and technical complexity while maintaining reliability. Moreover, the Excel interface supported repeatable, consistent input structures that facilitated usability for practitioners without LCA expertise. These qualities demonstrate that both the primary and secondary research objectives were effectively achieved, particularly the goals of enhancing flexibility, transparency, and industrial applicability.

## **5.3 Contribution to Knowledge**

This research contributes meaningfully to the growing field of sustainable manufacturing by presenting a structured and accessible tool that integrates modular design principles with life cycle assessment methodologies. The tool introduced in this thesis offers a real-world application that reduces redundancy and improves efficiency in environmental impact calculations. It demonstrates that modularization enables higher levels of reusability and scalability in LCA execution. The contribution of this work lies in its ability to operationalize these concepts into a practical Excel-based format, bridging theoretical insights with an adaptable solution suitable for modular metalworking environments.

## **5.4 Practical Implications**

The developed Excel-based modular LCA tool provides several key advantages that align with the needs of modern modular metalworking industries. The ability to conduct rapid environmental assessments without extensive technical knowledge directly addresses the demand for simplified and transparent sustainability tools in industrial contexts. By

reducing the reliance on full LCA software platforms, the tool enables broader adoption of LCA practices within manufacturing companies, especially those that handle frequent product customization and modular variations. Moreover, the parameter-driven structure allows for the consistent reuse of module-specific impact data, which enhances both operational efficiency and the accuracy of comparative assessments. Embedding modular environmental tools into daily decision-making processes empowers engineers and product developers to integrate sustainability considerations more proactively during design and planning stages. This positions the framework as a practical and scalable solution for supporting long-term environmental goals in manufacturing environments.

## 5.5 Limitations of the Study

Despite its clear advantages, this study has several limitations that should be acknowledged to contextualize its findings and guide future development:

- **Use of Generalized Emission Factors:** The tool employs standard emission factors that are not customized to reflect the variability in industrial processes or region-specific production systems. This may result in less accurate representations of environmental impacts for certain configurations.
- **Static Input Assumptions:** Transportation distances, energy consumption rates, and material sources are based on fixed assumptions. These may deviate from real operational scenarios, especially in dynamic manufacturing environments where processes vary frequently.
- **Limited Lifecycle Scope:** The tool focuses on cradle-to-gate assessments. It does not account for end-of-life phases such as disposal, reuse, or recycling, which are critical components in full sustainability evaluations.
- **Simplified User Interface Constraints:** While the Excel-based platform promotes usability, its flexibility is constrained compared to more advanced LCA software that allows scenario modelling or integration with real-time factory data.

These limitations highlight areas where future improvements can enhance the precision, scope, and application breadth of the tool.

## 5.6 Recommendations for Future Research

Future research should focus on enhancing the accuracy and contextual relevance of the LCA tool's impact database. This can be achieved through the following avenues:

- **Integration of Industry-Specific Emission Factors:** Developing datasets that reflect process- and region-specific values would greatly increase the credibility and precision of the tool.
- **Incorporation of Real-Time Operational Data:** Embedding IoT-enabled sensors or data logging systems into production processes could allow for real-time energy use, material consumption, and emissions data to be directly fed into the LCA tool. This would not only improve precision but also allow dynamic decision-making.
- **Expansion to Full Lifecycle Analysis and Impact Categories:** Future improvements to the Excel-based modular LCA tool should not only include the end-of-life stages, such as reuse, recycling, and disposal, but also incorporate a broader range of environmental impact categories. Global warming potential (GWP) causes further impact indicators such as acidification, eutrophication, ozone depletion, and human toxicity which should be integrated to offer a more holistic view of environmental performance. If these categories are included, it would align the tool closer along with international LCA standards strengthening its utility in comprehensive sustainability evaluations. This study also focused on cradle-to-gate emissions and future research should expand the scope to include end-of-life stages such as recycling, reuse, and disposal. The significance of these phases and increasing in circular economy models. They are decisive for a holistic sustainability assessment.
- **Adaptation to Other Industrial Domains:** The modular framework established in this research is suitable for metalworking assembly lines. It might be adapted and experimented

in other industries like electronics or automotive manufacturing to explore its cross-sector applicability and scalability. Integration of the tool with enterprise systems such as Enterprise Resource Planning (ERP) or Product Lifecycle Management (PLM) platforms could be explored by further enhancement and this integration would enable continuous data exchange between design, production, and sustainability teams, further enhancing decision-making and operational efficiency.

## **5.7 Concluding Remarks**

Overall, this research has demonstrated the value of modular thinking in sustainability assessments by offering a pragmatic and accessible solution to common barriers in Life Cycle Assessment (LCA) implementation. The Excel-based tool supports faster and more consistent evaluations across modular product configurations, which is particularly relevant in industries where customizability and rapid product turnaround are critical. The framework contributes to operationalizing sustainability principles by embedding simplified LCA into daily workflows and decision-making processes. This research validates the practicality of a modular, parameter-driven approach and encourages broader adoption of LCA methods in real-world manufacturing settings that might otherwise lack the expertise or resources to conduct full-scale assessments.

## **Acknowledgement of Writing Support Tools**

This thesis has benefited from the use of digital writing support tools to enhance the clarity and grammatical accuracy of the text. Grammarly was used to identify and correct language-related issues, while **AI-based assistance (ChatGPT)** was utilized to support academic expression, structure refinement, and consistency in writing style.

All intellectual content, research design, analysis, and interpretation presented in this work are solely the responsibility of the author. The tools were used strictly for language enhancement and did not influence the originality or substance of the research findings.

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## Appendices

### Appendix A: Example Module Calculation – Robotic Feeder

Example Calculation: Let's consider the Robotic Feeder Module using the following values from the Excel framework:

Parameter	Value
Material Mass (Steel)	12 kg
Emission Factor for Steel	2.19 kg CO <sub>2</sub> -eq/kg
Electricity Consumption	4.2 kWh
Emission Factor for Electricity	0.50 kg CO <sub>2</sub> -eq/kWh
Transport Distance	50 km
Emission Factor for Transport	0.75 kg CO <sub>2</sub> -eq/ton-km
Waste Ratio	3% (0.03)
Emission Factor for Waste	0.16 kg CO <sub>2</sub> -eq/kg scrap

#### Step-by-step Calculation:

Emission Type	Formula	Result (kg CO <sub>2</sub> -eq)
Steel Emissions	$12 \times 2.19$	26.28
Electricity Emissions	$4.2 \times 0.50$	2.10
Transport Emissions	$(12 \div 1000) \times 50 \times 0.75$	0.45
Waste Emissions	$12 \times 0.03 \times 0.16$	0.0576

**Total Emissions = 26.28 + 2.10 + 0.45 + 0.0576 = 28.89 kg CO<sub>2</sub>-eq**

## **Appendix B. Excel-Based LCA Framework (Tool Access)**

The complete Excel-based modular Life Cycle Assessment (LCA) framework developed for this thesis is available for public access via Google Drive. This tool includes all input sheets, automated calculation modules, emission factors, and data visualization elements used throughout the study.

To explore the framework, please use the following link:

**Google Drive Link:** [Master File](#)

This access is provided to allow for replication, validation, and future development based on the customizable structure of the framework. Please ensure proper citation if used for academic or research purposes.