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MÁSTER EN INGENIERÍA INDUSTRIAL

TRABAJO FIN DE MÁSTER

DEVELOPMENT OF A CONCEPT FOR SUSTAINABILITY-ORIENTED RISK MANAGEMENT IN MANUFACTURING SYSTEMS

Autor: Gonzalo Veuthey

Director: Daniel Schneider

Madrid

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DEVELOPMENT OF A CONCEPT FOR SUSTAINABILITY-ORIENTED RISK MANAGEMENT IN MANUFACTURING SYSTEMS

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Fdo.: Gonzalo Veuthey Fecha: 22/05/2023

Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

Daniel Schneider

Fdo.: Daniel Schneider Fecha: 22/05/2023

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Acknowledgments

I would like to express my deepest gratitude to my advisor, Daniel Schneider, for his unwavering guidance, experience, and support throughout this project. His encouragement, insightful feedback, and extensive knowledge have been invaluable to me, and I am grateful for the opportunity to work with him on such an exciting and significant topic.

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DEVELOPMENT OF A CONCEPT FOR SUSTAINABILITY-ORIENTED RISK MANAGEMENT IN MANUFACTURING SYSTEMS

Author: Veuthey, Gonzalo
Supervisor: Schneider, Daniel
Collaborating Entity: ICAI – Universidad Pontificia Comillas

ABSTRACT

This thesis presents a tool to accurately and systematically assess the environmental impacts of discrete manufacturing companies located in Germany, with a particular focus on the automotive, mechanical engineering, electrical & electronics, and chemical industries. The tool builds on LCA-based sustainability information obtained to develop a risk management tool to identify sustainability risks. The thesis demonstrates the feasibility of incorporating the results into financial risk analysis and highlights the potential benefits for investors interested in assessing the sustainability of their investments.

Keywords: Sustainability Risk Assessment (SRA), Life Cycle Assessment (LCA), Failure Mode and Effect Analysis (FMEA), Capital Asset Pricing Model (CAPM), Manufacturing Companies

1. Introduction

In recent decades, research on sustainability has grown steadily. For socio-political reasons, both governments and private institutions are increasingly investing in further research on this topic. The introduction of regulatory schemes such as the EU Emissions Trading Scheme (EU ETS) in industry has created a growing economic interest in adopting more sustainable production practices. In addition, the implementation of legal requirements to become more sustainable has increased and tends to become even more relevant in the future, especially in industrial applications.

However, sustainable manufacturing is a very complex issue due to the large number of stakeholders involved, such as manufacturers, suppliers, consumers, vendors, and recyclers. This level of complexity leads to disagreement on how to accurately assess the sustainability of manufacturing. Scientists have not found a unique and holistic way to weigh and compare sustainability performance, resulting in inconsistent results depending on the aspects analyzed. One established method for assessing sustainability is Life Cycle Assessment (LCA), a tool used to calculate the environmental impact of a product over its entire life cycle, potentially from cradle to grave.

Often, LCA results are processed without further contextualization, and the full potential of these results for operational risk management is not realized. Certain sustainability deficiencies not only pose reputational risks to a company, but can also lead to operational problems.

2. Objective of the Project

The manufacturing sector is one of the largest contributors to greenhouse gas emissions and resource depletion, making it a critical area for sustainable development. While there is a growing need for sustainability risk management in manufacturing systems, there is still a lack of practical tools that manufacturing companies can use to assess and manage sustainability risks. In addition, existing tools mainly focus on CO_2 emissions, energy and water consumption, while there are other very serious impact categories that need to be further explored and considered to gain a holistic view of a company's sustainable performance. Therefore, the objective of this thesis is to propose a risk management tool to assess manufacturing-related sustainability risks based on LCA sustainability data. Despite increasing research efforts on sustainability and its assessment, such a tool has not yet been successfully implemented. It could be the first step towards a more established tool in the future to systematically identify and assess the environmental impact of a manufacturing company.

3. Selection of 15 Impact Categories and its Threshold Values

According to the LCA-based sustainability information, there are fifteen impact categories that influence a company's sustainability performance. Each impact category was analyzed in detail to determine the threshold values that ultimately categorize the risk level of companies (low, medium, and high risk).

Table 1 below provides an overview of the thresholds for 8 of the 15 impact categories analyzed throughout the work for two industries. The remaining industries and impact categories can be found later in this thesis.

Table 1: Overview of the threshold values for 8 impact categories out of 15 for two industries

		Automotive Industry		**Mechanical Engineering**	
Impact Category	**Impact Indicator Unit**	**Low Values**	**High Values**	**Low Values**	**High Values**
Climate change	tons CO_2 eq emitted/M€ Revenue	10,07	15,11	10,97	16,46
Stratospheric ozone depletion	kg CFC-11 eq/M€ Revenue	2,16	3,24	2,35	3,53
Fine particulate matter formation	µg/m^3 air	10	20	10	20
Photochemical ozone formation	t C_2H_4 eq emitted/M€ Revenues	2,72	4,08	2,97	4,45
Acidification	µg SO_2 eq/m^3 air	15	20	15	20
Land use	tons soil loss eq/M€ revenue	967,4	1451,0	1346,0	2019,0
Water use	m^3 freshwater withdrawn/M€ Revenue	70,5	105,8	1813,3	2719,9
Resource depletion (fossils)	MWh eq Energy consumed/M€ Revenue	45,62	68,43	358,28	537,41

Some of the values were taken from EU standards that define the level of risk to humans, animals or the natural environment. In other cases, where EU standards were not available, the average of the top five companies in each industry was calculated and normalized using the revenue generated. This approach provides a normalized assessment of emissions intensity that takes into account differences in company size and products. It also provides a more comprehensive understanding of the relative emissions intensity associated with revenue generation in each industry in the German context. By comparing a company's emissions to industry averages and applying risk thresholds, this approach helps to identify companies that may be contributing more or less to each of the impact categories and provides valuable insights into the financial and sustainability performance of companies.

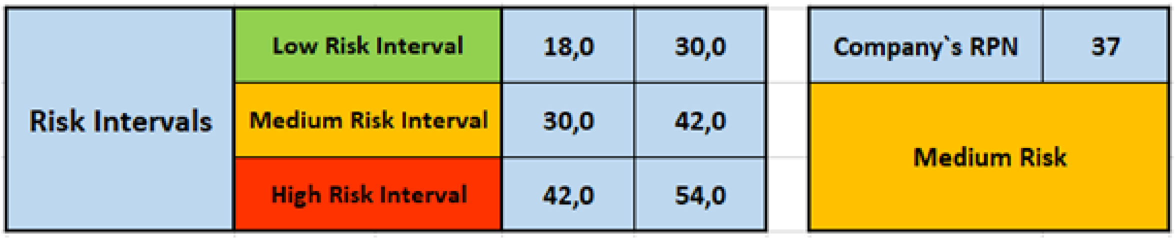
4. Risk Priority Number

The methodology used to assess and prioritize risks is Failure Mode and Effects Analysis (FMEA), which determines the company's risk according to the Risk Priority Number (RPN). The RPN is calculated using the following formula:

$$RPN = \sum_i SRV_i * O_i * D_i \tag{1}$$

where SRV is the Severity Risk Value Indicator, O is the Occurrence Factor and D is the Detection Indicator. This operation is performed for each of the 15 impact categories, and the values are then added together. Within each industry, an in-depth analysis of the financial performance and sustainable performance of the top five companies in each industry (based on revenue generated) was conducted.

The output of the tool is shown in Figure 1 below, which shows the low, medium and high-risk intervals for the weightings introduced (as they may vary from company to company) and derives the overall risk of the company.



Risk Intervals	Low Risk Interval	18,0	30,0
	Medium Risk Interval	30,0	42,0
	High Risk Interval	42,0	54,0

Company`s RPN	37
Medium Risk	

Figure 1: Example of the risk intervals and the overall company's RPN (Source: Own representation)

5. Financial Risk Analysis

The possibility of incorporating the results of sustainability risk assessment into financial risk analysis using the Capital Asset Pricing Model (CAPM) was explored. The CAPM is a widely used financial model that helps investors evaluate the expected return on an investment. The lack of an effective way to account for sustainability or environmental factors within the CAPM was addressed by including an additional variable called γ_{sust}. The formula used is the following:

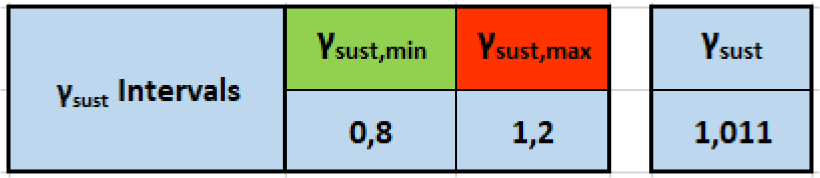
$$E(R_i) = R_f + \beta_i * \boldsymbol{\gamma_{sust}} * \left(\mathrm{E}(R_m) - R_f \right), \tag{2}$$

where $E(R_i)$ is the expected return an investor expects to receive from an investment in the asset, R_f is the risk-free rate, which is the rate of return on a risk-free investment such as a

U.S. Treasury bond (typically analyzed over a 10-year period), β_i is a measure of the volatility of an asset relative to the market, γ_{sust} is the sustainability indicator for each company and $\mathrm{E}(R_m)$ is the expected return of the market in which the company operates. γ_{sust} is calculated as follows:

$$\gamma_{sust} = \gamma_{sust,min} + (\mathrm{RPN} - RPN_{\min}) * \frac{(\gamma_{sust,\max} - \gamma_{sust,min})}{(RPN_{max} - RPN_{min})}, \tag{3}$$

The output of the tool including γ_{sust} is the following:



γ_{sust} Intervals	$\gamma_{sust,min}$	$\gamma_{sust,max}$		γ_{sust}
	0,8	1,2		1,011

Figure 2: Example of the output of the tool including γ_{sust} and its intervals (Source: Own representation)

The overall result of the methodology is that the more sustainable a company is, the lower the risk for investors to invest in it, and therefore the lower the expected return.

6. Conclusions

The objective of this thesis is to develop a tool to accurately and systematically assess the environmental impact of a manufacturing company. The development of this tool contributes to the advancement of sustainability risk management in manufacturing systems. The tool provides best practices compared to the industry leader and identifies potential areas for improvement. In addition, the tool allows for the comparison of sustainability risks associated with different manufacturing processes or companies within the same industry, providing valuable insights for manufacturing decision makers. Finally, the thesis demonstrates the feasibility of incorporating sustainability risk assessment results into financial risk analysis, highlighting the potential benefits for investors and analysts interested in assessing the sustainability of their investments.

DEVELOPMENT OF A CONCEPT FOR SUSTAINABILITY-ORIENTED RISK MANAGEMENT IN MANUFACTURING SYSTEMS

Autor: Veuthey, Gonzalo
Director: Schneider, Daniel
Entidad Colaboradora: ICAI – Universidad Pontificia Comillas

RESUMEN DEL PROYECTO

Esta tesis presenta una herramienta para evaluar de forma precisa y sistemática los impactos ambientales de empresas de fabricación discreta ubicadas en Alemania, con especial énfasis en las industrias de automoción, ingeniería mecánica, eléctrica y electrónica, y química. La herramienta se basa en la información de sostenibilidad obtenida según el Life Cycle Assessment (LCA) para desarrollar una herramienta de gestión de riesgos para identificar los riesgos de sostenibilidad. La tesis demuestra la viabilidad de incorporar los resultados al análisis de riesgos financieros y destaca los potenciales beneficios para los inversores interesados en evaluar la sostenibilidad de sus inversiones.

Palabras clave: Evaluación de Riesgos para la Sostenibilidad (ERS), Análisis del Ciclo de Vida (ACV), Análisis Modal de Fallos y Efectos (AMFE), Modelo de Valoración de Activos de Capital (MVAC), Empresas de Fabricación

1. Introducción

En las últimas décadas, la investigación sobre sostenibilidad no ha dejado de crecer. Por razones sociopolíticas, tanto los gobiernos como las instituciones privadas invierten cada vez más en seguir investigando sobre este tema. La introducción de regímenes reguladores como el Régimen Comunitario de Comercio de Derechos de Emisión (RCCDE) en la industria ha creado un creciente interés económico por adoptar prácticas de producción más sostenibles. Además, la aplicación de requisitos legales para ser más sostenibles ha aumentado y tenderá a ser aún más relevante en el futuro, especialmente en las aplicaciones industriales.

Sin embargo, la fabricación sostenible es una cuestión muy compleja debido al gran número de partes interesadas que intervienen, como fabricantes, proveedores, consumidores y vendedores. Este nivel de complejidad provoca desacuerdos sobre cómo evaluar con precisión la sostenibilidad de la fabricación. Los científicos no han encontrado una forma única y exhaustiva de sopesar y comparar el rendimiento de la sostenibilidad, lo que da lugar a resultados incoherentes en función de los aspectos analizados. Un método establecido para evaluar la sostenibilidad es el Life Cycle Assessment (LCA), una herramienta utilizada para calcular el impacto medioambiental de un producto a lo largo de todo su ciclo de vida, potencialmente desde su creación hasta su posible reciclaje.

A menudo, los resultados del LCA se procesan sin mayor contextualización, y no se aprovecha todo su potencial para la gestión de riesgos operativos. Ciertas deficiencias en materia de sostenibilidad no sólo suponen riesgos para la reputación de una empresa, sino que también pueden acarrear problemas operativos.

2. Objetivo del Proyecto

El sector de la fabricación es uno de los que más contribuyen a las emisiones de gases de efecto invernadero y al agotamiento de los recursos, lo que lo convierte en un área crítica para el desarrollo sostenible. Aunque cada vez es más necesaria la gestión de los riesgos de sostenibilidad en los sistemas de fabricación, siguen faltando herramientas prácticas que las empresas puedan utilizar para evaluar y gestionar dichos riesgos. Además, las herramientas existentes se centran principalmente en las emisiones de CO_2 y el consumo de energía y agua, mientras que hay otras categorías de impacto muy graves que deben considerarse más a fondo para obtener una visión integral del rendimiento sostenible de una empresa. Por lo tanto, el objetivo de esta tesis es proponer una herramienta de gestión para evaluar los riesgos de sostenibilidad relacionados con la fabricación basándose en los datos de sostenibilidad del LCA. A pesar de los crecientes esfuerzos de investigación sobre la sostenibilidad y su evaluación, todavía no se ha aplicado con éxito una herramienta de este tipo. Podría convertirse en el primer paso hacia una herramienta más consolidada en el futuro para identificar y evaluar sistemáticamente el impacto medioambiental de una empresa de fabricación.

3. Selección de 15 categorías de Impacto y sus Valores Umbral

Según la información sobre sostenibilidad basada en la LCA, existen quince categorías de impacto que influyen en los resultados de sostenibilidad de una empresa. Cada categoría de impacto se analizó en detalle para determinar los valores umbral que, en última instancia, categorizan el nivel de riesgo de las empresas (riesgo bajo, medio y alto).

La Tabla 1, a continuación, proporciona una visión general de los umbrales para 8 de las 15 categorías de impacto analizadas a lo largo del trabajo para dos industrias. El resto de las industrias y categorías de impacto pueden consultarse más adelante en esta tesis.

Tabla 1: Resumen de los valores umbral para 8 de las 15 categorías de impacto de dos industrias

		Automotive Industry		**Mechanical Engineering**	
Impact Category	**Impact Indicator Unit**	**Low Values**	**High Values**	**Low Values**	**High Values**
Climate change	tons CO_2 eq emitted/M€ Revenue	10,07	15,11	10,97	16,46
Stratospheric ozone depletion	kg CFC-11 eq/M€ Revenue	2,16	3,24	2,35	3,53
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Resource depletion (fossils)	MWh eq Energy consumed/M€ Revenue	45,62	68,43	358,28	537,41

Algunos de los valores se obtuvieron a partir de normas de la UE que definen el nivel de riesgo para las personas, los animales o el entorno natural. En otros casos, en los que no se disponía de normas de la UE, se calculó la media de las cinco principales empresas de cada sector y se normalizó utilizando los ingresos generados. Este enfoque proporciona una evaluación normalizada de la intensidad de las emisiones que tiene en cuenta las diferencias de tamaño y productos de las empresas. Al comparar las emisiones de una empresa con las medias del sector y aplicar umbrales de riesgo, este enfoque ayuda a identificar a las empresas que pueden estar contribuyendo más o menos a cada una de las categorías de impacto y proporciona información valiosa sobre los resultados financieros y de sostenibilidad de las empresas.

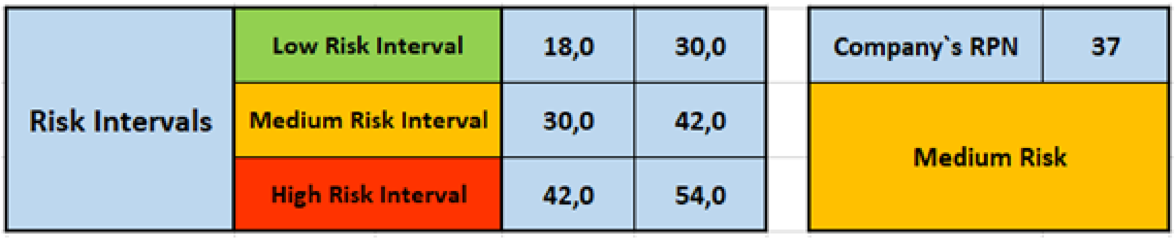
4. Número de Prioridad de Riesgo

La metodología utilizada para evaluar y priorizar los riesgos es el Análisis Modal de Fallos y Efectos (FMEA), que determina el riesgo de la empresa en función del Número de Prioridad de Riesgo (RPN). El RPN se calcula mediante la siguiente fórmula:

$$RPN = \sum_i SRV_i * O_i * D_i \qquad (1)$$

donde SRV es el Indicador de Valor de Riesgo de Gravedad, O es el Factor de Ocurrencia y D es el Indicador de Detección. Esta operación se realiza para cada una de las 15 categorías de impacto, y a continuación se suman los valores. Dentro de cada sector, se realizó un análisis en profundidad de los resultados financieros y del rendimiento sostenible de las cinco principales empresas de cada sector (en función de los ingresos generados).

El resultado de la herramienta se muestra en la Figura 1, que muestra los intervalos de riesgo bajo, medio y alto según las ponderaciones introducidas (ya que pueden variar de una empresa a otra) y obtiene el riesgo global de la empresa.



Risk Intervals			
	Low Risk Interval	18,0	30,0
	Medium Risk Interval	30,0	42,0
	High Risk Interval	42,0	54,0

Company`s RPN	37
Medium Risk	

Figura 1: Ejemplo de los intervalos de riesgo y del RPN global de la empresa (Fuente: Elaboración propia)

5. Análisis de Riesgos Financieros

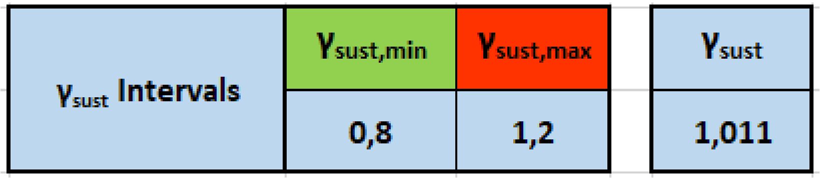
Se estudió la posibilidad de incorporar los resultados de la evaluación del riesgo de sostenibilidad al análisis del riesgo financiero mediante el Modelo de Valoración de Activos de Capital (CAPM). El CAPM es un modelo financiero ampliamente utilizado que ayuda a los inversores a evaluar el rendimiento esperado de una inversión. La falta de una forma eficaz de tener en cuenta la sostenibilidad o los factores medioambientales en el CAPM se abordó mediante la inclusión de una variable adicional denominada γ_{sust}. La fórmula utilizada es la siguiente:

$$E(R_i) = R_f + \beta_i * \boldsymbol{\gamma_{sust}} * \left(\mathrm{E}(R_m) - R_f \right), \qquad (2)$$

donde $E(R_i)$ es la rentabilidad esperada que un inversor espera recibir de una inversión en el activo, R_f es la tasa libre de riesgo, que es la tasa de rentabilidad de una inversión libre de riesgo como un bono del Tesoro de EE.UU. (normalmente analizado en un periodo de 10 años), β_i es una medida de la volatilidad de un activo en relación con el mercado, γ_{sust} es el indicador de sostenibilidad de cada empresa y $\mathrm{E}(R_m)$ es la rentabilidad esperada del mercado en el que opera la empresa. γ_{sust} se calcula del siguiente modo:

$$\gamma_{sust} = \gamma_{sust,min} + (\mathrm{RPN} - RPN_{\mathrm{min}}) * \frac{(\gamma_{sust,\mathrm{max}} - \gamma_{sust,min})}{(RPN_{max} - RPN_{min})}, \tag{3}$$

El resultado de la herramienta que incluye γ_{sust} es el siguiente:



γ_{sust} Intervals	$\gamma_{sust,min}$	$\gamma_{sust,max}$	γ_{sust}
	0,8	1,2	1,011

Figura 2: Ejemplo del resultado de la herramienta, incluidos γ_{sust} y sus intervalos (Fuente: elaboración propia)

6. Conclusiones

El objetivo de esta tesis es desarrollar una herramienta para evaluar de forma precisa y sistemática el impacto medioambiental de una empresa de fabricación. La creación de esta herramienta contribuye al avance de la gestión del riesgo de sostenibilidad en los sistemas de fabricación. La herramienta proporciona las mejores prácticas en comparación con el líder de la industria e identifica áreas potenciales de mejora. Además, la herramienta permite comparar los riesgos de sostenibilidad asociados a diferentes procesos de fabricación o empresas de un mismo sector, lo que proporciona información valiosa a los responsables de la toma de decisiones. Por último, la tesis demuestra la viabilidad de incorporar los resultados de la evaluación del riesgo de sostenibilidad al análisis del riesgo financiero, destacando los beneficios potenciales para los inversores y analistas interesados en evaluar la sostenibilidad de sus inversiones.

Índice de la memoria

Índice de figuras

Índice de tablas

Chapter 1. INTRODUCTION

In recent decades, the subject of sustainability has received considerable attention from both governments and private institutions. As a result, there has been a steady increase in research on sustainability-related topics, driven by socio-political reasons (WERBACH 2011, p. 2). This is largely due to increasing concerns about the negative environmental impacts of human activities, such as carbon emissions and waste generation. In response, governments and organizations are implementing initiatives to reduce their environmental footprint and move towards sustainable practices. The EU Emissions Trading Scheme (EU ETS), launched in 2005, is one of the most significant regulatory schemes aimed at reducing greenhouse gas emissions across Europe. The EU ETS is the largest carbon trading scheme in the world, covering approximately 45% of the European Union's greenhouse gas emissions (EUROPEAN COMMISSION 2016, p. 1). It is a cap-and-trade system that sets a maximum limit on the total emissions of participating industries, while allowing companies to trade pollution allowances with each other. This system creates a market for carbon emissions in which companies with low emissions can sell their excess allowances to companies with higher emissions. Companies that reduce their greenhouse gas emissions below their designated allowances can sell their excess allowances, providing a financial incentive to reduce emissions. In contrast, companies that emit more than their allocated allowances must purchase additional allowances or face penalties (EUROPEAN COMMISSION 2023d).

By putting a price on carbon emissions, the EU ETS is intended to incentivize companies to reduce their greenhouse gas emissions while encouraging the adoption of more sustainable production practices. In parallel, the implementation of other regulatory requirements to become more sustainable has increased, and this trend is expected to become even more important in the future, especially in industrial applications (OECD 2014, pp. 25 - 26). As a result, sustainability has become a key driver of innovation and competitiveness, and companies that adopt sustainable practices can benefit from reduced costs, increased efficiency, and enhanced brand reputation (HARVARD BUSINESS REVIEW 2014).

Nevertheless, sustainable manufacturing is a highly complex issue that involves a diverse range of stakeholders, including manufacturers, suppliers, consumers, vendors, and recyclers. These stakeholders often have different interests and priorities, which can make it more complex to reach consensus on sustainable manufacturing practices. This challenge also makes it difficult to accurately assess the sustainability of manufacturing processes. One of the established methods for assessing sustainability is Life Cycle Assessment (LCA), a tool used to evaluate the environmental impact of a product over its entire life cycle, from raw material extraction to disposal or recycling. However, due to the underlying nature of sustainable manufacturing, even LCA results can be inconsistent depending on the aspects analyzed, and scientists are still searching for a unique and holistic way to weigh and compare sustainability performance (POSINASETTI 2023).

Despite a growing body of research on the use of LCA in sustainability assessment, the full potential of the results is often not realized due to a lack of further interpretation. Sustainability shortcomings can have significant consequences for companies, including reputational risks and operational problems, and there is still a lack of effective risk management tools. Recognizing the need for a right risk management tool, the objective of this thesis is to propose a risk management tool to assess manufacturing-related sustainability risks based on sustainability data. Despite increasing research efforts in sustainability and its assessment, such a tool has not yet been successfully implemented (DELAI & TAKAHASHI 2014, p. 445). This work aims to address this gap and propose such a tool to help companies effectively manage sustainability risks and improve their overall sustainability performance.

1.1 PERSONAL MOTIVATION

The development of sustainable manufacturing systems has become an important topic for both academia and industry in recent years. As someone with a passion for the environment, I was motivated from the beginning to explore this area and contribute to the development of a more sustainable world.

The manufacturing sector is one of the largest contributors to greenhouse gas emissions and resource depletion, making it a critical area for sustainable development. While there is a growing need for sustainability risk management in manufacturing systems, there is still a lack of practical tools that manufacturing companies can use to assess and manage sustainability risks. In addition, existing tools mainly focus on CO_2 emissions, energy and water consumption, while there are other very serious impact categories that need to be further explored and considered to gain a holistic view of a company's sustainable performance. This lack of practical tools is my personal motivation to dive deep into this area and contribute to the development of a tool for LCA-based sustainability risk assessment in manufacturing systems. It could be the first step towards a more established tool in the future to systematically identify and assess the environmental impact of a manufacturing company.

The development of this tool will contribute to the advancement of sustainability-oriented risk management in manufacturing systems by providing a practical and systematic approach to identifying and assessing sustainability risks. The tool will enable manufacturing companies to better understand the environmental impacts of their operations and identify potential areas for improvement. In addition, the tool will make it possible to compare the sustainability risks associated with different manufacturing processes or companies within the same industry, providing valuable insights for manufacturing decision makers.

Through this research, I aim to contribute to the advancement of sustainability-oriented risk management in manufacturing systems that can support the transition to a more sustainable society and fulfill my personal motivation to create a better future for our planet.

1.2 OBJECTIVES OF THE PROJECT

The objective of this thesis is to develop a tool for LCA-based sustainability risk assessment in manufacturing systems. The tool shall build on LCA-based sustainability information obtained to accurately and systematically assess the environmental impact of a manufacturing company. This sustainability information shall then be used in a risk management tool to identify and assess manufacturing sustainability risks. The ultimate goal is to compare the sustainability risks associated with different manufacturing processes of diverse companies within the same industry. To achieve this goal, the following research questions (RQ) need to be answered:

- RQ 1: How can the state of the art regarding sustainability-oriented risk management in manufacturing systems be described?
- RQ 2: How should an approach based on LCA sustainability information for identifying and assessing sustainability risks be developed and prototypically implemented?
- RQ 3: What are the implications of this tool in terms of industrial applications?

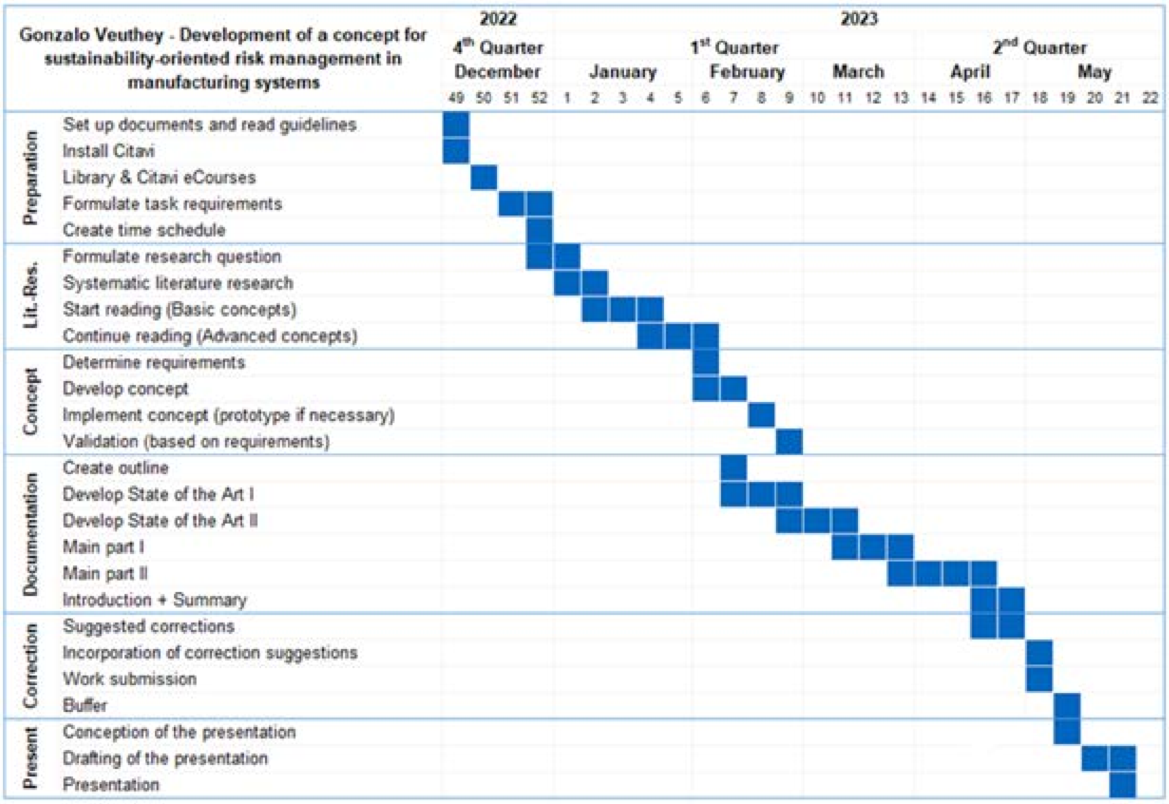
1.3 THESIS METHODOLOGY

The objective of this thesis is to propose a risk management tool to assess the sustainability risks of manufacturing companies based on the information obtained from an LCA. For this purpose, the following work methodology will be applied:

- Familiarization with scientific working methods and procedures
- Introduction to the topics of sustainability, Life Cycle Assessment (LCA), production, and risk management
- Literature research on the state of the art of sustainability risk management in manufacturing systems
- Analysis of the state of the art and definition of a need for action

- Development of an approach for the use of LCA-based sustainability information for the identification and assessment of sustainability risks
- Prototypical implementation of the developed approach in a suitable software environment
- Testing of the application of the concept
- Evaluation and critical discussion of the developed approach
- Summary and outlook for future research

The following Figure 1 shows the time schedule that was planned and followed throughout the thesis. It has been created using a Gantt chart in Excel and includes the relevant topics and milestones that will be covered throughout this work.



Gonzalo Veuthey - Development of a concept for sustainability-oriented risk management in manufacturing systems		2022				2023																					
		4th Quarter				1st Quarter													2nd Quarter								
		December				January				February				March					April				May				
		49	50	51	52	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Preparation	Set up documents and read guidelines	■																									
	Install Citavi	■																									
	Library & Citavi eCourses		■																								
	Formulate task requirements			■	■																						
	Create time schedule				■																						
Lit.-Res.	Formulate research question				■	■																					
	Systematic literature research					■	■																				
	Start reading (Basic concepts)						■	■	■																		
	Continue reading (Advanced concepts)								■	■	■																
Concept	Determine requirements										■																
	Develop concept										■	■															
	Implement concept (prototype if necessary)												■														
	Validation (based on requirements)													■													
Documentation	Create outline											■															
	Develop State of the Art I											■	■	■													
	Develop State of the Art II													■	■	■											
	Main part I															■	■	■									
	Main part II																	■	■	■	■						
	Introduction + Summary																				■	■					
Correction	Suggested corrections																				■	■					
	Incorporation of correction suggestions																						■				
	Work submission																						■				
	Buffer																							■			
Present	Conception of the presentation																							■			
	Drafting of the presentation																								■	■	
	Presentation																									■	

Figure 1: Gantt chart including the topics and timeframe of the thesis (Source: Own representation)

Chapter 2. THEORETICAL BACKGROUND

In this chapter, the fundamental principles of the work will be presented in order to provide the necessary knowledge to achieve the objective of the thesis. After explaining the concept of sustainability and sustainability assessment in section 2.1, section 2.2 provides an overview of risk assessment methodologies. Finally, section 2.3 introduces the key aspects to be analyzed in production and production systems in the industry.

2.1 SUSTAINABILITY AND SUSTAINABILITY ASSESSMENT

The following section will introduce the topic sustainability as well as the sustainability assessment.

2.1.1 GENERAL CONCEPTS ABOUT SUSTAINABILITY

The concept of sustainability has been debated for decades. However, recent socio-political and economic factors have prompted both governments and private entities to invest more in its further exploration. Sustainability was defined by the United Nations Brundtland Commission in 1987 as "meeting the needs of the present without compromising the ability of future generations to meet their own needs” (WORLD COMMISSION ON ENVIRONMENT AND DEVELOPMENT 1987). According to this definition, it is necessary to focus on the present while considering the consequences of our actions. Today, nearly 140 developing countries around the world are striving to achieve their development goals (WORLD BANK 2023). To protect the well-being of future generations, it is essential that these countries prioritize sustainable development to meet their current needs while mitigating the effects of climate change.

To this end, a concept called the Triple Bottom Line (TBL) has been introduced to measure a company's social and environmental impact (SLAPER 2011, p. 4). This concept in sustainable business and corporate social responsibility refers to three dimensions of performance: economic, social, and environmental.

The economic dimension includes financial performance, including profitability and return on investment. The social dimension refers to the impact of a company's activities on society, such as labor standards, community involvement, and human rights. The environmental dimension assesses a company's impact on the natural world, including its carbon footprint, waste management practices, and conservation efforts (SLAPER 2011, pp. 5 - 6). Adopting a triple bottom line approach to decision-making helps companies consider the long-term impact of their actions, rather than focusing solely on short-term financial gains.

Because these three dimensions cover broad and highly differentiated aspects that vary significantly from industry to industry, the United Nations has divided them into 17 Sustainable Development Goals.

2.1.2 SUSTAINABILITY ASSESSMENT

The concept of sustainability assessment is complex and has been widely used in research to evaluate the performance of companies within industries (SINGH ET AL. 2012, p. 281). As stated by NESS ET AL. (2007, p. 499) the objective of sustainability assessment is “to provide decision-makers with an evaluation of global to local integrated nature–society systems in short and long term perspectives in order to assist them to determine which actions should or should not be taken in an attempt to make society sustainable”. Additionally, according to HACKING & GUTHRIE (2008, p. 74), the use of sustainability assessments can further facilitate decision-makers to focus their plans on achieving more sustainable development.

The idea behind sustainability assessment is to analyze, quantify, synthesize, and communicate information. However, due to the large number of stakeholders involved in the manufacturing process, it is a very complex issue that can lead to different results depending on the indicators selected (HACKING & GUTHRIE 2008, pp. 78 - 80). This difficulty leads to discrepancies in how to accurately assess production-related sustainability, especially when different dimensions are measured simultaneously and aggregated into a single value.

Personal judgment plays an important role in determining indices and rating systems, making it difficult for scientists to find a unique and holistic way to weight and compare sustainability performance (NESS ET AL. 2007, p. 499). This is one of the reasons why there are several international efforts to measure sustainability (BUTNARIU & AVASILCAI 2015, p. 1234). However, of all the approaches, only a minority consider all three aspects - environmental, economic and social. In most cases, the focus is only on one of the three aspect (SINGH ET AL. 2012, p. 282), while their interconnection is also essential for the development of the system (SINGH ET AL. 2012, p. 282). If the metrics are not designed appropriately, they could lead to erroneous results that would ultimately generate incorrect measurements. It is therefore essential to select an appropriate sustainability metric.

NESS ET AL. (2007, p. 500) developed a holistic framework that incorporates the existing sustainability assessment tools that appear in the literature. This framework is shown in Figure 2, and with the input from BEBBINGTON ET AL. (2007, pp. 225 - 226), each of the tools has been categorized into three separate areas.

The first area, indicators and indices, is further subdivided into non-integrated and integrated. These quantitative measures represent a state of economic, social and/or environmental development and can be used for both short-term forecasting as well as for long-term decision making.

The second area, product-related assessment tools, focuses primarily on the material and/or energy flows of the product, linking the production and consumption of goods and services.

The last area is called integrated assessment, which brings together the tools that support decision making - change or project implementation in a specific region. Project-related tools are used to carry out analyses at the local level, while policy-related tools are used to carry out assessments at the local to global level, including their impact assessment.

Furthermore, as can be seen on the right-hand side of Figure 2, the tools are organized according to whether they are retrospective or prospective in their approach to examining the timeline. Retrospective tools look back in time, while prospective tools focus on predicting future outcomes.

The framework presented in Figure 2 includes several sustainability assessment tools found in the literature, and these are also the most commonly used. However, there are others that are not included in the framework that could be interesting to implement depending on the research purpose (MYLLYVIITA ET AL. 2017, pp. 3 - 4).

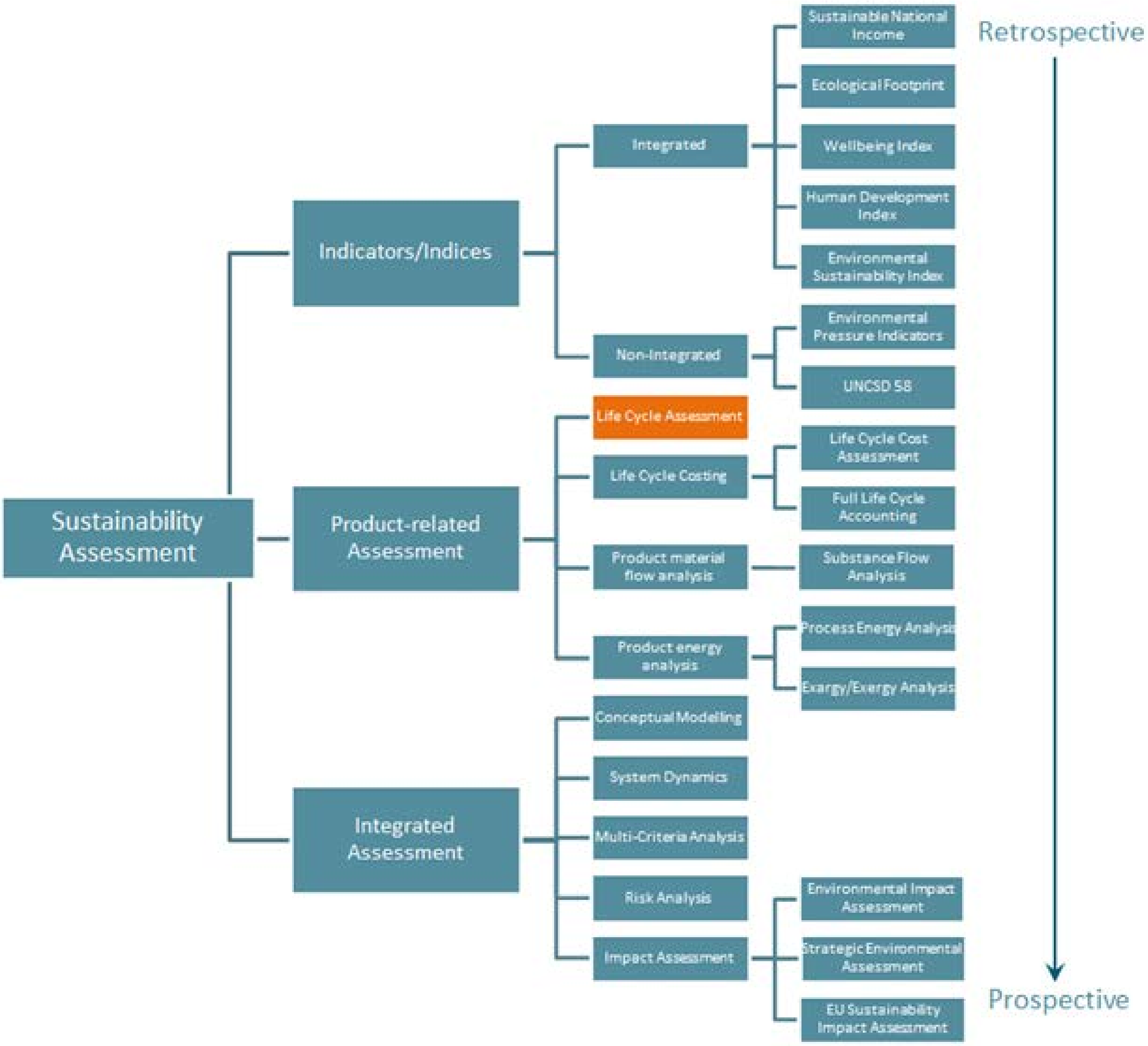


Figure 2: Framework for Sustainability Assessment Tools

(Source: Own representation based on NESS ET AL. 2007, p. 500)

One of the main tools used in the industry, marked in orange in Figure 2, that will be analyzed in this thesis is the Life Cycle Assessment (LCA), a tool used to calculate the impact of a product on the environment. It will be further explained in the next section.

2.1.3 LIFE CYCLE ASSESSMENT

According to MURALIKRISHNA & MANICKAM (2017, p. 57), Life Cycle Assessment (LCA) is a systematic methodology for evaluating the environmental impacts associated with all stages of the life cycle of a product, process, or service. It aims to promote resource conservation and environmental protection. LCA has been widely applied to address challenges related to resource depletion and environmental degradation throughout the industrial process, starting from raw material extraction, through material processing, manufacturing, distribution, use and possibly recycling (SHI ET AL. 2015, p. 211).

Due to the development and harmonization in the industry, the establishment of an international standard for the LCA was required and achieved, in particular within the ISO 14040 and ISO 14044 (KULCZYCKA & SMOL 2016, p. 831). Figure 3 is a representation of the four steps involved in the process of analyzing the environmental impact of a product (or service).

These steps are:

i) Goal and scope definition of the problem´s boundaries
ii) Life cycle inventory analysis of material and energy flows
iii) Life cycle impact assessment
iv) Interpretation of the results achieved

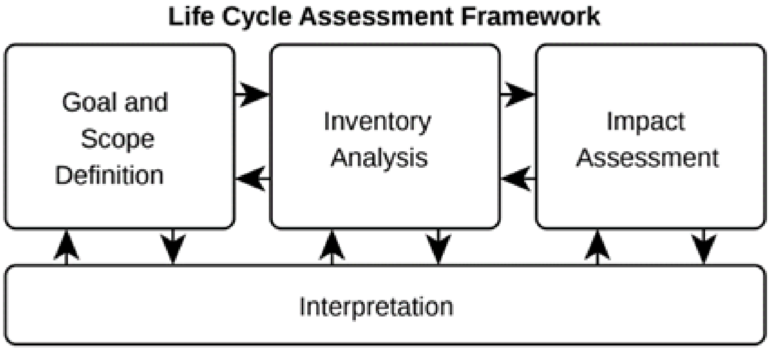


Figure 3: Steps of the LCA methodology according to ISO 14040 (Source: LAMPERTI TORNAGHI ET AL. 2018, p. 3)

The primary objective of a LCA is to compare the environmental impacts of two different products (JOLLIET ET AL. 2016, pp. 23 - 24). Due to the different nature of all types of products and models to be compared, several categories were evaluated. They can range from the very early stages of the process, such as the supply of raw materials, including their transportation, to the final stages of the life cycle, which could include the reuse, recovery, and recycling of the materials used. These impact categories have been grouped into three main areas (REZA ET AL. 2014, p. 254):

i) Upstream impacts of resource inputs, which include the use of both renewable and non-renewable resources
ii) Downstream impacts which include waste and emissions
iii) Associated socio-economic impacts, including monetary costs and purchased labor and services

Each category is then subdivided into the different issues they address, such as climate change, acidification, energy use, etc. Each of them is evaluated in different units so that normalization and weighting techniques can be applied to compare them (KULCZYCKA & SMOL 2016, p. 831).

Although LCA techniques have been around for several decades, the methodology is still evolving. It still has some limitations, such as the amount of input data required, the large amount of time needed to produce a comprehensive report, the difficulty of linking aspects from different dimensions, and so on. However, it is a tool that has improved in many areas in recent years, and if it continues to develop, combined with the development of databases, it could have a positive impact in the field of sustainability assessment in the future (FINNVEDEN ET AL. 2009, p. 17).

2.2 RISK MANAGEMENT

In today's society, mankind is constantly facing new changes and developments at a tremendous pace. This ever-changing environment presents manufacturing companies with new challenges that must be addressed to ensure long-term business success (SUÁREZ ET AL. 2021, pp. 1 - 2). Internal strategies to optimize production while taking into account external factors affect the future viability of a company's production and the realization of its business goals in a highly competitive market.

According to the International Organization for Standardization (ISO 2018), risk is defined as "the impact of uncertainty on objectives. This can include the organization's purpose, vision, and values, as well as the goals and objectives articulated at different levels of the organization." In addition, as stated in HUBBARD (2009, p. 7), some of the potential outcomes associated with risks may include loss, injury, disaster, or other both economic and non-economic outcomes.

The goal of risk management is to pursue coordinated efforts to identify, analyze, monitor, and ultimately minimize the impact of undesirable events while maximizing the realization of products or services that add value to the organization (DIONNE 2013, p. 19). Risk management strategies typically include avoiding, reducing, transferring, or accepting the potential consequences of a particular threat. Avoidance of a threat seeks to eliminate the negative consequence or likelihood of the threat, while reduction involves reducing the negative impact of the threat.

As DIONNE (2013, p. 9) states, there are five main types of risks, which can have several causes. These causes can be both external and internal to the company (USHVITSKII ET AL. 2015, pp. 1012 - 1013):

1. **Pure risk:** May or may not be insurable, is beyond the control of the individual and can only result in a loss with no possibility of financial gain.
2. **Market risk:** Due to changes in market factors such as market prices, interest rates, exchange rates, and other macroeconomic factors.
3. **Default risk:** Caused when borrowers fail to make payments on a loan or other credit obligation. It can be assessed by a lender, investor, or other interested party.
4. **Operational risk:** Loss resulting from inadequate or failed internal processes, people and systems, or from external events such as fraud. It is typically associated with the potential for financial loss, legal liability or damage to an organization's reputation.
5. **Liquidity Risk:** The risk of having insufficient funds to meet the entity's financial obligations as they fall due. This type of risk may result from a lack of cash, a shortage of liquid assets, and/or an inability to access the capital markets to raise capital. May degenerate into default risk.

This thesis will focus on the fourth type of risk mentioned above, operational risk. In particular, the main risks will be assessed during production, which will be explained in the following section.

2.2.1 OPERATIONAL RISKS IN MANUFACTURING

Operational risks refer to the potential risks that can arise during the daily production process of any type of product or service and can lead to potential losses or costs. These risks can be caused by a variety of factors, including inadequate resources, environmental issues, technical difficulties, and/or poor planning (GUERTLER & SPINLER 2015, p. 2). It is important for production managers and other stakeholders to be aware of the potential manufacturing risks and have a plan in place to mitigate or prevent them from occurring. According to CHAND (2021, p. 208), there are six main operational risks:

i) Failure of machines, equipment, or facilities as well as low Mean Time Between Failures (MTBF) that can be due to unforeseen environmental conditions, i.e., high moisture, corrosive water, high pollution, etc.
ii) Capacity bottleneck
iii) Increased Lead time

iv) Human error
v) Inefficient material handling
vi) System or software failure

This list of operational risks in manufacturing can have a wide range of impacts on a company, from minor disruptions to major financial losses. It is important for manufacturing companies to identify and assess their operational risks in order to develop strategies to mitigate or manage these risks (CHAND 2021, p. 212). This can include regularly implementing safety protocols, conducting assessments of manufacturing processes, and investing in quality control measures. By taking proactive steps to manage operational risks, manufacturing companies can reduce the likelihood of negative impacts to their business and increase their overall operational efficiency and profitability. The stages of successful risk management are outlined in the next section.

2.2.2 RISK MANAGEMENT PHASES

As mentioned earlier, there are several main types of risk that can come from a variety of sources. These uncertain causes can be both external and internal, but the way strategic departments predict, assess, and ultimately deal with them can have a tremendous impact on their outcomes.

Depending on the culture of the organization, some risk measures may be more revolutionary than others (RAZ ET AL. 2002, p. 103). However, the process typically consists of four phases, as shown in Figure 4. The process is sequential, one stage at a time, but circular.

Figure 4: Risk Management Process (Source: Own representation based on ELENA DOVAL *2019, p. 103)*

Each of the phases will be explained hereafter, also based on the input from (LAVANYA & MALARVIZHI 2008, RAZ ET AL. 2002, p. 105, AUSTRALIAN GOVERNMENT - DEPARTMENT OF FINANCE 2016, pp. 2 - 4):

1st Step: Risk Identification

The goal of this step is to create a comprehensive and customized list of future events that may be uncertain but are likely to have a positive or negative impact on the organization's objectives. To accomplish this, risks must be documented, including the risk event, the potential cause, and the potential impact if the risk occurs. In addition, it is important to identify the cause as early in the project as possible. Several techniques can be used to identify risks. They range from highly structured and sophisticated methods to more informal approaches, depending on the predictability of the risk.

2nd Step: Risk Evaluation

This step determines the potential impact of the risk on the project's objectives. It is necessary to determine the tolerability of each risk, i.e., which risks need to be addressed and what the priority should be. A risk assessment is performed by comparing the risk severity determined in the risk analysis step with the risk criteria identified in the likelihood and consequence criteria. This is done by establishing a risk threshold metric, above which all risks are considered unacceptable and below which all risks are considered tolerable. Treatment decisions should take into account the likelihood of the risk occurring, the impact of the risk, the exposure to the risk, and the time frame of the risk's occurrence, as well as financial, legal, regulatory, and other requirements.

To express risk in a quantitative way, the following formula can be implemented (ODUOZA 2020, p. 1293):

$$R = LO * DPH * FE * NP, \tag{1}$$

where R stands for risk level, LO for likelihood of occurrence of potential harm, DPH for degree of potential harm, FE for frequency of exposure and NP for number of persons exposed. According to this formula, risks can then be categorized as negligible (accepted), tolerable or intolerable depending on the value of the risk level.

Ultimately, when risk is accepted in a thoughtful and informed manner, the decision-making process is supported, and objectives are more likely to be achieved.

3rd Step: Risk Management

Risk management involves selecting and implementing appropriate strategies to avoid, transfer, mitigate or accept risk. The first step is to identify potential risk triggers. These triggers serve as warning signs when a risk is expected to occur. Then, the person responsible for resolving the risk should plan the appropriate response.

Each risk event should be addressed with at least one risk response. This may sound like a simple task, but it can be extremely complicated due to the complexity of the risks, the large number of people involved, the accuracy of the timeline, the cost of impact, etc.

4th Step: Risk Controlling

Because risks evolve over time, risk management should evolve with them to keep pace. In addition to identifying and planning for emerging risks that may become more critical, another important aspect of risk monitoring is to identify changes in the internal and external environment of the company. It also seeks to ensure that the implementation of measures for existing risks is still effective, while at the same time identifying further improvements for identified risks. Review cycles may vary from company to company and may be periodic or ad-hoc, but should include lessons learned, successes and failures.

These four steps make up the risk management plan, which is an iterative process that should be performed regularly. Different risks can occur at each stage of a project. Therefore, effective communication is an essential aspect of effective risk management. Status reports and risk review meetings should be held at each stage, and the results should be included in formal risk reports that are published internally and externally.

2.3 PRODUCTION AND PRODUCTION SYSTEMS

According to the Cambridge Dictionary, production is defined as the process of making or manufacturing any goods or services from components or raw materials. Another source involved in the process is the knowledge required to create the output that serves as value to individuals.

SEPPO (2011, p. 3) defines production as “all economic activities that aim directly or indirectly to satisfy human needs.” The way in which the output satisfies these human needs depends on the efficiency in the use of the input factors during the production process. The concept of production process is based on three main factors of production, namely land, labor and capital.

For production companies to be successful, there must be consumers of their products. Every production company is at the center of the interaction between its main stakeholders, which are customers, suppliers and the producer community (SEPPO 2011, p. 4). Consumers are the clients of each company. They can be private households, part of the public sector or external producers, which can also be different production companies. The aim of the suppliers is to provide the companies with materials, energy, capital and/or services. They have an enormous influence on the final quality and price of the produced object. Finally, producer associations represent all the people involved in production, from workers to owners. Their goal is to maximize the income of the enterprise.

As described in BELLGRAN & SÄFSTEN (2010, p. 38), a production system is the "collection of people, resources and processes that work together to produce a product or service". The term production system can refer to a wide variety of systems, from small-scale manufacturing operations to large-scale factories, and even to service-based organizations such as NGOs, hospitals, and schools.

There are many different factors that can influence the design and operation of a production system, including the type of goods or services to be produced, the available technology and resources, the economic losses due to low productivity, the upgrading of products as well as those of competitors, and the goals and constraints of the organization. In addition, the design process for a new production system involves a series of activities that may take several years to complete, including identifying the requirements, designing the equipment, layout and logistics flow, and selecting the necessary equipment suppliers (ISLAM ET AL. 2020, p. 741). Because these activities are considered difficult and time-consuming, they are typically divided into different projects and their results are added together.

Production systems have been analyzed for improvement since the beginning of the industrial revolution and have undergone tremendous development in recent decades. There are several different approaches to organizing and managing production systems, to name a few (PACHECO ET AL. 2014, p. 356, SLACK ET AL. 2013, pp. 465 - 471):

i. **Lean Manufacturing:** Emphasizes the elimination of waste and the continuous improvement of efficiency in the production process.

ii. **Mass production:** Production of very large quantities of goods using specialized machinery and division of labor. It is designed to achieve economies of scale and ultimately lower unit costs.

iii. **Just-in-Time (JIT):** Producing goods only when they are needed, rather than producing and storing them in inventory. This reduces the costs and risks associated with carrying excess inventory.

iv. **Custom manufacturing:** Involves producing goods to meet the specific needs of individual customers. It is typically used for products that are highly customized, highly specialized, or in low demand.

v. **Project-based production:** Involves organizing production around certain specific projects rather than around general departments or functions. It is often used in industries such as construction, engineering, and consulting.

Each of these approaches has its own set of principles and techniques and can be used individually or in different combinations depending on the needs and goals of the organization. Overall, the goal of a production system is to produce goods and services effectively and efficiently while minimizing costs and maximizing quality.

Chapter 3. STATE OF THE ART

The third chapter of this thesis serves to illustrate the state of research on product-related sustainability risk assessment systems. First, section 3.1explains the approach used in the research and categorization part. The following section 3.2 provides an introduction to the relevant sustainability risk assessment methodologies currently used in manufacturing systems. Then, section 3.2.1 introduces the methodology for conducting a sustainability risk assessment, while section 3.2.2 describes the existing sustainability risk assessment methodologies in manufacturing and their current uses and applications. Finally, the last section of the third chapter presents the shortcomings of existing sustainability risk assessment systems, including the areas that this thesis focuses on.

3.1 RESEARCH PROCEDURE AND CLASSIFICATION

A design and research methodology typically consists of four phases, research clarification, descriptive study I, prescriptive study, and descriptive study II (BLESSING & CHAKRABARTI 2009, pp. 13 - 41). In this section, the state of the art research will be analyzed, which refers to the second phase of the design and research methodology, descriptive study I (BLESSING & CHAKRABARTI 2009, pp. 13 - 41). The objective of the research is to identify the existing methodologies for sustainability risk assessment in manufacturing systems. However, the purpose of the research is not only to identify relevant areas of study and illustrate the status quo, but also to identify unresolved problems and open questions. It also serves to provide a better understanding of the topic and to demonstrate the relevance of the research question (BLESSING & CHAKRABARTI 2009, pp. 13 - 41). The following describes the approach taken to meet these requirements.

Through the analysis of the existing literature, various themes, sub-aspects and finally search terms were identified in order to conduct a methodologically sound literature search. For each topic, aspects were identified and for each aspect, additional synonyms were included in the search whenever possible. The aim was to represent the state of the art as comprehensively as possible.

The research was conducted using Scopus. Table 1 below shows the key search terms used for the literature search. Research topic combinations were created using the Boolean operators "AND" and "OR" to link search terms from different subject areas. In order to improve the quality of the search term combinations, they were checked for their completeness, meaningfulness, and logic.

Further restrictions were applied to limit the results to publications relevant to the research aspect. In Scopus, publications were restricted to the disciplines of engineering, environmental science, economics, econometrics and finance, and energy. In addition, journal articles, review publications, conference papers, and book chapters were selected as publication types. Furthermore, only publications published since 2014 were searched to ensure the relevance of the research.

Table 1: Selection of the relevant search terms for the literature research (Source: Own Representation)

Number	Subject Area	Sub-aspect	Search keyword
1	Sustainability	Ecologic	sust*, eco*, clima*, environment*, bio*, green*
		Economic	econ*, prod*, profit*
		Social	soci*, comm*, publ*, civ*, hum*
2	Sustainability - Assessment	Assessment	eval*, assess*, surv*, val*, explor*, resear*, benchmark*, rat*, scor*, measur*
		Analysis	compar*, exam*, invest*, inspect*, analy*, stud*, review*, breakdown
3	Production	Manufacturing	manufact*, install*, recycl*, creat*
		Production	produc*, fabric*, proce*, construct*

		Industry	industr*, expan*, corpor*
		Assembly	build*, assembl*, fit*, form*
		Disassembly	demol*, disman*, dissol*, disassembl*, remov*, dismount*
4	Operating Level	Network	network*, compan*, corporate*, organi*
		Site	loca*, area*, site*, plant*, branch*, institut*, station*, segment*
		System	system*, struct*
5	Methodology	Method	method*, technique, practice
		Approach	approach*, proce*, mechani*, formula
		Tool	tool, instrument, device
		Concept	concept*, idea*, theor*, hypoth*
		Model	model, represent*, reproduc*, framework
6	Risk – Management	Risk	risk*, prospect*, possib*, uncertain*
		Management	manage*, admin*, control*, govern*
		Identification	identif*
		Assessment	Redundant with Assessment under number 2 Sustainability - Assessment
			* = Placeholder for the different endings of the words

Finally, after limiting the search to publications written in English, just over 1500 results were found. The search results were evaluated for their relevance to the current research. First, the title and keywords were examined for relevant appearing titles. Publications that were classified as potentially relevant based on the title were then examined for their abstract. Finally, if the abstract showed relevance to the research objective under consideration, a content review of the publications was conducted, and if the relevance to the present work was confirmed, the publication was stored in a literature database. The results of the literature search are presented in the section 3.2.2.

The complete query used in Scopus during the literature research, including all applied filters, can be found in Appendix II.

3.2 SUSTAINABILITY RISK ASSESSMENT IN MANUFACTURING SYSTEMS

Sustainability Risk Assessment (SRA) in manufacturing systems is a systematic approach to identifying, evaluating, and prioritizing potential hazards and sustainability-related challenges that may impact the performance and long-term viability of a manufacturing system (WORLDFAVOR 2023).

The main objective of SRA is to ensure that the manufacturing system is aligned with the principles of sustainable development and that the negative environmental, social, and economic impacts of its operations are minimized (MARTINS 2019, pp.13 - 14). SRA typically involves a multidisciplinary team of experts and stakeholders who use a range of tools, methods, and metrics to analyze the sustainability risks and opportunities associated with the manufacturing system's operations, products, and supply chain (ELMARAGHY ET AL. 2021, p. 637). In addition, as manufacturing systems have evolved and will continue to evolve in the near future, risk assessment methodologies must evolve at the same pace. These changes are happening on four axes: products, technology, business strategies, and production. In the next few years, artificial intelligence will help human-centered decision making in risk assessment, with both advantages and disadvantages (ELMARAGHY ET AL. 2021, pp. 652 - 654).

Given that decision makers need to link social-ecological sustainability issues to tangible business impacts in order to successfully implement a strategic sustainability perspective, the results of the SRA can have a tremendous impact on the future of the company. They can help organizations implement sustainable practices and strategies to reduce risks and enhance opportunities in both the short and long term (SCHULTE & KNUTS 2022, p. 737). SRA is becoming increasingly important as organizations face growing pressure to demonstrate their sustainability performance and as consumers become more aware of the environmental and social impacts of the products they purchase.

3.2.1 METHODOLOGY OF SUSTAINABILITY RISK

The current methodology of sustainability risk assessment in manufacturing systems typically includes five stages, such as (ROBECO 2022, pp. 5 - 9, THIEDE & HERRMANN 2019, pp. 41 - 84):

i. **Context and Scope Definition:** In this phase, the objectives and boundaries of the SRA are defined, including the nature and extent of the sustainability risks and opportunities to be assessed.
ii. **Data Collection and Analysis:** The second step of the process involves gathering relevant data and information about the manufacturing system's operations, products, and supply chain. This information is then analyzed to identify potential sustainability risks and opportunities.
iii. **Risk and Opportunity Assessment:** This stage involves assessing the likelihood and impact of each identified sustainability risk and opportunity. A risk/opportunity matrix is often used to prioritize and categorize risks and opportunities.
iv. **Risk and Opportunity Management:** The fourth step is to develop and implement strategies and actions to manage the risks and opportunities identified in the previous step. This may include mitigation measures, risk transfer strategies, and opportunities for sustainability innovation and improvement.
v. **Monitoring and Review:** This stage involves monitoring the performance of the manufacturing system against the SRA objectives and periodically reviewing and updating the SRA to ensure its relevance and effectiveness.

The relationship within each of the five stages is presented in Figure 5.

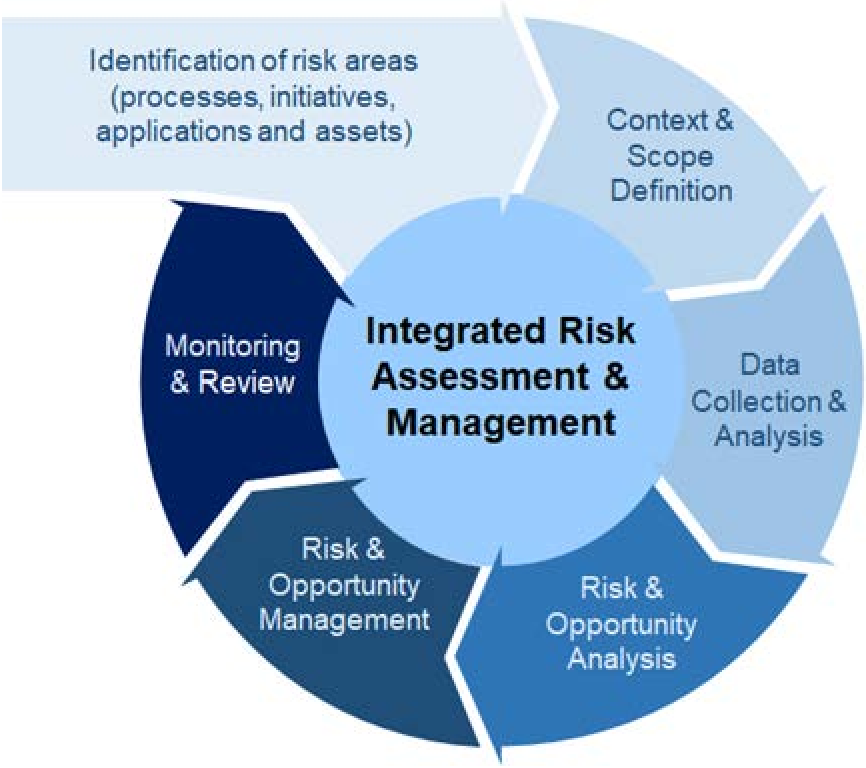


Figure 5: Integrated Risk Assessment Framework (Source: Own representation)

In addition, there are several relevant sustainability standards and frameworks that provide guidance on conducting SRA in manufacturing systems, such as ISO 26000:2010 or the Global Reporting Initiative (ISO 2023, GRI 2023). The former provides guidelines for social responsibility and includes a section on sustainability risk management, while the latter provides a globally recognized framework for sustainability reporting and includes guidelines for sustainability risk management. These standards and frameworks can provide useful reference and guidance for organizations seeking to conduct SRA in their manufacturing systems and demonstrate their sustainability performance.

To maximize the benefits of SRA in manufacturing systems, it is important for organizations to adopt a systematic and integrated approach that involves all relevant stakeholders and is regularly reviewed and updated. Some of these benefits include (PANIGRAHI & BAHINIPATI 2018, pp. 1002 - 1005):

- **Improve resource efficiency and reduce waste:** By identifying and addressing sustainability risks and opportunities, organizations can improve the efficiency of their operations, reduce waste, and minimize the environmental impact of their products.
- **Improve supply chain sustainability:** SRA can be used to assess the sustainability risks and opportunities of the entire supply chain, including suppliers, and help organizations ensure that their suppliers are adopting sustainable practices and reducing their environmental impact.
- **Strengthen stakeholder relationships:** SRA can help organizations better understand and respond to the concerns and expectations of their stakeholders, including customers, employees, investors and regulators, by demonstrating their commitment to sustainability and improving their sustainability performance.
- **Facilitate sustainability innovation:** By identifying and addressing sustainability risks and opportunities, companies can encourage and facilitate sustainability-related innovation and improvement, including the development of new products and processes that are more sustainable.
- **Improve reputation and competitiveness:** By demonstrating sustainability performance and addressing sustainability risks and opportunities, companies can enhance their reputation and competitiveness in a marketplace that is increasingly focused on sustainability.

In summary, SRA in manufacturing systems is an important tool to ensure the long-term viability and success of the system, and to reduce sustainability risks and enhance sustainability opportunities. It can also help organizations to comply with relevant sustainability regulations and standards and to improve their sustainability performance and reputation. The following section 3.2.2 provides an explanation of the existing methodologies currently used in the industry.

3.2.2 DESCRIPTION AND APPLICATIONS OF THE EXISTING METHODOLOGIES

As mentioned earlier, the term SRA has been the subject of research for many years. This section aims to analyze the articles that relate SRA more specifically to manufacturing systems.

ANAND ET AL. (2016, pp. 260 - 261) present a framework for sustainability risk assessment of a mechanical system at the conceptual design phase. The framework includes the six parameters (risks) required to develop the SRA: environmental risks (ER), functional risks (FR), manufacturing risks (MR), economic risks (ECR), societal risks (SCR), and disposal and recyclability risks (DRR). Some of the factors contributing to each of these parameters are shown in Table 2.

Table 2: Risk assessment parameters through sustainability (Source: ANAND ET AL. 2016, p. 261)

Nr.	**Risk Parameter**	**Contributing Factors**	**Nomenclature**
1	Environmental	Material and energy conservation, longevity materials, biocompatible materials, techno-environmental issues, ISO regulations, manufacturing strategies, consumer usage methods, green technologies, etc.	ER
2	Functional	Nonfulfillment of properties like strength, hardness, toughness, stiffness, wear resistance, friction, elasticity, intended function, durability, longevity, etc.	FR
3	Manufacturing	Material selection, compatible processing technologies, supply chain, toxic substances, intricate part geometry/profile, etc.	MR
4	Economic	Environmental cost, raw material cost, manufacture cost, wastage cost, recycle/disposal cost, etc.	ECR
5	Societal	Socio-political ethos, technological adaptability amd savviness, environmental consciousness/awareness, etc.	SCR
6	Disposability & Recyclability	Compatible technologies, availability of green channels/resources, emission of fumes/gases, energy requirements, bio compatibility, cost justification, disposal methodologies, legislation/ISO, etc.	DRR

Additionally, the relationship of each the risk assessment parameters can be found in the graph in Figure 6.

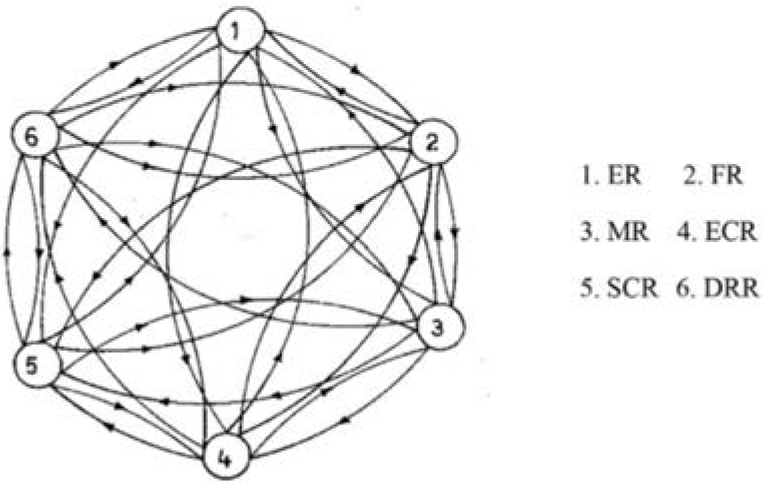


Figure 6: Relationship graph of the sustainability risk assessment parameters (Source: ANAND ET AL. 2016, p. 261)

The ultimate goal of ANAND ET AL. (2016, p. 265) was to develop an SRA index that could evaluate different mechanical design systems at the conceptual design stage from a risk analysis perspective.

Another study, conducted by CHATZITHEODOROU ET AL. (2021), develops a practical method to aid banks in assessing the sustainability risks of corporations by examining publicly available data. The approach utilizes a scoring system to evaluate 75 sustainability indicators across nine categories of risk that encompass all aspects of corporate sustainability. To assess the sustainability dimensions of corporate performance, the system draws on data from a range of reports, including corporate sustainability reports and financial statements.

The aim of CHATZITHEODOROU ET AL. (2021, pp. 1481 - 1482) is to establish a methodological framework for evaluating corporate sustainability risks, with the objective of assisting the banking sector in reducing the risks associated with lending decisions. The proposed framework consists of two distinct components, each serving a specific purpose. First, it presents a novel combination of financial and non-financial indicators for assessing a company's risk profile with respect to the adoption of cleaner production practices. Second, it develops a tool for the banking sector to assess different aspects of corporate performance on cleaner production practices, which can be utilized to optimize lending decisions and select socially and environmentally responsible projects. In conclusion, the proposed methodology provides a practical approach for classifying companies into three levels of overall risk, namely low, moderate, and high risk. To examine the suitability and practicality of the proposed framework, an analysis was conducted on a sample of reports published by 17 energy sector firms.

Furthermore, in CHATZITHEODOROU ET AL. (2021, p. 1478) a scoring system for assessing risk levels and their correlation with the credit decision is described. This system, illustrated in Table 3, aims to standardize the evaluation of information from sustainability reports that contain social and environmental data presented in a non-systematic manner. The scoring scale ranges from 0 to 5 points, with a higher score indicating lower risk. The score is based on the quality and significance of the information contained in the sustainability reports, which can be used by banks in their lending decisions as well as by manufacturing companies themselves.

Table 3: Levels of risk scoring system (Source: CHATZITHEODOROU ET AL. 2021, p. 1478)

Scoring Scale	**Risk Level**	**Description**
0 points	Very High	• Non-public information about a particular disclosure topic. • Banks are unable to assess the company's performance on this topic because they do not have access to the information.
1 point	High	• A company discloses qualitative information about a particular disclosure topic. • While qualitative information is important for understanding the business strategies and practices that companies use, it is not indicative of a company's actual or evolving performance.
2 points	Moderate	• Quantitative information about a specific disclosure topic without further information to assess the progress of the company's performance. • Used by companies that want to avoid any reference to information that reveals negative results of corporate management. • Also given when the company's performance in a disclosure topic is worse than in previous years.

3 points	Low	• Company presents information showing that the company's performance in a particular area is the same as the previous year. • Banks have a complete picture of company performance and an indication of stable company performance.
4 points	Very Low	• Company presents quantitative information indicating that the company's performance in a particular area is better than the previous year. • Banks have a complete picture of company performance and also an indication of improvement in company performance.

The researchers DELAI & TAKAHASHI (2014) proposed a reference model for a sustainability measurement system that organizations can use to incorporate sustainability measures into their performance measurement system. This model is intended to promote a culture of sustainability and support decision-making processes by addressing the problem of non-standard measures and their associated consequences. To create the reference model, the authors analyzed the complementarities, strengths, and weaknesses of eight well-known sustainability measurement initiatives.

These initiatives were selected in DELAI & TAKAHASHI (2014, pp. 440 - 441) as they cover all three dimensions of sustainability (economic, social, and environmental), have a broad focus (national or corporate), and are not strongly based on another initiative or guideline. The eight initiatives are as follows:

1. The Indicators of Sustainable Development of the Commission on Sustainable Development (CSD)
2. The Dashboard of Sustainability
3. The Barometer of Sustainability
4. The Global Reporting Initiative (GRI)
5. The Sustainability Metrics of the Institution of Chemical Engineers (IChemE)
6. The Dow Jones Sustainability Index (DJSI)
7. The Triple Bottom Line Index (TBL)
8. The ETHOS Corporate Social Responsibility Indicators

In the study of GARCÍA-GÓMEZ ET AL. (2021, pp. 1 - 5) the authors present a methodological framework for integrating sustainability issues into the risk management of industrial assets. The authors aim to enhance asset performance by managing assets in a controlled environment with clear limits and reliable information management. The proposed procedure provides general criteria and a methodology for identifying, analyzing, and evaluating sustainability aspects, impacts, and risks associated with assets that are owned and managed by an industrial enterprise. Based on the ISO 55000 and ISO 31000 standards, this process has the potential to prevent or mitigate undesirable events as well as identify new opportunities related to sustainability risks in industrial assets. It serves as a model to improve the analysis of sustainability risks in industrial assets.

A comparable hierarchical framework for the assessment of techno-economic and environmental sustainability using risk analysis was presented in the work of GARGALO ET AL. (2016, p. 1). The proposed tool is suitable for the early stages of conceptual process design and screening of potential process alternatives, and it enables the identification of the most promising and sustainable options. The framework consists of the following sequential steps:

1. identification of sources of techno-economic uncertainty and quantification of economic risk
2. monetary valuation of environmental impact categories
3. quantification of potential environmental risk
4. measurement of eco-efficiency of alternatives and identification of trade-offs
5. use of a sustainability risk assessment matrix for both qualitative and quantitative decision support, even for non-experts

The possibility of integrating risk assessment and sustainability evaluation into one conceptual framework was explored in the study conducted by SEXTON & LINDER (2014, p. 1409). The U.S. Environmental Protection Agency employs risk assessment as a decision-making tool to "characterize the nature and magnitude of risks to human health for various populations, such as residents, recreational visitors, both children, and adults" (UNITED

STATES ENVIRONMENTAL PROTECTION AGENCY 2022). On the other hand, sustainability assessment refers to the "evaluation of all environmental, social and economic negative impacts and benefits in decision-making processes towards more sustainable products throughout their life cycle" (LIFE CYCLE INITIATIVE 2022).

Over the years, risk assessment and sustainability evaluation have developed independently. More recently, however, there have been efforts to integrate the two concepts to achieve a holistic decision-making approach that balances environmental, economic, and social values, while being practical within data and time constraints. Table 4 illustrates the four possible combinations of risk assessment and sustainability evaluation and provides a description for each. This was discussed in the study conducted by SEXTON & LINDER (2014, p. 1409).

Table 4: Comparison of four ways to combine risk and sustainability assessments in decision-making (Source: SEXTON & LINDER 2014, p. 1415)

Relations between Assessments	**Brief Description**
1. independent assessments of risk and sustainability	Risk and sustainability are treated as separate areas of analysis and are assessed separately, with results from both used to inform decisions.
2. sustainability is incorporated into the risk assessment−risk management paradigm	Risk is the overarching conceptual construct and sustainability is assessed within this context.
3. risk is incorporated into the sustainability paradigm	Sustainability is the overarching conceptual construct, and risk is assessed and managed within this context.
4. integrated analysis of risk and sustainability	Risk and sustainability are merged into a single analytical domain and assessed using an integrated diagnostic approach that produces a clear, unified result.

Finally, in the study conducted by WEBER ET AL. (2015), the authors explore the integration of environmental, social, and sustainability criteria into the commercial credit risk assessment process. They examine the relationship between the sustainability performance of commercial borrowers and commercial credit risk for six Bangladeshi banks. According to WEBER ET AL. (2015, p. 2), a proactive engagement in environmental activities by firms is associated with lower credit risk. Furthermore, the integration of environmental, social, and sustainability factors into credit risk assessment leads to prudent credit risk management. As a result, some banks are incorporating sustainability criteria into their lending practices to manage risks and enhance their reputation. The authors suggest that implementing credit risk assessment models that incorporate sustainability risks will benefit lenders by reducing loan defaults and enabling them to direct loans towards sustainability leaders.

The following Table 5 summarizes the existing methodologies currently used in the industry to perform an SRA, as reviewed in the present section 3.2.2.

Table 5: Summary of the existing methodologies currently used in the industry to perform an SRA (Source: Own representation)

Article	**Main findings**
ANAND ET AL. 2016	• Framework for sustainability risk assessment of a mechanical system at the conceptual design phase • Inclusion of six risk parameters needed to develop an SRA and their relationship to develop an index that could evaluate different mechanical design systems at the conceptual design stage
CHATZITHEODOROU ET AL. 2021	• Methodological framework for assessing the sustainability risks of companies to help the banking sector reduce the risks associated with lending decisions. • The approach uses publicly available data to assess 75 financial and non-financial indicators across nine risk categories covering all aspects of corporate sustainability. • Classification of companies into three levels of overall risk, namely low, moderate, and high risk. This could lead to the selection of socially and environmentally responsible projects.

DELAI & TAKAHASHI 2014	• Reference model for a sustainability measurement system that organizations can use to incorporate sustainability measures into their performance measurement system. • Model covers all three dimensions of sustainability (economic, social, and environmental), has a broad focus (national or corporate), and is not strongly based on another initiative or guideline.
GARCÍA-GÓMEZ ET AL. 2021	• Methodological framework for integrating sustainability issues into the risk management of industrial assets in order to improve asset performance. • General criteria for identifying, analyzing, and evaluating sustainability issues, impacts, and risks associated with assets that are owned and managed by an industrial enterprise. • Potential to prevent or mitigate undesirable events and identify new opportunities related to sustainability risks.
GARGALO ET AL. 2016	• Assessment of techno-economic and environmental sustainability using risk analysis in order to identify the most promising and sustainable options. • Suitable for the early stages of conceptual process design and screening of potential process alternatives.
SEXTON & LINDER 2014	• Integration of risk assessment and sustainability evaluation into a single conceptual framework to achieve a holistic decision-making approach that balances environmental, economic, and social values while being practical within data and time constraints.
WEBER ET AL. 2015	• Integration of environmental, social, and sustainability criteria into the commercial credit risk assessment process. This leads to prudent credit risk management. • Banks are incorporating sustainability criteria into their lending practices to manage risks and enhance their reputation.

3.3 SHORTCOMINGS OF THE STATE OF THE ART AND NEED FOR ACTION

The previous section reviewed the progress of sustainability risk assessment in manufacturing systems. Although significant advancements have been made in several areas in recent years, there are still several shortcomings that require attention. In this section, the main areas where these shortcomings are more apparent will be identified and measures to address them will be provided in the subsequent chapters of this thesis.

One limitation that appears in the work of ANAND ET AL. (2016, p. 265) is the increase in the structural complexity of their approach as the number of parameters increases. The more variables involved, the more computational effort is required, which can be challenging. Additionally, subjectivity in assigning values to different indexes can lead to different results depending on the personal input of the researcher. To address this issue, a clear and standardized scoring scale should be established to ensure consistency across different researchers.

In the research conducted by CHATZITHEODOROU ET AL. (2021), a number of limitations in the existing literature were identified during the research phase. One of these limitations was the lack of an explicit threshold for the indicators when conducting sustainability assessments (CHATZITHEODOROU ET AL. 2021, p. 1483). The use of a threshold could help banks make more informed decisions when assigning risk categories to companies. Furthermore, there are different indicators that are measured in different terms and scales (e.g., a combination of financial and non-financial indicators), which requires the conversion of units to a common scale.

To address the limitations of the information provided by sustainability reports and financial statements, additional sources of information should be incorporated to ensure a more accurate assessment of credit risk. According to CHATZITHEODOROU ET AL. (2021, pp. 1483 - 1484), sustainability reports and financial statements may not provide detailed information on all the risk categories proposed in the framework. Additionally, some reports may be done voluntary, leading to differences in overall scores between companies. Inclusion of sector and external economic information could provide a more complete picture of a company's sustainability performance and help mitigate the impact of incomplete or biased information. This would help to ensure that credit risk assessment models provide a more accurate and reliable assessment of a borrower's sustainability performance.

As noted in DELAI & TAKAHASHI (2014, p. 467), none of the eight sustainability risk assessment initiatives analyzed provide a comprehensive coverage of all sustainability issues, and there is no consensus on what should be measured and how. Figure 7 shows that although the initiatives provide a comprehensive set of sustainability issues, none of them cover all ten dimensions that were under consideration.

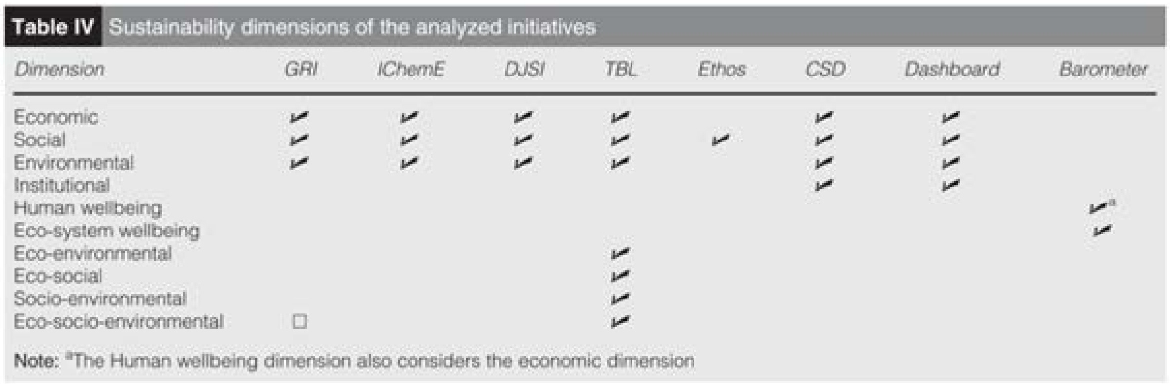


Table IV Sustainability dimensions of the analyzed initiatives

Dimension	*GRI*	*IChemE*	*DJSI*	*TBL*	*Ethos*	*CSD*	*Dashboard*	*Barometer*
Economic	✓	✓	✓	✓		✓	✓	
Social	✓	✓	✓	✓	✓	✓	✓	
Environmental	✓	✓	✓	✓		✓	✓	
Institutional						✓	✓	
Human wellbeing								✓[a]
Eco-system wellbeing								✓
Eco-environmental				✓				
Eco-social				✓				
Socio-environmental				✓				
Eco-socio-environmental	☐			✓				

Note: [a]The Human wellbeing dimension also considers the economic dimension

Figure 7: Sustainability dimensions covered by the analyzed initiatives (Source: DELAI & TAKAHASHI 2014, p. 445)

To elaborate further, DELAI & TAKAHASHI (2014, p. 445) noted that some initiatives, such as the Triple Bottom Line (TBL), try to capture two- or three-dimensional sustainability impacts, but there is no absolute consensus on the environmental themes and criteria to be applied. In addition, there are sub-themes in all the categories and not all of them are addressed, even if they cover the dimension.

It is also discussed that the use of ratio indicators, as opposed to absolute values, can have advantages in sustainability risk assessment (DELAI & TAKAHASHI 2014, p. 449). Ratio indicators allow for comparisons between companies of different sizes, which can be particularly important in credit risk assessment where companies of different sizes apply for loans. Ratios are more appropriate for measuring trends and performance evolution, allowing for comparison and benchmarking, and are therefore preferred. In addition, ratios can help identify areas of strength and weakness within an organization and can be used to track performance over time.

The challenge of recognizing sustainability issues and risks in industrial settings and their impact on the effectiveness of sustainability risk assessment is noted by GARCÍA-GÓMEZ ET AL. (2021, p. 19). On the other hand, SEXTON & LINDER (2014, p. 1416) suggest various opportunities for combining sustainability and risk assessment into an integrated analytical process. By integrating both approaches, the assessment can provide a more comprehensive view of the potential risks and impacts of a company's activities on the environment, society, and the economy. Furthermore, an integrated assessment approach can also help to identify trade-offs and synergies between different sustainability dimensions, which can inform decision-making and facilitate the development of more sustainable strategies.

Finally, XU ET AL. (2019, pp. 865 - 866) investigated the limitations of the supply chain sustainability risk framework. One of the main limitations is the narrow focus of each risk category. Therefore, it is important to expand the framework or timeframe to include all relevant aspects of each risk category. Another challenge is to determine the appropriate weighting factors for the sector-specific indicators, as different stakeholders may have different preferences. Moreover, the effectiveness of the scoring system in assessing the level of risk associated with the information provided for a particular disclosure topic could be improved by reconsidering the structure of the scoring system. Future research should focus on addressing these limitations to improve the overall effectiveness of the supply chain sustainability risk framework.

Comparing the limitations listed in this section 3.3 with the research questions included in the first section of this thesis, some of them remain unresolved. The first research question was “How can the state of the art regarding sustainability-oriented risk management in manufacturing systems be described?” This question has been partially answered in this section 3.3. The existing literature analyzes the methodologies used in industry to perform a sustainability risk assessment. However, the focus is on the assessment and less on the management techniques. Several assessment methodologies have been evaluated and some of them can be successful, but there is no management tool that stands out from the rest and is widely adopted in the industry. Therefore, there is room for improvement in the sector and this thesis aims to cover the shortcomings found in the literature.

The second research question, "How should an approach based on LCA sustainability information for identifying and assessing sustainability risks be developed and prototypically implemented?" also remains open. Some research is already incorporating LCA sustainability information into their sustainability risk assessments. However, this information is not systematically included, and no tool has been established that can successfully apply the LCA information to build a generic risk assessment tool that can be used across the manufacturing industry.

Finally, the last research question, "What are the implications of this tool in terms of industrial applications?" remains unanswered and needs to be further developed throughout this thesis before it can be fully answered.

The limitations identified in section 3.3 highlight the need for action by various stakeholders, such as governments and industry leaders. Proactive measures need to be taken to address these constraints. The following sections of this thesis will evaluate the potential courses of action that can be implemented to mitigate the limitations identified in the existing literature.

Chapter 4. CONTEXT AND REQUIREMENTS

The purpose of this section is to establish both the context and the requirements for developing the approach for using LCA-based sustainability information for the identification and assessment of sustainability risks. In section 4.1, the impact categories that will be addressed are selected, and the appropriate impact indicators are analyzed. Section 4.2 then explains the risk management methodology selected for the assessment, and section 4.3 presents the necessary adjustments made to fulfill the requirements of the approach.

4.1 SELECTION OF IMPACT CATEGORIES AND IMPACT INDICATORS

As mentioned in the previous section 2.1.3 of this thesis, a Life Cycle Assessment is a systematic methodology for evaluating the environmental impacts associated with all stages of the life cycle of a product, process, or service. In order to evaluate the environmental impacts mentioned above, 15 impact categories have been defined to group different emissions according to how they are generated and how they affect the environment. This means that different emissions that cause the same impact can be converted into the same impact category with their respective unit. Table 6 below provides an overview of the 15 environmental impact categories with their corresponding unit and description.

Table 6: Impact categories of an LCA (Source: Own representation)

Impact category	Impact indicator	Description	Source
Climate change	kg CO_2 eq	Indicator of a substance's potential to increase average global temperatures as a result of greenhouse gas (GHG) emissions. The largest contributor is generally the burning of fossil fuels such as coal, oil, and natural gas.	CLIMATE CHANGE CONNECTION 2020
Stratospheric ozone depletion	kg CFC-11 eq	Measures a substance’s potential to contribute to the depletion of the ozone layer in the Earth's atmosphere, which protects	HILLEGE 2019

		humankind from hazardous ultraviolet radiation. Its depletion can increase the risk of skin cancer and harm ecosystems.	
Human toxicity (cancer and non-cancer)	kg 1,4-DB eq/m^3 air	Measures the potential of a substance to cause harm to human health through exposure by ingestion, inhalation, or dermal contact. Divided into non-carcinogenic and carcinogenic toxicants.	Building Research Establishment 2020c
Fine particulate matter formation	µg/m^3 air	Indicator of the potential incidence of disease due to the emission and ingestion of particulate matter. It can be a mixture of solid particles and liquid droplets found in the air. Particles come in many sizes and shapes and can be made up of hundreds of different chemicals.	US Environmental Protection Agency 2022
Ionizing radiation	kg U^{235} eq/m^3 air	Damage to human health and ecosystems associated with the exposure to ionizing radiation from the nuclear fuel cycle and other activities, such as coal burning.	Hillege 2019
Photochemical ozone formation	kg C_2H_4 eq	Indicator of emissions of gases that affect the formation of photochemical ozone in the lower atmosphere (also known as "summer smog"). It attacks organic compounds in animals and plants and increases the incidence of respiratory problems.	Building Research Establishment 2020d
Acidification (terrestrial, freshwater)	kg SO_2 eq/m^3 air	Indicator of the potential of a substance to contribute to the formation of acid rain, which can damage ecosystems, buildings, and infrastructure.	Building Research Establishment 2020a
Eutrophication (freshwater)	Kg PO_4 eq/L water	Indicator of nutrient enrichment of freshwater, due to the release of nitrogen- or phosphorus-containing compounds. Can lead to harmful algal blooms that can leave water without enough oxygen for fish to survive.	AgImpacts 2021
Eutrophication (marine)	kg N eq/L water	Occurs when excessive amounts of nutrients (usually from human activities such as agriculture, sewage discharge and industrial activities) enter the marine ecosystem. When these nutrients enter marine waters, they can stimulate the growth of plankton and other aquatic plants, resulting in what is known as an algal bloom.	AgImpacts 2021

Eutrophication (terrestrial)	kg PO_4 eq/L water	Occurs when excessive amounts of nutrients, such as nitrogen and phosphorus, are added to the soil through activities like fertilization, animal waste deposition, and atmospheric deposition. These nutrients can be taken up by plants, leading to excessive growth and alteration of plant communities.	Space4Water 2020
Ecotoxicity potential (freshwater, terrestrial)	kg 1,4-DB eq/m^3 air	Indicator of the impact of toxic substances released into the environment on freshwater, marine and terrestrial ecosystems and their inhabitants. These substances have a tendency to accumulate in living organisms and can harm individual species as well as the functioning of the ecosystem.	Building Research Establishment 2020b
Land use	kg soil loss eq	Measure of the amount of land area used for agriculture, roads, housing, mining or to produce products or services.	Hauschild et al. 2018, pp. 181 - 182
Water use	m^3	Indicator of the relative amount of water used to produce a product or service, based on regionalized water scarcity factors.	Hillege 2019, Hauschild et al. 2018, pp. 181 - 183
Resource depletion (fossils)	MJ eq	Indicator of the potential of a substance to deplete natural fossil fuels. This depletion of fossil fuels may lead to the non-availability for future generations.	Hillege 2019
Resource depletion (minerals and metals)	kg Sb eq	Indicator of the potential of a substance to deplete natural non-fossil fuels or minerals	Hillege 2019

Table 6 was developed according to the ReCiPe 2016 framework. This framework consists of a methodology for conducting life cycle assessment studies that aim to evaluate the environmental impacts of products and processes over their entire life cycle. ReCiPe 2016 stands for "Reconciliation of Environmental Impact Categories and Indicator Methodologies" and was developed by a group of researchers from different European countries (M.A.J. Huijbregts et al. 2016, pp. 14 - 17).

The ReCiPe 2016 framework provides information on the modeled impact pathways and presents an overview of the value choices, or visions associated with environmental decisions, quantified through clustering into three perspectives: human health, ecosystem quality, and resource scarcity (JUNGBLUTH 2022, pp. 11 - 16).

The framework includes the relationship of the environmental impact categories to these three perspectives through their damage pathways. This overview is presented in Figure 8.

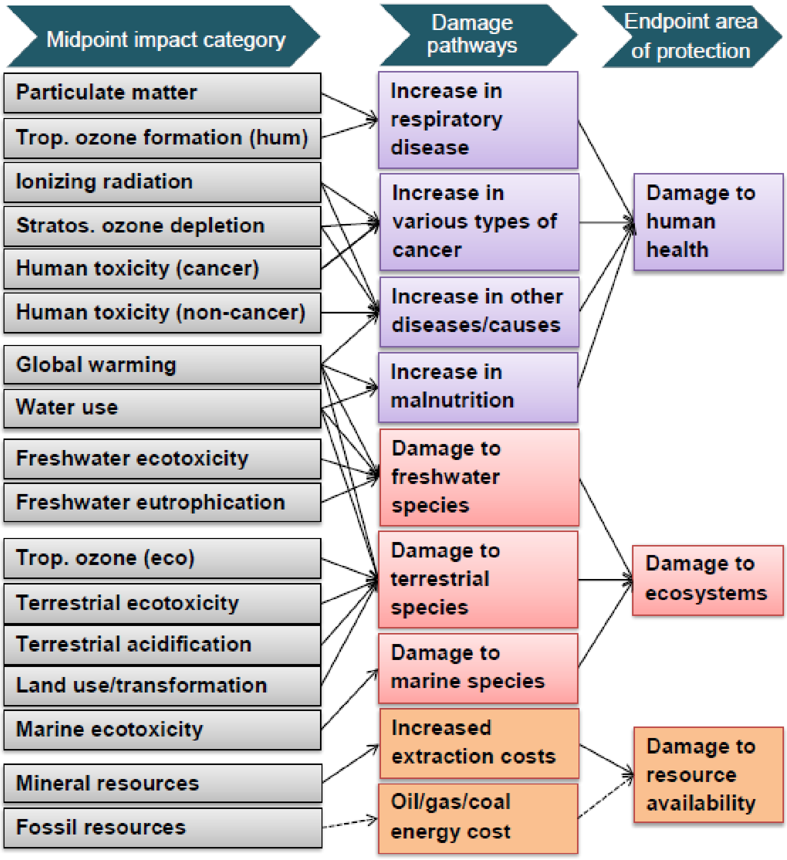


Figure 8: Overview of the 17 impact categories included in the ReCiPe 2016 framework and their relationship (Source: M.A.J. HUIJBREGTS ET AL. 2016, p. 17)

In order to develop a risk management tool that is as comprehensive as possible, this work will include all of the impact categories listed in Table 6 in the tool. The idea behind this is to develop a tool that is as general as possible and can be applied to any sector.

4.2 SELECTION OF THE RISK ASSESSMENT TOOL

As mentioned in section 2.2.2, the risk management process typically consists of four sequential phases, namely risk identification, risk evaluation, risk management, and risk controlling. This section focuses on the first two phases. The idea is to first create a list of risks that can positively or negatively impact the organization according to the impact categories listed in Table 6. The next step would be to evaluate the different risks accordingly to determine their potential impact on the project objectives. To do this, the tool selected for implementation is the Failure Mode and Effect Analysis (FMEA), which will be explained hereafter.

FMEA is a structured approach to identifying potential failures and their effects on a system, product or process. It is a proactive risk management tool used to identify, early in the process, the possible causes of failures, their potential effects and the actions that can be taken to prevent or mitigate them. The goal of FMEA is to identify potential problems before they occur and develop plans to reduce the likelihood of failure and improve overall process quality, reliability and safety. FMEA is used in a variety of industries, including automotive, aerospace, healthcare, and manufacturing (ANJALEE ET AL. 2021, pp. 2 - 3).

Normally, a multidisciplinary team works together to identify and analyze potential failure modes and their effects during the FMEA process, which can be applied to various stages of the product lifecycle, including design, development, manufacturing, maintenance, and service. The FMEA process typically includes eight steps (NGUYEN 2021, ROCKWELL AUTOMATION 2022):

1. **Scope Definition:** Define the system, product, or process to be analyzed.
2. **Team Formation:** Assemble a multidisciplinary team of experts who have knowledge and experience with the system, product, or process.
3. **Failure Mode Identification:** Identify all possible failure modes that could occur in the system, product, or process.
4. **Failure Mode Analysis:** Analyze each failure mode to determine its potential effects, causes, and methods of detection.

5. **Risk Assessment:** Assign a severity rating, occurrence rating, and detection rating to each failure mode and calculate the risk priority number (RPN) for each one.
6. **Risk Prioritization:** Prioritize the identified failure modes based on their RPN values and focus on those with the highest risk.
7. **Mitigation Planning:** Develop and implement plans to mitigate or eliminate the identified risks, such as design changes, process improvements, or additional testing.
8. **Follow-up and Monitoring:** Monitor the effectiveness of the mitigation plans and make any necessary adjustments.

An important aspect of FMEA is the use of Risk Priority Numbers (RPNs) to prioritize risks. RPNs are calculated by multiplying the severity, occurrence and detection ratings assigned to each potential failure mode. The severity rating indicates the potential impact of the failure, the occurrence rating indicates the likelihood of the failure occurring, and the detection rating indicates the ability to detect the failure before it occurs. The severity, occurrence, and detection ratings are typically measured on a quantitative scale from zero to ten. The RPN is then assigned based on these factors. The higher the RPN, the higher the priority for mitigation efforts (MASCIA ET AL. 2020, p. 314).

RPNs allow organizations to prioritize their risk mitigation efforts and allocate resources accordingly. It is important to note, however, that RPNs should not be the only factor considered when determining mitigation efforts. Other factors, such as the cost and feasibility of mitigation, should also be considered (MASCIA ET AL. 2020, p. 316 - 318).

Because it is a commonly used tool in industry, it is standardized and governed by standards such as IEC 60812:2018 (VDE VERLAG 2018). FMEA requires input from experts in different areas of the organization, including engineering, manufacturing, quality assurance and customer service. This ensures that all potential failure modes and their effects are thoroughly analyzed and evaluated, and that mitigation plans are comprehensive and effective.

An important aspect of FMEA is that it should not be a one-size-fits-all solution. Instead, it should be tailored to the specific needs and requirements of each organization and should be part of a larger risk management and quality improvement program. In addition, FMEA should not be a one-time event. It should be an ongoing process that is reviewed periodically to ensure it remains relevant and effective. It can be a time-consuming process and requires a high level of expertise and cooperation from a multidisciplinary team. However, the benefits of FMEA, such as reduced costs associated with failure, improved quality and increased customer satisfaction, make it a valuable tool for organizations that prioritize risk management and quality improvement over the long term (BESTERFIELD ET AL. 2012, pp. 277 - 279).

In summary, Failure Mode and Effect Analysis is a powerful risk management tool that strives to deliver high quality products or services while minimizing risk early in the process and ensuring customer satisfaction. By focusing on the highest risks, FMEA enables organizations to make informed decisions, prioritize resources, and improve quality and safety. In addition, FMEA is a continuous improvement process that can be updated and refined over time as new information becomes available. This ensures that the organization's risk management processes remain current and effective (FORD MOTOR COMPANY 2011, pp. 24 - 28).

4.3 REQUIREMENTS AND ADJUSTMENTS FOR SUSTAINABILITY RISK ASSESSMENT IN MANUFACTURING

Since FMEA can be applied to many sectors and industries worldwide, the aim of this section is to provide the context on which this thesis will focus. The goal of the thesis will be to focus on discrete manufacturing companies located in Germany for the year 2022. The requirements were conducted according to the systematic requirements standards for engineering studies (RUPP 2021, pp. 129 - 140, PARTSCH 2010, pp. 56 - 62).

Discrete manufacturing is the process of "creating finished goods by assembling parts that can be easily seen, counted, or touched. Manufacturers using this production process typically assemble parts to create subsystems or finished products" (INBOUND LOGISTICS 2023). An assembly line consisting of multiple workstations is used to produce various components that are finally assembled at the end of the production cycle to create the physical good. In theory, the manufactured products can be disassembled and recycled at the end of their life (HAYES 2023).

Germany is a global hub for discrete manufacturing, with a long history of producing high-quality products in industries such as automotive, machinery, electrical and electronics, chemicals, furniture, apparel, and food processing. Some of the world's best-known discrete manufacturing companies are German, known for their emphasis on quality, innovation, and precision engineering. They have helped establish Germany as a leader in advanced manufacturing and continue to drive innovation and economic growth at home and around the world. Germany's manufacturing sector is a major contributor to the country's economy, accounting for a significant share of GDP and employment. The industry has faced challenges in recent years due to global competition and technological disruption, but German manufacturers continue to innovate and adapt to maintain their position as leaders in the field (ENCYCLOPEDIA BRITANNICA 2023).

The research focuses on discrete manufacturing companies based in Germany for the year 2022, with a particular spotlight on the automotive, mechanical engineering, electrical & electronics, and chemical industries, which are the top four industries in Germany (ORTH 2023). Within each industry, an in-depth analysis of the financial performance as well as the sustainable performance of the top five companies in each industry (based on the revenues or sales generated) is conducted for the given year. Each company is one of the largest contributors in terms of revenue to its respective industry and can be identified as one of the most prominent companies in the world (RESEARCH GERMANY 2023a, 2021, 2023b, 2023c, WIKIMEDIA COMMONS 2023). The list of companies and their respective industries is shown in Table 7.

Table 7: List of analyzed companies in their respective industries (Source: Own representation)

Automotive Industry	**Machinery Industry**	**Electrical & Electronics Industry**	**Chemical Industry**
Volkswagen Group	Siemens AG	Siemens AG	BASF SE
BMW Group	Robert Bosch GmbH	Robert Bosch GmbH	Bayer AG
Mercedes-Benz Group AG	ThyssenKrupp AG	Infineon Technologies	Henkel Group
Opel Automobile GmbH (Stellantis Group)	GEA Group AG	Würth Elektronik GmbH (Wurth Group)	Boehringer Ingelheim GmbH
Ford-Werke GmbH (Ford Motor Company)	Enercon GmbH	Hella KGaA Hueck (Forvia Group)	Merck Group

In order to perform a holistic sustainability risk assessment, sustainability information is required. Considering that only a minority of companies in Germany perform an LCA as it is currently voluntary, the sustainability information will be retrieved from the publicly available sustainability reports conducted internally or externally by the companies. In order to assess the different discrete manufacturing companies operating in Germany, the FMEA analysis will be performed using the impact categories from Table 6.

In assessing the emissions of discrete manufacturing companies in Germany, the study will focus specifically on Scopes 1 and 2. Scope 1 emissions are direct emissions from owned or controlled sources, such as emissions from on-site combustion of fossil fuels or emissions from company-owned vehicles. Scope 2 emissions, on the other hand, are indirect emissions resulting from the generation of purchased electricity, heat, or steam consumed by the company (PLAN A ACADEMY 2023).

The inclusion of both Scope 1 and Scope 2 emissions in the study will provide insight into the direct and indirect emissions of companies, helping to assess their environmental impact and sustainability performance. This information will contribute to a more comprehensive understanding of the companies overall sustainability practices and their potential impact on their respective industries and the environment. Scope 3 emissions, which include indirect emissions from the entire value chain, including suppliers and customers, are not included in the analysis. The reason for this is that the nature of the products manufactured is completely different and comparing the use phase would lead to completely different results. Therefore, only the manufacturing phase is evaluated.

The study will use a quantitative research approach and the research design will be cross-sectional, examining company financial and sustainability data for the year 2022. However, if data for 2022 is not available, the most recently published information will be used as an alternative.

The results of this research will provide valuable insights into the financial and sustainability performance of discrete manufacturing companies in Germany, specifically in the automotive, mechanical engineering, electrical & electronics, and chemical industries. By identifying the top five companies in each industry based on revenue, the study aims to contribute to the understanding of the competitive landscape and economic dynamics of these key industries in Germany. These could provide best practices compared to the industry leader and areas for improvement for individual companies.

Chapter 5. LCA INFORMATION FOR SUSTAINABILITY RISK ASSESSMENT AND IDENTIFICATION

The purpose of this chapter is to develop the concept that will serve as a guide for identifying high, medium, and low risk companies in the manufacturing sector. First, section 5.1 will explain in detail how the 15 impact categories listed in Table 6 can be assessed for each industry to determine sustainability risks. Secondly, section 5.2 provides the summary table for each impact category in each industry. Finally, section 5.3 explains how the risk priority number is calculated for each company and then classified as a low, medium or high-risk company.

5.1 DETAILED EXPLANATION OF THE 15 IMPACT CATEGORIES

In order to develop a risk management tool that is as comprehensive as possible, this work will include all of the impact categories listed in Table 6 in the tool. The idea is to develop a tool that is as generic as possible and can be applied to any company in any sector or industry.

Below is a description of each impact category and the corresponding unit of measurement. It is important to note that some of the units are not exactly the same as those listed in Table 6. This is due to the fact that the literature found to analyze some of the impact categories used different units. Where this is the case, conversion techniques are used. Finally, for each impact category, it is explained how the low, medium and high-risk values were determined, including specific examples where appropriate:

1. Climate Change (tons CO_2 eq emitted/M€ Revenue)

In order to assess the level of CO_2 eq emissions that could be considered "high", a comprehensive approach was taken that took into account the potential influence of company size. First, the automotive industry had to be treated differently than the other three industries because more detailed information was available for each vehicle, while the other industries had more general data. To do this, the total vehicle sales in Germany for each automaker were multiplied by the tons of CO_2 eq emitted per vehicle (this information was found in each company's sustainability report). This value was then divided by the revenue generated in Germany to obtain the average tons of CO_2 eq emitted per million revenues generated in Germany for the top five automakers. Another measure of the same order of magnitude, but in a different unit, would be grams of CO_2 eq emitted per euro of revenue generated, which would be more appropriate for smaller companies.

Table 8 below shows the specific emissions intensity for the automotive industry in Germany in 2022 and how it was calculated. Based on the average value of **12.59 tons of CO_2 eq emitted per million of revenue generated**, it was decided that companies emitting less than 80% of the average value would be considered low risk, companies emitting more than 120% of the average value would be considered high risk, and those in the middle would be considered medium risk.

Table 8: Specific values for CO_2 emissions in the automotive industry in Germany (Source: Own representation)

Company	Vehicles sales Germany	t CO_2 eq per vehicle	Mt CO_2 eq Germany	M€ Revenues Germany	t CO_2 eq emitted/M€ Revenue Germany	Source 1	Source 2
Volkswagen Group	1029623	0,651	0,670	49054	13,66	Volkswagen Group 2023a, pp. 128, 129, 333	Volkswagen Group 2023b, p. 53
BMW Group	278421	0,320	0,089	15413	5,78	BMW Group 2023, pp. 68, 72, 109, 232	
Mercedes-Benz Group AG	328800	0,303	0,100	23085	4,32	Mercedes-Benz Group 2023a, pp. 52, 53, 57	Mercedes-Benz Group 2023b, p. 116

Opel GmbH (Stellantis Group)	371000	0,350	0,130	9046	14,35	Stellantis N.V. 2023, pp. 39, 286	Stellantis N.V. 2021, p. 83
Ford Motor Company	182000	0,810	0,147	5937	24,83	FORD MOTOR COMPANY 2023a, pp. 4, 178	FORD MOTOR COMPANY 2023b, p. 81
AVERAGE	**437969**	**0,487**	**0,227**	**20507**	**12,59**		

A similar approach was used for the remaining industries: chemicals, electrical & electronics, and machinery. To account for differences in local company size relative to the global market, the revenue generated by each company in Germany was divided by the company's total global revenue. This resulted in a relative size value for each company in its respective German industry. However, since data on total CO_2 eq emissions per country was not available, the relative size of each company was used as a proxy to allocate total emissions (available data) to Germany. The allocated emissions were then divided by the revenues generated in Germany to obtain the average tons of CO_2 eq emitted per million revenues generated (or grams of CO_2 eq emitted per euro generated) for the top companies in each industry. The tables with the specific emission intensity values of the CO_2 eq for the remaining three sectors in Germany can be found in Appendix III.

This approach allows for a normalized assessment of emissions intensity that accounts for differences in company size and provides a more comprehensive understanding of the relative emissions intensity associated with revenue generation in each industry in the German context.

2. Stratospheric Ozone Depletion (kg CFC - 11 eq/M€ Revenue)

The stratospheric ozone depletion potential was also assessed using a similar approach based on global warming potential (GWP) values as defined by the Intergovernmental Panel on Climate Change (IPCC). The GWP value for CFC-11 over 100 years was considered to be

4660, which means that 1 kg CFC-11 eq is equivalent to 4660 kg CO_2 eq in terms of its global warming potential over a time horizon of 100 years (IPCC 2013, p. 731).

Using this information, high, medium and low values for kg CFC - 11 eq were calculated for companies in German industry, taking into account the climate impact category. These values were further normalized to the total revenues generated by the companies in 2022. This approach allowed a comprehensive assessment of the potential impact of CFC-11 eq emissions on stratospheric ozone depletion, taking into account the global warming potential and the company's revenue generation as a normalization factor.

3. Cancer and non-cancer Human Toxicity (mg 1,4 - DB eq/m^3 air)

In assessing the category of human toxicity effects, including both cancer and non-cancer effects, the hazardous substance 1,4-dibromutane (1,4 - DB) has been classified as a Highly Hazardous Substance under the Canadian regulation at OSHA 29 CFR 1910.1200 (SANTA CRUZ BIOTECHNOLOGY, INC. 2010, p. 7). Section 8 of the regulation, which provides information on exposure controls and personal protection, states that concentrations of 1,4 - DB eq greater than 100 mg/m3 in air are considered harmful to humans.

Based on this information, a risk classification was established for 1,4 - DB exposure levels. Airborne concentrations below 60 mg/m^3 were considered low-risk, concentrations between 61 and 99 mg/m^3 were considered moderate-risk, and airborne concentrations equal to or greater than 100 mg/m^3 were considered high-risk in terms of human toxicity effects. Because this information affects human health regardless of the work performed, the same thresholds were considered for the four industries analyzed.

This classification system serves as a reference for evaluating the potential risks associated with exposure to 1,4 - DB in air with respect to human health, taking into account the exposure controls and personal protection measures specified by OSHA 29 CFR 1910.1200 (US DEPARTMENT OF LABOR 2023).

4. Fine Particulate Matter Formation (µg/m³ air)

In assessing the impact category of particulate matter formation, the European Commission issued Directive 2008/50/EC, which sets air quality standards and objectives for the European Union (EU). As part of this directive, PM2.5 objectives have been set at the national level to target population exposure to particulate matter. The average exposure indicator used to set these objectives is calculated as the 3-year running annual mean PM2.5 concentration averaged over selected monitoring stations in agglomerations and larger urban areas (EUROPEAN COMMISSION 2023a).

The limit value to be met by January 1, 2020, according to Directive 2008/50/EC, is set at 20 µg/m³ of air (EUROPEAN COMMISSION 2023b). Based on this, a risk classification has been established for PM2.5 concentrations. Concentrations below 10 µg/m³ of air were considered low risk, concentrations between 11 and 19 µg/m³ of air were considered medium risk, and concentrations greater than or equal to 20 µg/m³ of air were considered high risk with respect to the effects of particulate matter formation. These concentration limits were considered the same for the four industries analyzed throughout the thesis.

This classification system provides a framework for assessing the potential risks associated with different PM2.5 concentration levels in relation to EU air quality standards and objectives, with the aim of protecting public health from exposure to particulate matter pollution.

5. Ionizing Radiation (Bq/m³ air)

In assessing the ionizing radiation impact category, a conversion of units was needed to measure the risk levels. In a life cycle assessment, the impact indicator is typically measured in kg U-235 eq per cubic meters of air. However, to assess the hazardous effects of ionizing radiation on human health, it was necessary to convert to Becquerels (Bq) per m^3 of air, a unit used to measure radioactivity.

The specific activity of U-235, which represents the radioactivity of U-235, is 80 Bq/mg. This means that 1 kg of U-235 eq/m^3 of air is equivalent to 80 million Bq/m^3 of air (IAEA 2023).

According to the World Health Organization (WHO), radon is a radioactive gas produced by the natural radioactive decay of uranium. Radon concentrations are generally low outdoors due to rapid dilution, but can be higher indoors and in areas with minimal ventilation, posing a potential health risk, particularly for lung cancer. Therefore, WHO has established a national annual average indoor radon concentration reference level of 100 Bq/m^3 air, below which there is a low risk of ionizing radiation effects. Reference levels for high risk in indoor concentrations are considered to be 300 Bq/m^3 of indoor air. Values in between are considered moderate risk (WORLD HEALTH ORGANIZATION 2023).

These reference levels provide a framework for assessing the potential risks associated with radon concentrations in indoor air, regardless of the industry being analyzed, in relation to WHO guidelines for the protection of public health from exposure to ionizing radiation.

6. Photochemical Ozone Formation (tons C_2H_4 eq emitted/M€ Revenues)

For the Photochemical Ozone Creation Effect category, an approach similar to that used for the Stratospheric Ozone Depletion Effect category was followed, but using Global Warming Potential (GWP) values for non-methane volatile organic compounds (NMVOCs) from the Intergovernmental Panel on Climate Change (IPCC) for a 100-year time horizon (IPCC 2012).

In the table, the GWP value for ethylene (C_2H_4) is listed as 3.7. This means that 1 kg of C_2H_4 eq is equivalent to 3.7 kg of CO_2 eq in terms of its global warming potential over a 100-year time horizon.

Once the averages for each industry have been calculated, low-risk companies are those that emit up to 80% of the average tons of C_2H_4 eq emitted (normalized by the revenue of each company in the industry), while high-risk companies are those that emit more than 120% of the industry average. Companies that fall between these ranges are considered medium risk.

This approach makes it possible to assess ethylene equivalent emissions in terms of their contribution to photochemical ozone creation, which is a key factor in air pollution and smog formation. By comparing a company's emissions to industry averages and applying risk thresholds, this approach helps identify companies that may be contributing more or less to this impact category.

7. Terrestrial and Freshwater Acidification (µg SO_2 eq/m^3 air)

For the terrestrial and freshwater acidification impact category, data from the European Environment Agency's 2019 Air Quality in Europe report was used. The EU has set limit values for sulphur dioxide (SO_2) to protect vegetation in designated zones under the Air Quality Directive 2008/EC/50 (EUROPEAN ENVIRONMENT AGENCY 2014). The limit value for the annual average concentration of SO_2 is set at 20 µg/m^3 to prevent damage to the health of humans and vegetation. In addition, there is a limit of 350 µg/m^3 that cannot be exceeded for very short periods of time (less than one hour) (EUROPEAN ENVIRONMENT AGENCY 2019, pp. 13, 45).

Based on these values, low-risk companies are those that emit less than 15 µg SO_2 eq per m^3 of air on an annual average. High-risk companies are those that emit more than 20 µg SO_2 eq per m^3 of air, which is the EU limit. Companies that fall in between are considered medium risk. The same values are used for all companies in the four sectors analyzed. This approach makes it possible to assess emissions of SO_2, which is a major contributor to acidification of both terrestrial and fresh water, and helps to identify companies that may be contributing less or more to this impact category.

8. Freshwater Eutrophication (mg PO_4 eq/L water)

For the freshwater eutrophication impact category, information from the Water Framework Directive (WFD), more specifically Directive 2000/60/EC was used (DIARIO OFICIAL DE LAS COMUNIDADES EUROPEAS 2000, EUROPEAN COMMISSION 2023c). This Directive establishes rules to prevent the deterioration of the status of water bodies in the EU and to achieve good status for rivers, lakes and groundwater. France has implemented this directive and set limit values for several pollutants in freshwater, but since it is an EU directive, the same values have been adopted for Germany.

Based on the information obtained, values less than 0.5 mg PO_4 eq/L water are considered good quality and therefore low risk. Values between 0.6 and 1.9 mg PO_4 eq/L water are considered as medium quality and hence medium risk businesses, while values above 2 mg PO_4 eq/L water are considered as poor quality and thus high risk businesses (MEDD & AGENCES DE L'EAU 2003, p. 3). This approach allows the assessment of phosphorus equivalent emissions, which are a major contributor to freshwater eutrophication, and helps to identify companies that may be contributing to good, moderate or poor freshwater quality based on the established thresholds.

9. Marine Eutrophication (mg N eq/L water)

For the marine eutrophication impact category, information from the Water Framework Directive was again used. Directive 2000/60/EC provides guidelines for assessing the quality of marine waters (EUROPEAN COMMISSION 2023c). Based on this Directive, values below 2 mg N eq/L water are considered good quality and therefore low risk. Values between 2.1 and 9.9 mg N eq/L water are considered as moderate quality and thus medium risk, while values equal to or above 10 mg N eq/L water are considered as poor quality and consequently high risk (MEDD & AGENCES DE L'EAU 2003, p. 25). This approach allows the assessment of nitrogen emissions, which are a major contributor to marine eutrophication.

10. Terrestrial Eutrophication (mg PO_4 eq/L water)

The terrestrial eutrophication impact category uses the same unit of measurement as the freshwater eutrophication impact category, namely mg PO_4 eq per liter of water. This is because the objective is to assess the potential impact on groundwater in terrestrial ecosystems. Therefore, the same thresholds for phosphorus equivalent concentration in water have been used because the hazardous effects are the same whether the water is freshwater or groundwater. The effects of the phosphorus equivalent are also found in the soil surrounding the groundwater. Values below 0.5 mg PO_4 eq/L water are considered good quality and consequently low risk, values between 0.6 and 1.9 mg PO_4 eq/L water are considered moderate quality and therefore medium risk, and values equal to or above 2 mg PO_4 eq/L water are considered poor quality and thus high risk (MEDD & AGENCES DE L'EAU 2003, p. 3). Again, these values apply to any company operating in any of the four industries analyzed in this thesis.

11. Freshwater and Terrestrial Ecotoxicity Potential (mg 1,4 - DB eq/m^3 air)

The ecotoxicity potential impact category serves as an indicator of the potential impact of toxic substances released into the environment on freshwater and terrestrial ecosystems. These substances have a tendency to accumulate in living organisms and can cause harm to individual species and disrupt ecosystem functioning. The unit of measurement for this effect category is milligrams of 1,4 - dichlorobenzene (1,4 - DB) equivalent per cubic meter of air, which is the same unit used for the effect category for human carcinogenic and non-carcinogenic toxicity. Therefore, according to information provided in Section 8 of the OSHA 29 CFR 1910.1200 exposure controls regulation, levels below 60 mg/m^3 are considered low risk, levels between 61 and 99 mg/m^3 are considered moderate risk, and levels above 100 mg/m^3 are considered high risk (SANTA CRUZ BIOTECHNOLOGY, INC. 2010, p. 7). These thresholds are the same for all four industries analyzed and can be used to assess the potential environmental risk of companies in terms of potential ecotoxicity impacts based on the concentration of 1,4 – DB equivalent in air emissions.

12. Land Use (tons soil loss eq used/M€ revenue)

The land use impact category was evaluated based on the planet boundary of kilograms of soil loss equivalent, as determined by SALA ET AL. (2020) using environmental factor metrics in the LCA results. The planet boundary was set at 1.27 x 10^13 kg soil loss eq (SALA ET AL. 2020, p. 7). To assign this planet boundary to the analyzed country, Germany, the country's GDP was considered. In 2020, Germany's GDP was US$3.89 trillion, representing 4.6% of the world's GDP, as shown in Figure 9 below. Therefore, the allocated land use limit for Germany was calculated to be 5.80 x 10^11 kg soil loss equivalent.

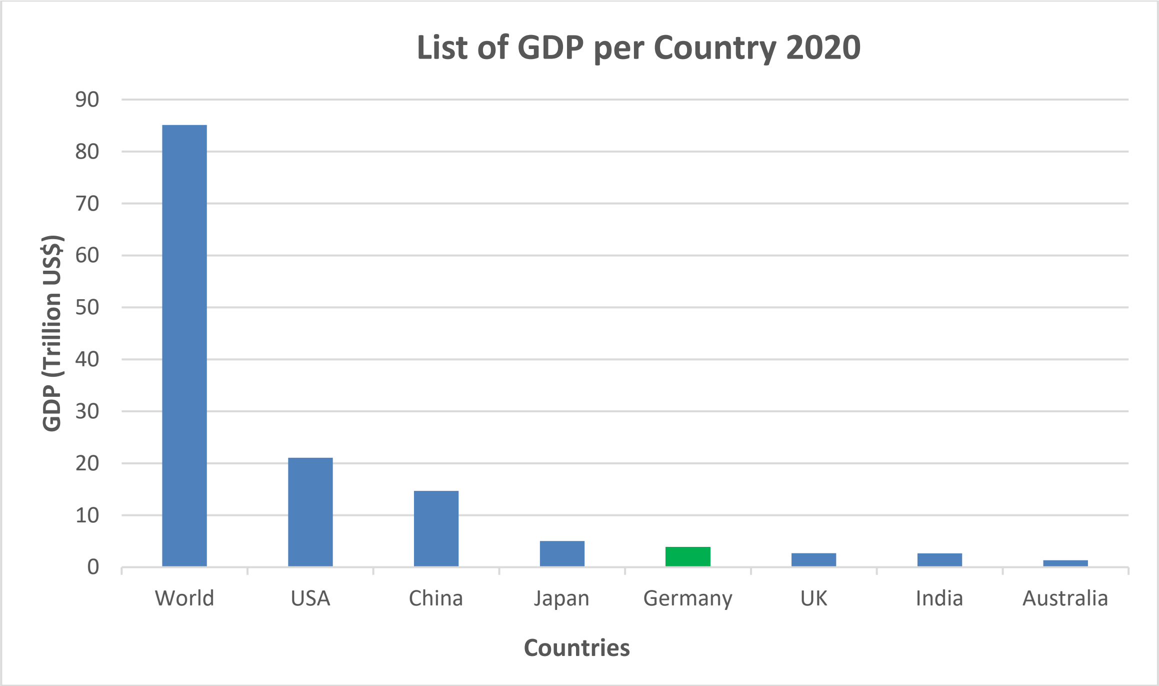


Figure 9: List of GDP per country 2020 (Source: Own representation based on WORLD BANK OPEN DATA 2023)

However, since the scope of the study was limited to the German manufacturing industry, the next step was to determine the gross value added of all activities contributing the most to GDP. Among these activities, the manufacturing industry had the largest contribution to GDP with 21%, which corresponds to a total of 1.20 x 10^11 kg soil loss equivalent, as shown in the following Table 9.

Table 9: Contribution to GDP by all German activities in 2020 (Source: Own representation based on EUROSTAT 2023a)

	Current prices, M€ (2020)	**Percentage of GDP (2020)**
Total - all activities	3.087.963	100%
Manufacturing	**636.977**	**21%**

Public administration, defense, education, human health, social work activities	604.572	20%
Wholesale and retail trade, transport, accommodation, and food service activities	479.023	16%
Professional, technical, administrative & support service activities	350.098	11%
Real estate activities	332.634	11%
Construction	167.329	5%
Information and communication	154.671	5%
Financial and insurance activities	123.517	4%

Subsequently, the gross value added was determined for the four analyzed industries within the manufacturing sector, namely automotive, mechanical engineering, electrical and electronics, and chemicals. To serve as an example, the **automotive industry accounts for 21% of the total manufacturing industry and 4% of the total GDP of Germany in 2020**. This information was used to assign the respective soil loss values to each industry, as shown in the following Table 10.

Table 10: Contribution to the manufacturing sector by the four analyzed industries (Source: Own representation based on EUROSTAT 2023b)

	Current prices, M€ (2020)	**Percentage of Manufacturing (2020)**	**Percentage of GDP (2020)**
Total - all activities	3.087.963	-	100%
Manufacturing	636.977	100%	21%

Manufacture of motor vehicles, trailers, and of other transport equipment	**131.938**	**21%**	**4%**
Manufacture of machinery and equipment	93.993	15%	3%
Manufacture of chemicals and chemical products	49.386	8%	2%
Manufacture of electrical equipment	43.055	7%	1%
Manufacture of computer, electronic and optical products	42.344	7%	1%

To further refine the assessment, the tons of soil loss equivalent were normalized by dividing each value by the average revenue generated by the top five companies in each industry. This resulted in a normalized land use impact for a company based on the revenue it generated. Companies with values below 80% of the average were considered low risk, those above 120% of the average were considered high risk, and those in between were considered medium risk.

The values of the normalized land use impact for a company based on its generated revenues for the four industries analyzed, as well as the total planet boundary land use, are shown in the following Table 11.

Table 11: Values of the normalized land use impact and total planet boundary land use (Source: Own representation)

	Planet Boundary Land use (kg soil loss eq)	**Tons soil loss eq land used per million € revenue generated**
Germany	5,80E+11	-
Manufacturing Sector	1,20E+11	-
Automotive Industry	2,48E+10	**1209,21**

Mechanical Engineering Industry	1,77E+10	**1682,51**
Electrical & Electronics Industry	1,61E+10	**2058,81**
Chemical Industry	9,28E+09	**2087,30**

13. Water Use (m^3 freshwater withdrawn/M€ Revenue)

The water use impact category was evaluated by normalizing freshwater withdrawals to the revenue generated by each company to account for the potential influence of company size. In the case of the automotive industry, a more detailed approach was required due to the availability of specific information for each vehicle. Total vehicle sales in Germany per automaker were multiplied by the freshwater cubic meters consumed per vehicle, which was obtained from the companies' respective sustainability reports. The resulting value was then divided by the revenue generated in Germany to obtain the average water consumption per million revenues generated for the top five automakers.

Table 12 presents the specific water consumption for the automotive industry in Germany in 2022, along with the calculations used to obtain these values. Based on the average water consumption of **88.17 m^3 per million sales** generated, companies that consume less than 80% of this average are considered low risk, while those that consume more than 120% are classified as high risk. Companies that fall between these thresholds are considered medium risk. This approach allows for a more comprehensive assessment of the impact of water use, taking into account both the absolute amount of water used and the size and revenue of the company.

Table 12: Specific values for freshwater consumption in the automotive industry in Germany (Source: Own representation)

Company	**Vehicles sales Germany**	**m^3 freshwater per vehicle**	**M m^3 freshwater consumed Germany**	**M€ Revenues Germany**	**m^3 freshwater Germany/M€ Revenue**	**Source 1**	**Source 2**
Volkswagen Group	1029623	3,75	3,86	49054	78,71	Volkswagen Group 2023a, pp. 128, 129, 333	Volkswagen Group 2023b, pp. 31,32
BMW Group	278421	1,9	0,53	15413	34,32	BMW Group 2023, pp. 68, 72, 108, 315	
Mercedes-Benz Group AG	328800	4,07	1,34	23085	58,03	Mercedes-Benz Group 2023a, pp. 52, 53, 57	Mercedes-Benz Group 2023c
Opel GmbH (Stellantis Group)	371000	3,91	1,45	9046	160,36	Stellantis N.V. 2023, pp. 39, 286	Stellantis N.V. 2021, pp. 41, 240
Ford Motor Company	182000	3,57	0,65	5937	109,44	FORD MOTOR COMPANY 2023a, pp. 4, 178	FORD MOTOR COMPANY 2023c, p. 20
AVERAGE	**437969**	**3,44**	**1,57**	**20507**	**88,17**		

For the other industries, the same approach as for the automotive industry was used to account for potential differences in company size. This was done by dividing the revenue generated by each company in Germany by the company's total worldwide revenue. This allowed a relative size value to be calculated for each company within its respective industry in Germany.

Since data on total freshwater withdrawal per country was not available, the relative size of each company was used as a proxy to allocate water consumption to Germany. The allocated freshwater consumption in cubic meters was then divided by the revenues generated in Germany to obtain the average freshwater consumption per million revenues generated for the top companies in each industry.

Tables showing the specific freshwater consumption of the chemical, electrical and electronic, and machinery industries in Germany are provided in Appendix IV.

14. Fossils Resource Depletion (MWh eq Energy consumed/M€ Revenue)

For the fossil resource depletion impact category, a similar approach was used as for the water use impact category. The total energy consumed by the company was divided by the revenue generated to determine the risk of the companies analyzed. However, due to the complexity of the energy consumption analysis, only the automotive industry was analyzed in detail, while the other industries were evaluated based on the relative size of the company compared to their worldwide operations.

Table 13 contains the specific energy consumption for the automotive industry in Germany in 2022. Based on the average energy consumption of **57.02 MWh per million sales generated**, companies that consume less than 80% of this average are considered low risk, while those that consume more than 120% are classified as high risk. Companies that fall between these thresholds are considered medium risk. This approach provides a useful indicator for companies to understand their energy consumption and their relative position in terms of risk compared to other companies in their industry.

Table 13: Specific values for energy consumption in the automotive industry in Germany (Source: Own representation)

Company	**Vehicles sales Germany**	**MWh consumed per vehicle**	**GWh consumed Germany**	**M€ Revenues Germany**	**MWh Energy consumed/M€ Revenue**	**Source 1**	**Source 2**
Volkswagen Group	1029623	2,16	2227	49054	45,40	VOLKSWAGEN GROUP 2023a, pp. 128, 129, 333	VOLKSWAGEN GROUP 2023b, pp. 31,32

BMW Group	278421	2,13	593	15413	38,48	BMW Group 2023, pp. 68, 72, 108, 315	
Mercedes-Benz Group AG	328800	3,05	1004	23085	43,49	Mercedes-Benz Group 2023a, pp. 52, 53, 57	Mercedes-Benz Group 2023c
Opel GmbH (Stellantis Group)	371000	1,98	735	9046	81,20	Stellantis N.V. 2023, pp. 39, 286	Stellantis N.V. 2021, pp. 41, 240
Ford Motor Company	182000	2,50	454	5937	76,53	FORD MOTOR COMPANY 2023a, pp. 4, 178	FORD MOTOR COMPANY 2023c, p. 20
AVERAGE	**437969**	**2,36**	**1003**	**20507**	**57,02**		

Tables with specific energy consumption values for the chemical, electrical and electronic, and mechanical engineering industries in Germany can be found in Appendix IV.

15. Minerals and Metals Resource Depletion (kg Sb eq used/M€ revenue Germany)

The minerals and metals resource depletion impact category was evaluated using a similar approach to the land use impact category. The planet boundary for minerals and metals resource depletion was set at 2.19 x 10^8 kg Sb eq, as determined by Sala et al. (2020, p.7) using environmental factor metrics in the LCA results. In order to assign this planet boundary to Germany, the GDP of different countries worldwide and specifically for Germany were considered. The values of the GDP of the most important countries in the world and the resources used are found in Table 14.

Table 14: List of GDP per country for 2020 (Source: Own representation based on WORLD BANK OPEN DATA 2023)

Country	GDP (Trillion US$)	% Global GDP	Planet Boundary Resource Use, Mineral and Metals (kg Sb eq)
World	85,12	100%	2,19E+08
USA	21,06	24,7%	5,42E+07
China	14,69	17,3%	3,78E+07
Japan	5,04	5,9%	1,30E+07
Germany	**3,89**	**4,6%**	**1,00E+07**
UK	2,70	3,2%	6,96E+06
India	2,67	3,1%	6,86E+06

Next, the gross value added of the activities that contribute most to Germany's GDP was determined using data from Table 9 and Table 10. This allowed the calculation of the kilograms of Sb equivalent allocated to the manufacturing sector, specifically for the four industries of interest.

To assess the overall risk of companies, the kilograms of Sb equivalent consumed were normalized by dividing the value of each industry by the average of the revenues generated by the top five companies in each industry. This resulted in a normalized resource depletion impact for each company based on its generated revenues. Companies with values below 80% of the average were considered low risk, those above 120% of the average were classified as high risk, and those in between were considered medium risk.

The normalized resource depletion impact values for a company based on its generated revenue for the four industries analyzed, as well as the total planet limit, are shown in the following Table 15.

Table 15: Values of the normalized resource depletion impact and total planet boundary (Source: Own representation)

	Planet Boundary Resource Use, mineral and metals (kg Sb eq)	**kilograms Sb eq used per million € revenue generated**
Germany	1,00E+07	-
Manufacturing Sector	2,06E+06	**-**
Automotive Industry	4,28E+05	**20,85**
Mechanical Engineering Industry	3,05E+05	**29,01**
Electrical & Electronics Industry	2,77E+05	**35,50**
Chemical Industry	1,60E+05	**35,99**

5.2 SUMMARY TABLE FOR THE THRESHOLD VALUES OF THE 15 IMPACT CATEGORIES

Table 16 below provides a summary of the thresholds for the fifteen impact categories analyzed in section 5.1. Each impact category contains both high and low values that determine the risk to the company included in each of the four industries analyzed.

Table 16: Summary table containing the high and low values that determine the threshold values for the fifteen impact categories analyzed throughout the four industries (Source: Own representation)

		Automotive Industry		**Mechanical Engineering Industry**		**Electrical & Electronics Industry**		**Chemical Industry**	
Impact Category	**Impact Indicator Unit**	**Low Values**	**High Values**	**Low Values**	**High Values**	**Low Values**	**High Values**	**Low Values**	**High Values**
Climate change	tons CO_2 eq emitted/M€ Revenue Germany	10,07	15,11	10,97	16,46	21,52	32,29	92,97	139,46
Stratospheric ozone depletion	kg CFC-11 eq/M€ Revenue Germany	2,16	3,24	2,35	3,53	4,62	6,93	19,95	29,93
Human toxicity (cancer and non-cancer)	mg 1,4-DB eq/ m^3 air	60	100	60	100	60	100	60	100
Fine particulate matter formation	µg/m^3 air	10	20	10	20	10	20	10	20
Ionizing radiation	Bq/m^3 air	100	300	100	300	100	300	100	300
Photochemical ozone formation	t C_2H_4 eq emitted/M€ Revenues Germany	2,72	4,08	2,97	4,45	5,82	8,73	25,13	37,69
Acidification (terrestrial, freshwater)	µg SO_2 eq/m^3 air	15	20	15	20	15	20	15	20

Eutrophication (freshwater)	mg PO_4 eq/L water	0,5	2	0,5	2	0,5	2	0,5	2
Eutrophication (marine)	mg N eq/L water	2	10	2	10	2	10	2	10
Eutrophication (terrestrial)	mg PO_4 eq/L water	0,5	2	0,5	2	0,5	2	0,5	2
Ecotoxicity potential (freshwater, terrestrial)	mg 1,4-DB eq/ m^3 air	60	100	60	100	60	100	60	100
Land use	tons soil loss eq/M€ revenue Germany	967,4	1451,0	1346,0	2019,0	1647,0	2470,6	1669,8	2504,8
Water use	m^3 freshwater withdrawn/M€ Revenue in Germany	70,5	105,8	1813,3	2719,9	467,4	701,1	4529,2	6793,8
Resource depletion (fossils)	MWh eq Energy consumed/M€ Revenue Germany	45,62	68,43	358,28	537,41	63,66	95,48	274,78	412,17
Resource depletion (minerals and metals)	kg Sb eq used/M€ revenue Germany	16,68	25,02	23,21	34,82	28,40	42,60	28,79	43,19

5.3 DETERMINATION OF RISK PRIORITY NUMBER

Once the thresholds for the 15 impact categories were determined in the previous section 5.2, the next step was to calculate the company's Risk Priority Number (RPN) according to the values entered in the Excel template derived from the LCA. The template also includes a weighting column in case more or less importance is to be given to a specific impact category.

The RPN is calculated according to the next formula:

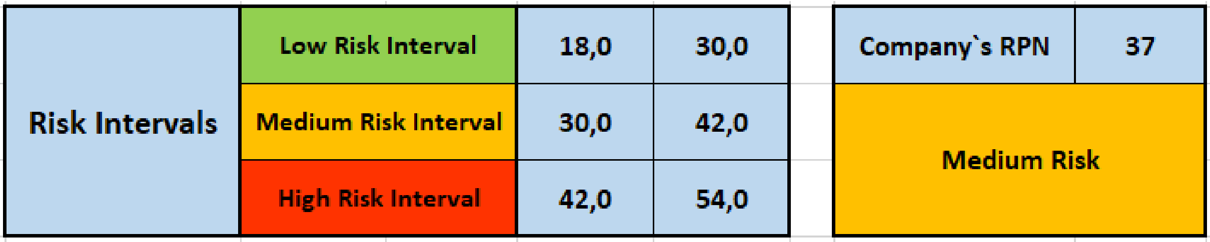
$$RPN = \sum_i SRV_i * O_i * D_i \qquad (2)$$

where SRV is the Severity Risk Value Indicator, O is the Occurrence Factor and D is the Detection Indicator. This operation is performed for each of the 15 impact categories and then the values are added together.

The severity risk value is calculated by multiplying the individual risk of each indicator by its respective weight. Since risk is to be quantified and the previous section only distinguished between low, medium and high risk, it was first necessary to convert the attributes into quantifiable factors. To do this, low risk categories were assigned a value of 1, medium risk categories a value of 2, and high-risk categories a value of 3. These values may be adjusted in the future as they might depend on the needs of the companies.

The occurrence and detection values in the tool were initially set to 1, as this is the base scenario. However, the values can be customized for each company and the calculations are done automatically.

Finally, the tool will determine the overall RPN of the company and will also display the low, medium and high-risk intervals for the weightings introduced (as they may vary from company to company). It will then automatically derive the overall risk of the company according to these intervals. An example of the tool's output is shown in the following Figure 10.



Risk Intervals	🟩 Low Risk Interval	18,0	30,0
	🟨 Medium Risk Interval	30,0	42,0
	🟥 High Risk Interval	42,0	54,0

Company`s RPN	37
🟨 Medium Risk	

Figure 10: Example of the risk intervals and the overall company's RPN (Source: Own representation)

Chapter 6. ECONOMIC ANALYSIS

In the following chapter 6, the possibility of incorporating the results of the concept developed in chapter 5 to assess sustainability risk in manufacturing companies will be examined. First, section 6.1 provides an introduction to the Capital Asset Pricing Model (CAPM), which is then adapted in section 6.2 to include sustainability in order to assess the risk within the expected return of an investment.

6.1 CAPITAL ASSET PRICING MODEL

The Capital Asset Pricing Model (CAPM) is a widely used financial model that helps investors evaluate the expected return on an investment. It has become an important tool for investors and financial analysts and its purpose is to describe "the relationship between systematic risk, or the general hazards of investing, and the expected return on assets" (KENTON 2003).

The CAPM model calculates the expected return of an asset by taking into account the risk-free rate of return, the expected market return, and the beta of the asset. The CAPM formula is as follows:

$$E(R_i) = R_f + \beta_i * \left(\mathrm{E}(R_m) - R_f \right), \tag{3}$$

where $E(R_i)$ is the expected return an investor expects to receive from an investment in the asset, R_f is the risk-free rate, which is the rate of return on a risk-free investment such as a U.S. Treasury bond (typically analyzed over a 10-year period), β_i is a measure of the volatility of an asset relative to the market, and $\mathrm{E}(R_m)$ is the expected return of the market in which the company operates.

In the formula, beta represents the sensitivity of the asset's returns to movements in the market. A beta of 1 means that the asset's returns move in line with the market, while a beta greater than 1 means that the asset is more volatile than the market, and a beta less than 1 means that the asset is less volatile than the market (CORPORATE FINANCE INSTITUTE 2020).

The CAPM formula allows investors to determine the expected return on an investment based on its risk-free rate plus a premium proportional to the asset's beta. The premium is calculated by multiplying the market risk premium (the difference between the expected market return and the risk-free rate) by the asset's beta. The model assumes that investors are rational and risk-averse, i.e. they demand a higher expected return for taking on additional risk. The model also assumes that investors have access to all relevant information about an asset and will diversify their portfolios to reduce risk (CORPORATE FINANCE INSTITUTE 2020).

While the CAPM is a useful tool for evaluating the expected return of an investment and understanding the relationship between risk and return in financial markets, it has some limitations. Some of these are listed below (ACCA 2023, DIKSHA 2017):

1. **Assumptions:** The CAPM is based on several assumptions that may not hold true in the real world. For example, it assumes that all investors have access to the same information and that they are all rational and risk averse. These assumptions may not always hold in practice, which can affect the accuracy of the model.
2. **Market efficiency:** The CAPM assumes that financial markets are efficient. What this means is that all assets are priced correctly based on all available information. Markets, nonetheless, may not always be efficient, which can lead to mispricing of assets and affect the accuracy of the model.
3. **Beta measurement:** The accuracy of the CAPM depends on the actual correctness of the beta measurement, which is often estimated based on historical data. However, historical data may not always be a reliable indicator of future performance, which can affect the accuracy of the beta measurement and the overall accuracy of the CAPM.
4. **Ignoration of other factors:** The CAPM considers only the risk-free rate and the market return as factors affecting asset returns. It does not take into account other factors that may affect returns, such as inflation, interest rates, or changes in market conditions.

Another important limitation is that the CAPM does not explicitly incorporate sustainability or environmental, social and governance factors. The model is primarily focused on measuring the risk and return of financial assets based on their exposure to systematic risk factors, such as changes in the overall market or interest rates.

Therefore, the objective of section 6.2 is to find a way to incorporate these factors into the CAPM.

6.2 IMPLEMENTATION OF A SUSTAINABILITY FACTOR TO THE CAPM MODEL

Despite its limitations, the CAPM model remains a popular tool for evaluating the expected return on an investment and understanding the relationship between risk and return in financial markets. As mentioned in section 6.1, the main limitation that will be addressed throughout this thesis is the fact that the CAPM does not take into account sustainability or environmental factors, but rather focuses solely on economic factors.

However, there is a growing interest in integrating environmental, social and political factors into financial analysis and decision making. Both researchers and investors have proposed modifications to the CAPM that incorporate sustainability factors, such as adjusting the expected return of an asset based on its sustainable performance or incorporating sustainability factors into the beta calculation (ZERBIB 2022, pp. 1346 - 1348).

The way in which sustainability will be incorporated in this thesis is by adapting the CAPM to include an additional variable that will be referred to as γ_{sust}. This variable will serve as a sustainability indicator that will affect the expected return calculated with the CAPM model. The adjusted CAPM formula is as follows:

$$E(R_i) = R_f + \beta_i * \boldsymbol{\gamma_{sust}} * \left(\mathrm{E}(R_m) - R_f \right), \tag{4}$$

where all variables are the same as in the CAPM formula except for γ_{sust}, which serves as a sustainability indicator for each company.

As can be seen in the previous formula, if γ_{sust} equals 1, it has no impact at all on the CAPM. A company with a γ_{sust} value of 1 would be one where most, if not all, of its impact indicators are slightly above or below the industry averages. The way in which γ_{sust} is calculated is the following:

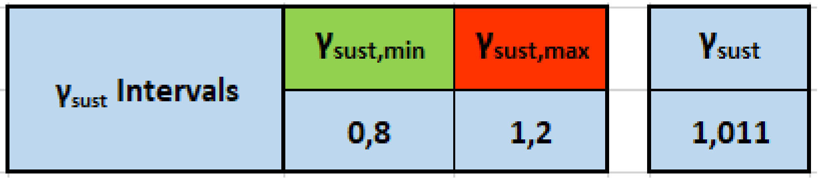
$$\gamma_{sust} = \gamma_{sust,min} + (\mathrm{RPN} - RPN_{\mathrm{min}}) * \frac{(\gamma_{sust,\mathrm{max}} - \gamma_{sust,min})}{(RPN_{max} - RPN_{min})}, \tag{5}$$

where $\gamma_{sust,max}$ and $\gamma_{sust,min}$ are the maximum and minimum values of the interval of γ_{sust}, respectively, and RPN_{max} and RPN_{min} are the maximum and minimum values of the interval of RPN, respectively.

All the parameters involved in the formula depend on the weighting values entered manually, which may be different for each company. Therefore, the general formula has been given. However, for the base scenario, where all weightings are equal to one and the range of γ_{sust} was set between 0.8 and 1.2 to lock the effect of γ_{sust}, the formula is as follows:

$$\gamma_{sust} = 0.8 + (\mathrm{RPN} - 15) * \frac{(1.2 - 0.8)}{(45 - 15)} \tag{6}$$

Thanks to the previous equation, the γ_{sust} of each company can be automatically calculated in the Excel template according to the input parameters introduced by each company. An example of the output of the γ_{sust} calculation tool is presented in the following Figure 11.



γ_{sust} Intervals	$\gamma_{sust,min}$	$\gamma_{sust,max}$	γ_{sust}
	0,8	1,2	1,011

Figure 11: Example of the output of the tool including γ_{sust} and its intervals (Source: Own representation)

If γ_{sust} is less than 1, it would mean that the company is more sustainable than the industry average. Therefore, the expected return of the investment would decrease according to formula (4) and investors would be willing to get less from the assets because they are more sustainable and have less risk in the future. On the other hand, if γ_{sust} is greater than 1, it means that the company is less sustainable than the industry average and the expected return increases. The reason for this is that the less sustainable a company is today, the riskier it is to survive in the future without changing its current operations due to new regulations that will be introduced and that favor sustainable companies.

The overall result of the methodology is that the more sustainable a company is, the lower the risk for investors to invest in it and therefore the lower the expected return. The model is designed to take into account a broader range of risk factors, including economic, environmental and social considerations, and can be a useful tool for investors and analysts interested in assessing the sustainability of their investments.

Chapter 7. SUMMARY AND NEXT STEPS

7.1 SUMMARY

This thesis focuses on the development of a sustainability risk assessment approach for discrete manufacturing companies located in Germany in 2022, with a particular focus on the automotive, mechanical engineering, electrical & electronics, and chemical industries. The overall objective of this research is to develop an approach for using Life Cycle Assessment (LCA)-based sustainability information to accurately and systematically identify and assess sustainability risks in manufacturing companies.

Chapter 2. provides a theoretical background on sustainability and sustainability assessment in general, with a particular focus on the phases and objectives of LCA as an important methodology for sustainability assessment. The chapter also covers the topic of risk management and its phases, along with a discussion of the potential operational risks that can occur during manufacturing operations. In addition, the chapter defines production and production systems, which are the two areas that the thesis focuses on.

Chapter 3. presents a comprehensive review of the state of the art in product-related sustainability risk assessment systems, with a particular focus on sustainability risk assessment methodologies currently used in manufacturing systems. The chapter discusses the approach used in the research and categorization part and presents the methodology for conducting a sustainability risk assessment. The chapter also highlights the shortcomings of existing sustainability risk assessment systems found in the literature and the measures that will be taken to address them during this thesis.

Chapter 4. establishes both the context and the requirements for developing the approach for using LCA-based sustainability information to identify and assess sustainability risks. The chapter first introduces the fifteen impact categories that have been analyzed according to the LCA methodology and its impact indicator unit. The chapter then explains the methodology used, the Failure Mode and Effects Analysis (FMEA) methodology, including how it assesses and prioritizes risks. The chapter concludes by discussing the adjustments made to apply the FMEA methodology to the context of the thesis, which is discrete manufacturing companies located in Germany for the year 2022, with a particular focus on the top four industries that contribute most to Germany's GDP. Within each industry, an in-depth analysis of the financial performance as well as the sustainable performance of the top five companies in each industry (based on revenues generated) was conducted.

Chapter 5. develops the thresholds for the fifteen impact categories of the LCA. The chapter explains in detail the procedure used to determine the threshold values for each of the impact categories. Some of the values were taken from EU standards that define risk levels for humans, animals or the natural environment. In other cases, where no EU standards were available, the average of the top five companies in each industry was calculated and normalized using the revenues generated. This approach provides a normalized assessment of emissions intensity that takes into account differences in company size and products. It also provides a more comprehensive understanding of the relative emissions intensity associated with revenue generation in each industry in the German context. By comparing a company's emissions to industry averages and applying risk thresholds, this approach helps to identify companies that may be contributing more or less to each of the impact categories and provides valuable insights into the financial and sustainability performance of companies. The chapter also describes how the thresholds were calculated in cases where only planetary boundaries were found in the literature search (e.g. land use or mineral and metal resource depletion), and how they were allocated to Germany and to the individual sectors according to the GDP. Finally, the chapter explains how the overall risk of the company is determined according to the introduced weightings and values. The tool displays the low, medium and high risk intervals for the introduced weightings (as they may vary from company to company) and then automatically derives the overall risk of the company.

Chapter 6. explores the possibility of incorporating the results of sustainability risk assessment into financial risk analysis using the Capital Asset Pricing Model (CAPM). The lack of an effective way to account for sustainability or environmental factors within the

CAPM was addressed by including an additional variable called γ_{sust}. This variable serves as a sustainability indicator that affects the expected return calculated with the CAPM model. The overall result of the methodology is that the more sustainable a company is, the lower the risk for investors to invest in it and therefore the lower the expected return. The chapter concludes by highlighting the broader range of risk factors, including economic, environmental and social considerations, that the model takes into account, making it a useful tool for investors and analysts interested in assessing the sustainability of their investments.

The goal of this thesis was to develop a tool to accurately and systematically assess the environmental impact of a manufacturing company. All three research questions posed in section 1.2 were answered throughout the thesis. The study also aimed to contribute to the understanding of the competitive landscape and economic dynamics of four key industries in Germany. These could provide best practices compared to the industry leader and areas for improvement for individual companies.

Overall, the thesis makes a significant contribution to the field of sustainability risk assessment by developing an approach for using LCA-based sustainability information to identify and assess sustainability risks in manufacturing operations. In addition, the thesis demonstrates the feasibility of incorporating sustainability risk assessment results into financial risk analysis, highlighting the potential benefits for investors and analysts interested in assessing the sustainability of their investments.

7.2 NEXT STEPS

“Sustainable manufacturing is the most important aspect to be considered by all production engineers, not because it is a fad but a necessity as an obligation to the world we live in” (POSINASETTI 2023). This section presents the next steps that could be taken to improve the existing results of the proposed work:

1. **Updating the threshold values:** It is important to note that some of the thresholds used in the fifteen impact categories are based on EU standards that are more than ten years old (e.g. the Freshwater Initiative on freshwater eutrophication). It is therefore recommended that these values are updated with more recent data. Also, for the values that are not derived from EU standards, but calculated as averages and then normalized, the aim of the work was to build a first step towards a more established tool in the future. These values may change in the coming years, especially if the sustainable performance of companies continues to increase, but the goal was to serve as a reference and then be updated in the future. This will improve the accuracy of the tool and make it more relevant to current environmental standards.
2. **Further development of the tool:** The thesis serves as a reference tool for companies to estimate their environmental impacts. However, the tool can be further developed to make it more robust and reliable. For example, the tool can be improved to automatically pull industry average data for the impact categories for which a company lacks data. This will ensure that no impact category is underestimated. In addition, future studies can improve by using methods such as analytic hierarchy process to develop a more appropriate and flexible weighting system based on stakeholder involvement.
3. **Expanding the sample size:** The sample size used in the thesis consisted of only twenty companies from four industries. This is not a statistically significant sample size. Therefore, it is recommended that the sample size is expanded for future research to make the results more reliable and to draw correct and valid conclusions about the quality of reporting.
4. **Analysis of data from other industries:** The results of the thesis were limited to four industries. It would be interesting to analyze data from other industries to see if the results are in line with expectations or if there are significant differences. This will make the tool more comprehensive and applicable to a wider range of industries.
5. **Extrapolation of the results to other countries:** The thesis focused on the German market. However, it would be valuable to extrapolate the results to other countries in the European Union and worldwide. This will provide a broader perspective on the environmental impacts of companies in different countries and help identify areas where improvements can be made.

Overall, the tool can serve as a first step towards a more established practical tool for systematically assessing and managing the sustainability risks of a manufacturing company in the future. Further development of this tool will enable companies to better understand the environmental impacts of their operations and identify potential areas for improvement. In addition, the tool will make it possible to compare the sustainability risks associated with different manufacturing processes or companies within the same industry, providing valuable insights for manufacturing decision makers.

Chapter 8. REFERENCES

ACCA 03/05/2023

Association of Chartered Certified Accountants (ACCA): CAPM: theory, advantages, and disadvantages. <https://www.accaglobal.com/gb/en/student/exam-support-resources/fundamentals-exams-study-resources/f9/technical-articles/CAPM-theory.html> - 03/05/2023.

AGIMPACTS 2021

AgImpacts: Eutrophication Potential. <https://agimpacts.mit.edu/indicators/eutrophication-potential/> - 26/03/2023.

ANAND ET AL. 2016

Anand, A.; Khan, R. A.; Wani, M. F.: Development of a sustainability risk assessment index of a mechanical system at conceptual design stage. Journal of Cleaner Production 139 (2016), S. 258-266.

ANJALEE ET AL. 2021

Anjalee, J. A.; Rutter, V.; Samaranayake, N. R.: Application of failure mode and effects analysis (FMEA) to improve medication safety in the dispensing process - a study at a teaching hospital, Sri Lanka. BMC public health 21 (2021) 1, S. 1430.

AUSTRALIAN GOVERNMENT - DEPARTMENT OF FINANCE 2016

Australian Government - Department of Finance: An Overview of the Risk Management Process (2016).

BASF 2023

BASF: Management Report BASF 2022 (2023).

BAYER AG 2023

Bayer AG: Bayer Annual Report 2022 (2023).

BEBBINGTON ET AL. 2007

Bebbington, J.; Brown, J.; Frame, B.: Accounting technologies and sustainability assessment models. Ecological Economics 61 (2007) 2-3, S. 224-236.

BELLGRAN & SÄFSTEN 2010

Bellgran, M.; Säfsten, K.: Production Development. London: Springer London 2010. ISBN: 978-1-84882-494-2.

BESTERFIELD ET AL. 2012

Besterfield, D.; Besterfield-Michna, C.; Besterfield, G.; Besterfield-Sacre, M.; Urdhwareshe, H.; Urdhwareshe, R.: Total Quality Management (2012).

BLESSING & CHAKRABARTI 2009

Blessing, Lucienne T.M.; Chakrabarti, Amaresh (Hrsg.): DRM, a Design Research Methodology. London: Springer London 2009. ISBN: 978-1-84882-586-4.

BMW GROUP 2023

BMW Group: BMW Group Report 2022 (2023).

BOEHRINGER INGELHEIM 2022

Boehringer Ingelheim: Performance Indicators | Boehringer Ingelheim. <https://www.boehringer-ingelheim.com/sustainability/environment-health-and-safety/performance-indicators> - 07/05/2023.

BOEHRINGER INGELHEIM 2023

Boehringer Ingelheim: Summary Report 2022 (2023).

BOSCH GMBH 2022a

Bosch GmbH: Bosch Annual Report 2021 (2022).

BOSCH GMBH 2022b

Bosch GmbH: Bosch Sustainability Report 2021 (2022).

BUILDING RESEARCH ESTABLISHMENT 2020a

Building Research Establishment: Acidification : BRE Group. <https://tools.bregroup.com/greenguide/page.jsp?id=2105> - 25/03/2023.

BUILDING RESEARCH ESTABLISHMENT 2020b

Building Research Establishment: Ecotoxicity. <https://tools.bregroup.com/greenguide/page.jsp?id=2099> - 26/03/2023.

BUILDING RESEARCH ESTABLISHMENT 2020c

Building Research Establishment: Human Toxicity. <https://tools.bregroup.com/greenguide/page.jsp?id=2098> - 26/03/2023.

BUILDING RESEARCH ESTABLISHMENT 2020d

Building Research Establishment: Photochemical Ozone Creation. <https://tools.bregroup.com/greenguide/page.jsp?id=2104> - 25/03/2023.

BUTNARIU & AVASILCAI 2015

Butnariu, A.; Avasilcai, S.: The Assessment of The Companies' Sustainable Development Performance. Procedia Economics and Finance 23 (2015), S. 1233-1238.

CHAND 2021

Chand, M.: Strategic assessment and mitigation of risks in sustainable manufacturing systems. Sustainable Operations and Computers 2 (2021), S. 206-213.

CHANG ET AL. 2019

Chang, C.-C.; DiGiovanni, K.; Mei, Y.: Sustainability. Water environment research : a research publication of the Water Environment Federation 91 (2019) 10, S. 1129-1149.

CHATZITHEODOROU ET AL. 2021

Chatzitheodorou, K.; Tsalis, T. A.; Tsagarakis, K. P.; Evangelos, G.; Ioannis, N.: A new practical methodology for the banking sector to assess corporate sustainability risks with an application in the energy sector. Sustainable Production and Consumption 27 (2021), S. 1473-1487.

CLIMATE CHANGE CONNECTION 2020

Climate Change Connection: CO2 equivalents | Climate Change Connection. Connecting Manitobans to climate change facts and solutions. <https://climatechangeconnection.org/emissions/co2-equivalents/> - 25/03/2023.

CORPORATE FINANCE INSTITUTE 29/02/2020

Corporate Finance Institute: Capital Asset Pricing Model (CAPM). Corporate Finance Institute. <https://corporatefinanceinstitute.com/resources/valuation/what-is-capm-formula/> - 03/05/2023.

DELAI & TAKAHASHI 2014

Delai, I.; Takahashi, S.: Sustainability measurement system: a reference model proposal. Social Responsibility Journal 7 (2014) 3, S. 438-471.

DIARIO OFICIAL DE LAS COMUNIDADES EUROPEAS 2000

Diario Oficial de las Comunidades Europeas: DIRECTIVA 2000/60/CE DEL PARLAMENTO EUROPEO Y DEL CONSEJO (2000).

DIKSHA 2017

Diksha, P.: CAPM: Assumptions and Limitations | Securities | Financial Economics. <https://www.economicsdiscussion.net/portfolio-management/capm/capm-assumptions-and-limitations-securities-financial-economics/29904> - 03/05/2023.

DIONNE 2013

Dionne, G.: Risk Management: History, Definition, and Critique. Risk Management and Insurance Review 16 (2013) 2, S. 147-166.

ELENA DOVAL 2019

Elena Doval: Risk management process in projects (2019).

ELMARAGHY ET AL. 2021

ElMaraghy, H.; Monostori, L.; Schuh, G.; ElMaraghy, W.: Evolution and future of manufacturing systems. CIRP Annals 70 (2021) 2, S. 635-658.

ENCYCLOPEDIA BRITANNICA 10/03/2023

Encyclopedia Britannica: Manufacturing of Germany. <https://www.britannica.com/place/Germany/Highways> - 10/03/2023.

EUROPEAN COMMISSION 2016

European Commission: The EU Emissions Trading System (EU ETS) (2016).

EUROPEAN COMMISSION 19/04/2023a

European Commission: Air. <https://environment.ec.europa.eu/topics/air_en> - 19/04/2023.

EUROPEAN COMMISSION 19/04/2023b

European Commission: EU air quality standards. <https://environment.ec.europa.eu/topics/air/air-quality/eu-air-quality-standards_en> - 19/04/2023.

EUROPEAN COMMISSION 20/04/2023c

European Commission: Water Framework Directive. <https://environment.ec.europa.eu/topics/water/water-framework-directive_en> - 20/04/2023.

EUROPEAN COMMISSION 04/05/2023d

European Commission: EU Emissions Trading System (EU ETS). <https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en> - 05/05/2023.

EUROPEAN ENVIRONMENT AGENCY 2014

European Environment Agency: Sulphur dioxide - Annual limit value for the protection of ecosystems. <https://www.eea.europa.eu/data-and-maps/figures/sulphur-dioxide-annual-limit-value-for-the-protection-of-ecosystems> - 20/04/2023.

EUROPEAN ENVIRONMENT AGENCY 2019

European Environment Agency: Air quality in Europe — 2019 report (2019).

EUROSTAT 25/04/2023a

Eurostat: Statistics | Gross value added and income by industry breakdowns. Gross value added and income by industry breakdowns. <https://ec.europa.eu/eurostat/databrowser/view/NAMA_10_A10__custom_5728634/default/table?lang=en> - 25/04/2023.

EUROSTAT 25/04/2023b

Eurostat: Statistics | National accounts aggregates by industry.

<https://ec.europa.eu/eurostat/databrowser/view/NAMA_10_A64__custom_5728636/default/table?lang=en> - 25/04/2023.

EVONIK INDUSTRIES AG 2023

Evonik Industries AG: Evonik Financial Report 2022 (2023).

FINNVEDEN ET AL. 2009

Finnveden, G.; Hauschild, M. Z.; Ekvall, T.; Guinée, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.; Suh, Sangwon: Recent developments in Life Cycle Assessment. Journal of environmental management 91 (2009) 1, S. 1-21.

FORD MOTOR COMPANY 2011

FORD MOTOR COMPANY: Failure Mode and Effects Analysis. FMEA Handbook (with Robustness Linkages) (2011).

FORD MOTOR COMPANY 2023a

FORD MOTOR COMPANY: 2022 Annual Report (2023).

FORD MOTOR COMPANY 2023b

FORD MOTOR COMPANY: Climate Change 2022 (2023).

FORD MOTOR COMPANY 2023c

FORD MOTOR COMPANY: Integrated Sustainability and Financial Report 2023 (2023).

FORVIA GROUP 2023a

Forvia Group: Annual Results 2022 (2023).

FORVIA GROUP 2023b

Forvia Group: FORVIA Sustainability Report 2022 (2023).

GARCÍA-GÓMEZ ET AL. 2021

García-Gómez, F. J.; Rosales-Prieto, V. F.; Sánchez-Lite, A.; Fuentes-Bargues, J. L.; González-Gaya, C.: An Approach to Sustainability Risk Assessment in Industrial Assets. Sustainability 13 (2021) 12, S. 6538.

GARGALO ET AL. 2016

Gargalo, C. L.; Carvalho, A.; Gernaey, K. V.; Sin, G.: A framework for techno-economic

& environmental sustainability analysis by risk assessment for conceptual process evaluation. Biochemical Engineering Journal 116 (2016), S. 146-156.

GEA 2023a

GEA: Annual Report 2022 (2023).

GEA 2023b

GEA: Sustainability Report 2022 (2023).

GRI 07/02/2023

GRI: GRI - Home. <https://www.globalreporting.org/> - 07/02/2023.

GUERTLER & SPINLER 2015

Guertler, B.; Spinler, S.: When does operational risk cause supply chain enterprises to tip? A simulation of intra-organizational dynamics. Omega 57 (2015), S. 54-69.

HACKING & GUTHRIE 2008

Hacking, T.; Guthrie, P.: A framework for clarifying the meaning of Triple Bottom-Line, Integrated, and Sustainability Assessment. Environmental Impact Assessment Review 28 (2008) 2-3, S. 73-89.

HARVARD BUSINESS REVIEW 2014

Harvard Business Review: Why Sustainability Is Now the Key Driver of Innovation. <https://hbr.org/2009/09/why-sustainability-is-now-the-key-driver-of-innovation> - 09/05/2023.

HAUSCHILD ET AL. 2018

Hauschild, M. Z.; Rosenbaum, R. K.; Olsen, S. I.: Life Cycle Assessment - Theory and Practice: Springer 2018.

HAYES 09/03/2023

Hayes, K.: What Is Discrete Manufacturing? 2023 Benefits & Features. <https://www.selecthub.com/manufacturing/discrete-manufacturing/> - 10/03/2023.

HENKEL 2023a

Henkel: Henkel Annual Report 2022 (2023).

HENKEL 2023b

Henkel: Henkel Sustainability Report 2022 (2023).

HILLEGE 2019

Hillege, L.: Impact Categories (LCA) - Overview. <https://ecochain.com/knowledge/impact-categories-lca/> - 22/02/2023.

HUBBARD 2009

Hubbard, D. W.: The Failure of Risk Management: Why It's Broken and How to Fix It (2009).

IAEA 19/04/2023

International Atomic Energy Agency (IAEA): Depleted Uranium. <https://www.iaea.org/topics/spent-fuel-management/depleted-uranium> - 19/04/2023.

INBOUND LOGISTICS 2023

Inbound Logistics: Discrete Manufacturing: Definition, Benefits, and Examples (2023).

INFINEON TECHNOLOGIES AG 2023a

Infineon Technologies AG: Infineon Annual Report 2022 (2023).

INFINEON TECHNOLOGIES AG 2023b

Infineon Technologies AG: Sustainability at Infineon 2022 (2023).

IPCC 22/02/2012

Intergovernmental Panel on Climate Change (IPCC): Chapter 2: Changes in Atmospheric Constituents and in Radiative Forcing. 2.10.3.2 Carbon Monoxide - AR4 WGI. <https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-3-2.html> - 19/04/2023.

IPCC 2013

Intergovernmental Panel on Climate Change (IPCC): CLIMATE CHANGE 2013. The Physical Science Basis (2013).

ISLAM ET AL. 2020

Islam, M. H.; Chavez, Z.; Birkie, S. E.; Bellgran, M.: Key Factors on Utilizing the

Production System Design Phase for Increasing Operational Performance. In: Lalic, B. et al. (Hrsg.): Advances in Production Management Systems. Towards Smart and Digital Manufacturing. Cham: Springer International Publishing 2020, S. 740-748. ISBN: 978-3-030-57996-8. (IFIP Advances in Information and Communication Technology).

ISO 2018
ISO: ISO 37000:2018 - Risk management (2018).

ISO 07/02/2023
ISO: ISO 26000:2010. <https://www.iso.org/standard/42546.html> - 07/02/2023.

JOLLIET ET AL. 2016
Jolliet, O.; Saadé-Sbeith, M.; Shaked, S.; Jolliet, A.; Crettaz, P.: Environmental life cycle assessment. Boca Raton: CRC Press Taylor & Francis Group 2016.
ISBN: 9781439887660.

JUNGBLUTH 2022
Jungbluth, N.: Bewertungsmethoden in der Ökobilanzierung (2022).

KENTON 18/11/2003
Kenton, W.: Capital Asset Pricing Model (CAPM) and Assumptions Explained. Investopedia. <https://www.investopedia.com/terms/c/capm.asp> - 03/05/2023.

KULCZYCKA & SMOL 2016
Kulczycka, J.; Smol, M.: Environmentally friendly pathways for the evaluation of investment projects using life cycle assessment (LCA) and life cycle cost analysis (LCCA). Clean Technologies and Environmental Policy 18 (2016) 3, S. 829-842.

LAMPERTI TORNAGHI ET AL. 2018
Lamperti Tornaghi, M.; Loli, A.; Negro, P.: Balanced Evaluation of Structural and Environmental Performances in Building Design. Buildings 8 (2018) 4, S. 52.

LAVANYA & MALARVIZHI 2008
Lavanya, N.; Malarvizhi, T.: Risk analysis and management: a vital key to effective project management. <https://www.pmi.org/learning/library/risk-analysis-project-management-7070> - 14/12/2022.

LIFE CYCLE INITIATIVE 2022

Life Cycle Initiative: Life Cycle Sustainability Assessment - Life Cycle Initiative. <https://www.lifecycleinitiative.org/starting-life-cycle-thinking/life-cycle-approaches/life-cycle-sustainability-assessment/> - 14/02/2023.

M.A.J. HUIJBREGTS ET AL. 2016

M.A.J. Huijbregts et al.: ReCiPe 2016. A harmonized life cycle impact assessment method at midpoint and endpoint level (2016).

MARTINS 2019

Martins, C.: SUSTAINABILITY IN MANUFACTURING - A SYSTEMATIC LITERATURE REVIEW (2019).

MASCIA ET AL. 2020

Mascia, A.; Cirafici, A. M.; Bongiovanni, A.; Colotti, G.; Lacerra, G.; Di Carlo, M.; Digilio, F. A.; Liguori, G. L.;Lanati, A.; Kisslinger, A.: A failure mode and effect analysis (FMEA)-based approach for risk assessment of scientific processes in non-regulated research laboratories. Accreditation and Quality Assurance 25 (2020) 5-6, S. 311-321.

MEDD & AGENCES DE L'EAU 2003

MEDD & Agences de l'eau: SYSTEME D'EVALUATION DE LA QUALITE DE L'EAU DES COURS D'EAU. GRILLES D'EVALUATION SEQ-EAU (VERSION 2) (2003).

MERCEDES-BENZ GROUP 2023a

Mercedes-Benz Group: Annual Report 2022 (2023).

MERCEDES-BENZ GROUP 2023b

Mercedes-Benz Group: Sustainability Report 2022 (2023).

MERCEDES-BENZ GROUP 18/04/2023c

Mercedes-Benz Group: Key figures environment - Mercedes-Benz Group Sustainability Report 2022. <https://sustainabilityreport.mercedes-benz.com/2022/facts-figures/key-figures/key-figures-environment.html#gebertable59> - 29/04/2023.

MERCK KGAA 2023

Merck KGaA: Annual Report 2022 (2023).

MURALIKRISHNA & MANICKAM 2017

Muralikrishna, I. V.; Manickam, V.: Life Cycle Assessment. (Hrsg.): Environmental Management: Elsevier 2017, S. 57-75. ISBN: 9780128119891.

MYLLYVIITA ET AL. 2017

Myllyviita, T.; Antikainen, R.; Leskinen, P.: Sustainability assessment tools – their comprehensiveness and utilisation in company-level sustainability assessments in Finland. International Journal of Sustainable Development & World Ecology 24 (2017) 3, S. 236-247.

NESS ET AL. 2007

Ness, B.; Urbel-Piirsalu, E.; Anderberg, S.; Olsson, L.: Categorising tools for sustainability assessment. Ecological Economics 60 (2007) 3, S. 498-508.

NGUYEN 2021

Nguyen, J.: FMEA Explained: 2021 Guide. <https://www.capvidia.com/blog/fmea-guide> - 09/03/2023.

ODUOZA 2020

Oduoza, C. F.: Framework for Sustainable Risk Management in the Manufacturing Sector. Procedia Manufacturing 51 (2020), S. 1290-1297.

OECD 2014

Organisation for Economic Co-operation and Development (OECD): Regulatory Policy and the Road to Sustainable Growth (2014).

ORTH 27/03/2023

Orth, M.: Germany as an industrialised country – the main facts. Fazit Communication GmbH. <https://www.deutschland.de/en/topic/business/germanys-industry-the-most-important-facts-and-figures> - 19/04/2023.

PACHECO ET AL. 2014

Pacheco, D.; Pergher, I.; Jung, C.; Scwenberg ten Caten, C.: STRATEGIES FOR INCREASING PRODUCTIVITY IN PRODUCTION SYSTEMS. Independent Journal of Management & Production 5 (2014) 2.

PANIGRAHI & BAHINIPATI 2018

Panigrahi, S.; Bahinipati, B.: Sustainable supply chain management - A review of literature and implications for future research (2018).

PARTSCH 2010

Partsch, H. A.: Requirements-Engineering systematisch. Berlin, Heidelberg: Springer Berlin Heidelberg 2010. ISBN: 978-3-642-05357-3.

PLAN A ACADEMY 08/04/2023

Plan A Academy: What are Scopes 1, 2 and 3 of Carbon Emissions? <https://plana.earth/academy/what-are-scope-1-2-3-emissions> - 08/04/2023.

POSINASETTI 05/05/2023

POSINASETTI, N.: Sustainable Manufacturing: Principles, Applications and Directions. <https://www.industr.com/en/sustainable-manufacturing-principles-applications-and-directions-2333598> - 05/05/2023.

RAZ ET AL. 2002

Raz, T.; Shenhar, A. J.; Dvir, D.: Risk management, project success, and technological uncertainty. R&D Management 32 (2002) 2, S. 101-109.

RESEARCH GERMANY 2021

Research Germany: List of the 50 largest Vehicle Manufacturers in Germany | incl. Revenue. <https://www.researchgermany.com/product/list-of-the-largest-vehicle-manufacturers-in-germany-revenue-included/> - 19/04/2023.

RESEARCH GERMANY 2023a

Research Germany: List of the 300 Largest Electrical Engineering Companies in Germany. <https://www.researchgermany.com/product/top-companies-in-the-electrical-industry-list-of-the-largest-electrical-engineering-companies/> - 19/04/2023.

RESEARCH GERMANY 2023b

Research Germany: List of the 500 Largest Mechanical Engineering Companies in Germany. <https://www.researchgermany.com/product/mechanical-engineering-companies-germany/> - 19/04/2023.

RESEARCH GERMANY 2023c

Research Germany: List of the 700 Largest Chemical Companies in Germany. <https://www.researchgermany.com/product/chemistry-companies-germany/> - 19/04/2023.

REZA ET AL. 2014

Reza, B.; Sadiq, R.; Hewage, K.: Emergy-based life cycle assessment (Em-LCA) for sustainability appraisal of infrastructure systems: a case study on paved roads. Clean Technologies and Environmental Policy 16 (2014) 2, S. 251-266.

ROBECO 2022

ROBECO: Sustainability risk integration & organizational impact (2022).

ROCKWELL AUTOMATION 2022

Rockwell Automation: Guide to Failure Mode and Effects Analysi(FMEA). <https://www.plex.com/industries/automotive/guide-failure-mode-and-effects-analysis-fmea> - 09/03/2023.

RUPP 2021

Rupp, C.: Requirements-Engineering und -Management. Das Handbuch für Anforderungen in jeder Situation. SOPHIST-Gesellschaft für Innovatives Software-Engineering; Carl Hanser Verlag. 7., aktualisierte und erweiterte Auflage. München: Hanser 2021. ISBN: 9783446455870.

SALA ET AL. 2020

Sala, S.; Crenna, E.; Secchi, M.; Sanyé-Mengual, E.: Environmental sustainability of European production and consumption assessed against planetary boundaries. Journal of environmental management 269 (2020), S. 110686.

SANTA CRUZ BIOTECHNOLOGY, INC. 2010

Santa Cruz Biotechnology, Inc.: Material Safety Data Sheet 1,4-Dibromobutane (2010).

SCHULTE & KNUTS 2022

Schulte, J.; Knuts, S.: Sustainability impact and effects analysis - A risk management tool for sustainable product development. Sustainable Production and Consumption 30 (2022), S. 737-751.

SEPPO 2011

Seppo: PRODUCTION AND PRODUCTIVITY AS SOURCES OF WELL BEING (2011).

SEXTON & LINDER 2014

Sexton, K.; Linder, S. H.: Integrated assessment of risk and sustainability in the context of regulatory decision making. Environmental science & technology 48 (2014) 3, S. 1409-1418.

SHI ET AL. 2015

Shi, J.; Liu, Z.; Zhang, H.; Jiang, Q.; Li, T.: Life Cycle Assessment: State of the Art and Future Perspectives. Recent Patents on Mechanical Engineering 8 (2015) 3, S. 211-221.

SIEMENS AG 2023a

Siemens AG: Full Siemens Report (2023).

SIEMENS AG 2023b

Siemens AG: Sustainability Report 2022 (2023).

SINGH ET AL. 2012

Singh, R. K.; Murty, H. R.; Gupta, S. K.; Dikshit, A. K.: An overview of sustainability assessment methodologies. Ecological Indicators 15 (2012) 1, S. 281-299.

SLACK ET AL. 2013

Slack, N.; Brandon-Jones, A.; Johnston, R.: Operations Management. Seventh Edition (2013).

SLAPER 2011

Slaper, T. F.: The Triple Bottom Line: What Is It and How Does It Work? (2011).

SPACE4WATER 2020

Space4Water: Eutrophication Potential. <https://www.space4water.org/water/eutrophication-potential> - 26/03/2023.

STELLANTIS N.V. 2021

Stellantis N.V.: Corporate Social Responsibility Report 2020 (2021).

STELLANTIS N.V. 2023

Stellantis N.V.: Annual Report and Form 20-F (2023).

SUÁREZ ET AL. 2021

Suárez, D.; Díaz-Puente, J. M.; Bettoni, M.: Risks Identification and Management Related to Rural Innovation Projects through Social Networks Analysis: A Case Study in Spain. Land 10 (2021) 6, S. 613.

THIEDE & HERRMANN 2019

Thiede, S.; Herrmann, C.: Eco-Factories of the Future. 2019. ISBN: 978-3-319-93729-8.

THYSSENKRUPP AG 2022

ThyssenKrupp AG: Annual Report 2021 (2022).

THYSSENKRUPP AG 07/05/2023

ThyssenKrupp AG: Environment and energy. <https://www.thyssenkrupp.com/en/company/sustainability/environment/energy> - 07/05/2023.

UN GLOBAL COMPACT NETWORK GERMANY 10/12/2022

UN Global Compact Network Germany: Sustainable Development Goals. <https://www.globalcompact.de/en/our-work/sustainable-development-goals> - 10/12/2022.

UNITED NATIONS 29/08/2018

United Nations: Social Development for Sustainable Development. <https://www.un.org/development/desa/dspd/2030agenda-sdgs.html> - 07/04/2023.

UNITED NATIONS 2022

United Nations: THE 17 GOALS | Sustainable Development. <https://sdgs.un.org/goals> - 10/12/2022.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY 2022

United States Environmental Protection Agency: About Risk Assessment | US EPA. <https://www.epa.gov/risk/about-risk-assessment#tab-2> - 14/02/2023.

US DEPARTMENT OF LABOR 19/04/2023

US Department of Labor: 1910.1200 - Hazard Communication. Occupational Safety and Health Administration. <https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.1200> - 19/04/2023.

US ENVIRONMENTAL PROTECTION AGENCY 2022

US Environmental Protection Agency: Particulate Matter (PM) Basics | US EPA. <https://www.epa.gov/pm-pollution/particulate-matter-pm-basics> - 25/03/2023.

USHVITSKII ET AL. 2015

Ushvitskii, L.; Kulagovskaya, T.; Ter-Grigor’yants, A.; Solovyova, I.; Mezentseva, E.: Methodological tools for risk assessment in industrial enterprises (2015).

VDE VERLAG 2018

VDE VERLAG: IEC 60812:2018. Failure modes and effects analysis (FMEA and FMECA). <https://www.vde-verlag.de/iec-normen/225834/iec-60812-2018.html> - 02/04/2023.

VOLKSWAGEN GROUP 2023a

Volkswagen Group: Annual Report 2022 (2023).

VOLKSWAGEN GROUP 2023b

Volkswagen Group: Sustainability Report 2022 (2023).

WEBER ET AL. 2015

Weber, O.; Hoque, A.; Ayub Islam, M.: Incorporating environmental criteria into credit risk management in Bangladeshi banks. Journal of Sustainable Finance & Investment 5 (2015) 1-2, S. 1-15.

WERBACH 2011

Werbach, A.: Strategy for sustainability. Strategic Direction 27 (2011) 10.

WIKIMEDIA COMMONS 2023

Wikimedia Commons: Electronics companies of Germany. <https://commons.wikimedia.org/wiki/Category:Electronics_companies_of_Germany> - 19/04/2023.

WORLD BANK 31/01/2023

World Bank: The Costs of Meeting the 2030 Sustainable Development Goal Targets on Drinking Water, Sanitation, and Hygiene. <https://www.worldbank.org/en/topic/water/publication/the-costs-of-meeting-the-2030-sustainable-development-goal-targets-on-drinking-water-sanitation-and-hygiene> - 31/01/2023.

WORLD BANK OPEN DATA 25/04/2023

World Bank Open Data: GDP (current US$). <https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?end=2020&locations=DE-1W-US-CN&start=2000> - 25/04/2023.

WORLD COMMISSION ON ENVIRONMENT AND DEVELOPMENT 1987

World Commission on Environment and Development: Our Common Future: Report of the World Commission on Environment and Development (1987).

WORLD HEALTH ORGANIZATION 19/04/2023

World Health Organization: Radon. <https://www.who.int/news-room/fact-sheets/detail/radon-and-health> - 19/04/2023.

WORLDFAVOR 05/02/2023

Worldfavor: Why sustainable risk assessment is crucial for enterprises to thrive. <https://blog.worldfavor.com/why-sustainable-risk-assessment-is-crucial-for-enterprises-to-thrive> - 06/02/2023.

WÜRTH GROUP 2022a

Würth Group: Nachhaltigkeitsperformance 2021 (2022).

WÜRTH GROUP 2022b

Würth Group: Würth Group 2021 Annual Report (2022).

XU ET AL. 2019

Xu, M.; Cui, Y.; Hu, M.; Xu, X.; Zhang, Z.; Liang, S.; Qu, S.: Supply chain sustainability risk and assessment. Journal of Cleaner Production 225 (2019), S. 857-867.

ZERBIB 2022

Zerbib, O. D.: A Sustainable Capital Asset Pricing Model (S-CAPM): Evidence from Environmental Integration and Sin Stock Exclusion. Review of Finance 26 (2022) 6, S. 1345-1388.

APPENDIX I

Integration of the Sustainable Development Goals

In 2015, the United Nations General Assembly (UNGA) developed a set of 17 Sustainable Development Goals (SDGs) to be achieved by 2030, with the goal of creating a “shared blueprint for peace and prosperity for people and the planet, now and into the future" (United Nations 2022)

As Figure 12 shows, the SDGs cover a broad and interdependent range of issues, each with its own specific targets and metrics to track progress. They range from poverty and other socioeconomic disadvantages to initiatives to improve health and education, reduce inequality, and promote economic development, while addressing climate change and protecting marine and terrestrial ecosystems (Chang et al. 2019, pp. 1129 - 1132).

Figure 12: Summary of the 17 Sustainable Development Goals developed by the United Nations (Source: UN Global Compact Network Germany 2022)

The 17 SDGs aim to promote gender equality and empower women, while realizing the human rights of all and taking into account environmental constraints. The goals consist of

169 specific targets and were designed to balance the three dimensions of sustainable development: economic, social, and environmental. The economic dimension of sustainable development is represented by five SDGs, followed by the environmental dimension, which consists of four SDGs. The social dimension of sustainable development is the largest, with eight SDGs. It is important to note that these goals are integrated and indivisible, so progress on one goal can positively impact progress on the others (UNITED NATIONS 2018).

Of the 17 SDGs, the main one that will be addressed in this work is number 12, "Responsible Consumption and Production", from the economic perspective. SDG 12 aims to ensure sustainable consumption and production patterns, which includes minimizing the negative environmental impacts of economic activities, reducing waste, and increasing resource efficiency. The work is in line with the focus on using LCA-based sustainability information to compare sustainability risks in different manufacturing processes and within different companies in the same industry. By using an LCA to provide sustainability information related to manufacturing processes, this thesis can help manufacturing companies identify areas where they can reduce their environmental impacts, promote responsible consumption and production patterns, and improve resource efficiency. The use of a risk management tool can also provide a systematic approach to assessing sustainability risks within manufacturing operations. This would allow companies to identify areas of their operations that may have a high sustainability risk and develop strategies to mitigate these risks.

Within the same economic dimension, this work can also contribute in a secondary way to the achievement of SDG 9, "Industry, Innovation and Infrastructure". SDG 9 aims to build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation. The manufacturing industry plays a critical role in achieving this goal, as it is a key driver of economic growth and technological innovation. However, the manufacturing industry also has significant environmental impacts that can hinder progress towards achieving SDG 9. By developing a sustainability-oriented risk management tool for manufacturing systems, the research can help minimize the negative environmental impacts of manufacturing while promoting inclusive and sustainable industrialization. The tool can provide best practices from top performing companies in each of the 15 impact categories analyzed to encourage continuous improvement.

In addition to contributing to SDG 12 and SDG 9, this work can also add value to the achievement of SDG 13, "Climate Action," which is in the environmental dimension. SDG 13 aims to take urgent action to combat climate change and its effects. The manufacturing sector is a major contributor to greenhouse gas emissions, which are a key driver of climate change. Throughout this work, much emphasis has been placed on climate change and the actions taken by several leading companies to reduce CO_2 emissions. In addition, the tool can foster innovation by encouraging manufacturing companies to explore new, more sustainable ways of conducting business operations, such as using renewable energy sources and reducing waste.

In summary, the development of a sustainability-oriented risk management tool for manufacturing systems can contribute to the achievement of multiple SDGs, including SDG 12, SDG 9, and SDG 13. By providing a systematic approach to sustainability risk assessment and promoting sustainable practices, this research has the potential to minimize the negative environmental impacts of the manufacturing industry, promote sustainable consumption and production patterns, and contribute to the fight against climate change.

The summary of the table with the three SDGs addressed in this thesis, their role and dimension are presented in Table 17.

Table 17: Summary of the three main SDGs addressed, their role and dimension (Source: Own representation)

SDG Dimension	SDG Identified	Role	Goal
Economy	SDG12: Responsible	Primary	Ensure **sustainable consumption and production patterns**, including minimizing the negative environmental

	Consumption and Production		impacts of economic activities, reducing waste, and increasing resource efficiency.
Economy	SDG 9: Industry, Innovation & Infrastructure	Secondary	Build resilient infrastructure, promote inclusive and **sustainable industrialization**, and **foster innovation.**
Biosphere	SDG 13: Climate Action	Secondary	Take urgent action to **combat climate change** and its impacts.

In terms of quantifying each of the three SDGs, it is difficult to quantify the impact of the thesis on each of them. This is because some companies may use the information provided by the thesis more efficiently than others, making it complicated to find a common value for each industry.

Overall, the SDGs provide a common framework and guiding principle for the challenges of the 21st century (UN GLOBAL COMPACT NETWORK GERMANY 2022). Successful implementation of the goals will require the commitment of policymakers, civil society and the business sector. Businesses have a key role to play in achieving the SDGs, not only by addressing the challenges they present, but also by recognizing the risks and opportunities that can be addressed through responsible and sustainable corporate governance.

APPENDIX II

Query Scopus

The complete query used in Scopus during the literature research, including all applied filters, is the following:

(sust* OR eco* OR clima* OR environment* OR bio* OR green*) AND (econ* OR prod* OR profit*) AND (soci* OR comm* OR publ* OR civ* OR hum*) AND (eval* OR assess* OR surv* OR val* OR explor* OR resear* OR benchmark* OR rat* OR scor* OR measur*) AND (compar* OR exam* OR invest* OR inspect* OR analy* OR stud* OR review* OR breakdown) AND (manufact* OR install* OR recycl* OR creat*) AND (produc* OR fabric* OR proce* OR construct*) AND (industr* OR expan* OR corpor*) AND (build* OR assembl* OR fit* OR form*) AND (demol* OR disman* OR dissol* OR disassembl* OR remov* OR dismount*) AND (method* OR technique OR practice) AND (approach* OR proce* OR mechani* OR formula) AND (tool OR instrument OR device) AND (concept* OR idea* OR theor* OR hypoth*) AND (model OR represent* OR reproduc* OR framework) AND (risk* OR prospect* OR possib* OR uncertain*) AND (manage* OR admin* OR control* OR govern*) AND (identif*) AND (network* OR compan* OR corporate* OR organi*) AND (loca* OR area* OR site* OR plant* OR branch* OR institut* OR station* OR segment*) AND (system* OR struct*) AND (LIMIT-TO (DOCTYPE , "re") OR LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp")) AND (LIMIT-TO (PUBYEAR , 2023) OR LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015) OR LIMIT-TO (PUBYEAR , 2014) OR LIMIT-TO (PUBYEAR , 2013) OR LIMIT-TO (PUBYEAR , 2012) OR LIMIT-TO (PUBYEAR , 2011) OR LIMIT-TO (PUBYEAR , 2010)) AND (EXCLUDE (SUBJAREA , "CHEM") OR EXCLUDE (SUBJAREA , "MATE") OR EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "CENG") OR EXCLUDE (SUBJAREA , "SOCI") OR EXCLUDE (SUBJAREA , "BUSI") OR EXCLUDE (SUBJAREA , "AGRI") OR EXCLUDE (SUBJAREA , "COMP") OR EXCLUDE (SUBJAREA , "MEDI") OR EXCLUDE (SUBJAREA , "PHYS") OR EXCLUDE (SUBJAREA , "PHAR") OR EXCLUDE (SUBJAREA , "EART") OR EXCLUDE (SUBJAREA , "IMMU") OR EXCLUDE (SUBJAREA , "MATH") OR EXCLUDE (SUBJAREA , "DECI") OR EXCLUDE (SUBJAREA , "NEUR") OR EXCLUDE (SUBJAREA , "MULT") OR EXCLUDE (SUBJAREA , "ARTS") OR EXCLUDE (SUBJAREA , "PSYC") OR EXCLUDE (SUBJAREA , "HEAL") OR EXCLUDE (SUBJAREA , "NURS") OR EXCLUDE (SUBJAREA , "VETE") OR EXCLUDE (SUBJAREA , "DENT")) AND (LIMIT-TO (LANGUAGE , "English"))

APPENDIX III

TABLES WITH THE SPECIFIC EMISSION INTENSITY VALUES OF THE CO_2 EQUIVALENT FOR THE MECHANICAL ENGINEERING, ELECTRICAL & ELECTRONICS, AND CHEMICAL INDUSTRIES IN GERMANY

Mechanical Engineering Industry

Table 18: Specific values for CO_2 emissions in the mechanical engineering industry in Germany (Source: Own representation)

Company	M€ Total Revenues	M€ Revenues Germany	% of total revenue	total tCO_2 eq emitted	Allocated tCO_2 eq Germany	tCO_2 eq emitted/M€ Revenue	Source 1	Source 2
Siemens AG	71977	11961	17%	582000	96716	8,09	(Siemens AG 2023a, p. 14)	(Siemens AG 2023b, p. 69)
Robert Bosch GmbH	78748	15714	20%	907000	180990	11,52	(Bosch GmbH 2022a, p. 159)	(Bosch GmbH 2022b, p. 65)
ThyssenKrupp AG	41140	13894	34%	1187712	401120	28,87	(ThyssenKrupp AG 2022, p. 252)	(ThyssenKrupp AG 2023)
GEA Group AG	5165	429	8%	33018	2743	6,39	(GEA 2023a, p. 51)	(GEA 2023b, p. 147)
AVERAGE	**49257**	**10500**	**20%**	**677432**	**170392**	**13,72**		

Electrical & Electronics Industry

Table 19: Specific values for CO_2 emissions in the electrical & electronics industry in Germany (Source: Own representation)

Company	M€ Total Revenues	M€ Revenues Germany	% of total revenue	total tCO_2 eq emitted	Allocated tCO_2 eq Germany	tCO_2 eq emitted/M€ Revenue	Source 1	Source 2
Siemens AG	71977	11961	17%	582000	96716	8,09	(Siemens AG 2023a, p. 14)	(Siemens AG 2023b, p. 69)
Robert Bosch GmbH	78748	15714	20%	907000	180990	11,52	(Bosch GmbH 2022a, p. 159)	(Bosch GmbH 2022b, p. 65)
Infineon Technologies	14218	1594	11%	886671	99406	62,36	(Infineon Technologies AG 2023a, p. 2)	(Infineon Technologies AG 2023b, p. 31)
Würth Elektronik	17060	6939	41%	38931	15835	2,28	(Würth Group 2022b, p. 57)	(Würth Group 2022a, pp. 88 - 91)
Hella (Forvia Group)	25458	2772	11%	1280000	139357	50,28	(Forvia Group 2023a, p. 37)	(Forvia Group 2023b, p. 27)
AVERAGE	41492	7796	20%	738920	106461	**26,91**		

Chemical Industry

Table 20: Specific values for CO_2 emissions in the chemical industry in Germany (Source: Own representation)

Company	M€ Total Revenues	M€ Revenues Germany	% of total revenue	total tCO_2 eq emitted	Allocated tCO_2 eq Germany	tCO_2 eq emitted/M€ Revenue Germany	Source 1	Source 2
BASF SE	87327	15170	17%	18400000	3196354	210,70	(BASF 2023, pp. 94, 135)	
Bayer AG	50739	2477	5%	3030000	147920	59,72	(Bayer AG 2023, pp. 38, 169)	
Henkel Group	22397	2506	11%	398000	44532	17,77	(Henkel 2023a, p. 212)	(Henkel 2023b, p. 140)
Boehringer Ingelheim GmbH	24149	2092	9%	357000	30926	14,78	(Boehringer Ingelheim 2023, pp. 3, 8)	(Boehringer Ingelheim 2022)
Merck Group	22232	1532	7%	1667000	114872	74,98	(Merck KGaA 2023, pp. 114, 249)	
Evonik Industries AG	18488	2904	16%	5904000	927370	319,34	(Evonik Industries AG 2023, pp. 35, 36, 66)	
AVERAGE	37555	4447	11%	4959333	743662	**116,22**		

APPENDIX IV

TABLES WITH THE SPECIFIC FRESHWATER AND ENERGY CONSUMPTION FOR THE MECHANICAL ENGINEERING, ELECTRICAL & ELECTRONICS, AND CHEMICAL INDUSTRIES IN GERMANY

Mechanical Engineering Industry

Table 21: Specific values for freshwater and energy consumption in the mechanical engineering industry in Germany (Source: Own representation)

Company	M€ Revenues Germany	M m^3 Freshwater withdrawal	GWh Energy consumed	M m^3 Allocated Freshwater Germany	GWh Allocated Energy Germany	m^3 Freshwater Germany/M€ Revenue	MWh Energy Germany/M€ Revenue	Source 1	Source 2
Siemens AG	11961	12,93	2723	2,15	452	179,6	37,8	(SIEMENS AG 2023a, p. 14)	(SIEMENS AG 2023b, pp. 116, 118)
Robert Bosch GmbH	15714	18,81	8042	3,75	1605	238,9	102,1	(BOSCH GMBH 2022a, p. 159)	(BOSCH GMBH 2022b, pp. 68, 74)
ThyssenKrupp AG	13894	353	66000	119,22	22290	8580,5	1604,3	(THYSSENKRUPP AG 2022, p. 252)	(THYSSENKRUPP AG 2023)
GEA Group AG	429	0,35	243	0,03	20	67,4	47,1	(GEA 2023a, p. 51)	(GEA 2023b, p. 149)
AVERAGE	**10500**	**96,27**	**19252**	**31,29**	**6092**	**2266,6**	**447,8**		

Electrical & Electronics Industry

Table 22: Specific values for freshwater and energy consumption in the electrical & electronics industry in Germany (Source: Own representation)

Company	M€ Revenues Germany	M m^3 Freshwater withdrawal	GWh Energy consumed	M m^3 Allocated Freshwater Germany	GWh Allocated Energy Germany	m^3 Freshwater Germany/M€ Revenue	MWh Energy Germany/M€ Revenue	Source 1	Source 2
Siemens AG	11961	12,93	2723	2,15	452	179,6	37,8	(Siemens AG 2023a, p. 14)	(Siemens AG 2023b, pp. 116, 118)
Robert Bosch GmbH	15714	18,81	8042	3,75	1605	238,9	102,1	(Bosch GmbH 2022a, p. 159)	(Bosch GmbH 2022b, pp. 68, 74)
Infineon Technologies	1594	34,05	2568	3,82	288	2394,8	180,6	(Infineon Technologies AG 2023a, p. 2)	(Infineon Technologies AG 2023b, p. 28)
Würth Elektronik	6939	0,03	112	0,01	46	1,5	6,6	(Würth Group 2022b, p. 57)	(Würth Group 2022a, pp. 86, 89)
Hella (Forvia Group)	2772	2,71	1800	0,30	196	106,5	70,7	(Forvia Group 2023a, p. 37)	(Forvia Group 2023b, pp. 29, 33)
AVERAGE	**7796**	**13,71**	**3049**	**2,01**	**517**	**584,3**	**79,6**		

Chemical Industry

Table 23: Specific values for freshwater and energy consumption in the chemical industry in Germany (Source: Own representation)

Company	M€ Revenues Germany	M m^3 Freshwater withdrawal	GWh Energy consumed	M m^3 Allocated Freshwater Germany	GWh Allocated Energy Germany	m^3 Freshwater Germany/M€ Revenue	MWh Energy Germany/M€ Revenue	Source 1	Source 2
BASF SE	15170	1590	52900	276,2	9190	18207	606	(BASF 2023, pp. 94, 137, 145)	
Bayer AG	2477	53	9861	2,6	481	1045	194	(Bayer AG 2023, pp. 79, 80, 169)	
Henkel Group	2506	8	2265	0,9	253	347	101	(Henkel 2023a, p. 212)	(Henkel 2023b, pp. 140, 141)
Boehringer Ingelheim GmbH	2092	6	2046	0,6	177	265	85	(Boehringer Ingelheim 2023, pp. 3, 8)	(Boehringer Ingelheim 2022)
Merck Group	1532	13	2432	0,9	168	594	109	(Merck KGaA 2023, pp. 116, 118, 249)	
Evonik Industries AG	2904	250	17850	39,2	2804	13511	965	(Evonik Industries AG 2023, pp. 35, 36, 64, 72)	
AVERAGE	**4447**	**320**	**14559**	**53,4**	**2179**	**5662**	**343**		