MAPPING GRI INDEXES TO BUSINESS PROCESSES FOR PROCESS MINING SUSTAINABILITY ANALYSIS: A CASE STUDY IN MANUFACTURING

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Mariia Smirnova

Examiners: Professor Jari Porras (LUT University)
Professor Henry Muccini (University of L’Aquila)
Professor Patricia Lago (Vrije Universiteit Amsterdam)

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ABSTRACT

Lappeenranta-Lahti University of Technology LUT

LUT School of Engineering Science

Software Engineering

Mariia Smirnova

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Supervisor: Professor Stefanie Betz (Hochschule Furtwangen University & LUT University)

Examiners: Professor Jari Porras (LUT University)
Professor Henry Muccini (University of L'Aquila)
Professor Patricia Lago (Vrije Universiteit Amsterdam)

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Sustainability's significance in business operations has led organizations to report their sustainability efforts, but a challenge arises in identifying which business processes to consider and which KPIs to use. Existing process mining frameworks only partially address sustainability aspects, necessitating the proposal of a Green Process Mining framework. This approach incorporates sustainability metrics from GRI Standards as attributes in the event log, enabling process mining tools to offer insights into the sustainability performance of business processes. The aim of this work is to develop framework to analyze business processes from all dimensions of sustainability using process mining tools. The DSR method is used to create a framework. It is evaluated in case study in manufacturing. As a result, proposed framework can assess sustainability of processes holistically, assist Green BPM, and improve sustainability reporting KPIs. However, it is not always feasible and justified.

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LIST OF ABBREVIATIONS

BI Business Intelligence

BPM Business Process Management

BPMN Business Process Model and Notation

BPR Business Process Re-engineering

CEP Complex Event Processing

CRM Customer Relationship Management

CSO Chief Sustainability Officer

CSR Corporate Social Responsibility

CSRD Corporate Sustainability Reporting Directive

DSR Design Science Research

EnMS Energy Management System

ERP Enterprise Resource Planning

ESG Environmental, Social and Governance

GHG Greenhouse Gas

GRC Governance, Risk, and Compliance

GRI Global Reporting Initiative

LCA Life Cycle Assessment

LCC Life Cycle Cost

LCSA Life Cycle Sustainability Assessment

O-LCA Organizational Life Cycle Assessment

OCPM Object-Centric Process Mining

PAS Publicly Available Specification

PDCA Plan-Do-Check-Act

PDM Product Data Management

PDM Process Diagnostics Method

PQL Process Query Language

SAP Systems Applications and Products

SDG Sustainable Development Goals

SKPI Sustainability Key Performance Indicator

SLCA Social Life Cycle Assessment

SME Small and medium-sized enterprises

TBL Triple Bottom Line

UNGC United Nations Global Compact

WBCSD World Business Council for Sustainable Development

WFM Workforce Management

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1 INTRODUCTION

Sustainability has become an increasingly important aspect of business operations. Following Corporate Social Responsibility (CSR) companies not only manage their resources efficiently, but also minimizing their impact on the environment and society. The shift towards sustainability is now crucial for companies' survival, as consumer preferences increasingly favor eco-friendly businesses. As an illustration, a retail chain that embraced sustainable sourcing and packaging increased customer loyalty and enhanced profitability. In addition, the latest Corporate Sustainability Reporting Directive (CSRD) mandates the large companies and listed Small and medium-sized enterprisess (SMEs) to report environment, social affairs, and governance indexes from 2024. Even though sustainability reporting helps companies to disclose their environmental and social performance, promote transparency, and enhance accountability, it also brings some challenges. Specifically, companies may struggle with identifying the business processes that have high impact on environment and society, thus require improvement and determining the most effective strategies to implement these enhancements.

For this purpose, the companies may employ data science to gain insights and optimize their operations. One such approach is process mining, which serves as a valuable data science technique for the systematic analysis and evaluation of business processes. Process mining involves the extraction, analysis, and visualization of event data generated during the execution of processes within an organization. By applying advanced data analytic and statistical methods to these event logs, process mining enables organizations to gain a comprehensive understanding of their processes, identify bottlenecks, inefficiencies, and deviations from expected behavior, and finally, enhance process performance and efficiency.

English philosopher Francis Bacon stated: ”We must obey forces we want to command,” which means that in order to have control over something or achieve a desired outcome, one should understand and comply with the underlying forces or factors at play. If one do not understand them, the outcome might be dangerous. This concept can be applied to the sustainability analysis of business processes. When analyzing process, it is essential to understand the various factors that influence the environmental, economic, and social impacts of it. Process mining can identify and assess these factors that contribute to sustainability outcomes. For example, in the case of energy consumption and CO_2 emissions, process mining can help uncover patterns of resource usage, identify bottlenecks, and reveal inefficiencies that lead to increased energy consumption or emissions. It can detect which activities or subprocesses contribute the most to the overall environmental impact. Thus, organizations should manage to ”obey” forces through process mining analysis in order to ”command” over the sustainability aspects of their business processes.

Today’s research on process mining focus on concepts of sustainability only partially and implicitly. There are studies that investigate environmental impact of business process with regards to CO_2 emissions (Brehm, Slamka, and Nickmann, 2022). Other studies apply process mining to analyze the social (trust and privacy issues, customer satisfaction, fairness) or economic perspectives (Pohl, Qafari, and Van der Aalst, 2022; Qafari and Van der Aalst, 2019; Werner, 2017). There is another line of research dedicated to Green Business Process Management (BPM). The frameworks describe the metrics for sustainable processes, but process mining as such is not used for further analysis (Safitri, Sarno, and Budiawati, 2018). Finally, Ortmeier et al. (2021) proposed the framework to integrate process mining into Life Cycle Assessment (LCA). This approach involves the incorporation of energy and resource data into the event log, followed by the visualization of energy consumption within the process map.

Ultimately, while current research has touched upon various aspects of sustainability, there remains a need for a more comprehensive and integrated approach. This includes considering not only energy consumption and resource utilization, but also other sustainability indicators such as operating cost, Greenhouse Gas (GHG) emissions, diversity, social benefits, etc. By incorporating these additional metrics, organizations can develop a more holistic understanding of the economic, environmental and social impacts of their business processes, enabling them to make informed decisions and prioritize sustainability initiatives effectively. Moreover, Van der Aalst and Carmona (2022, p. 32) argue that process mining can play a role in realizing sustainability goals, raising ”interesting research questions leading to new concepts and techniques”. That is why the future research should focus on developing standardized and universally applicable approach to integrating process mining and sustainability.

1.1 Aim of Research

The goal of this research is to develop **the framework to analyze business processes from all dimensions of sustainability using process mining tools**.

To achieve this objective the following research questions are defined:

RQ1*: What are the existing frameworks to use process mining for sustainable BPM?*

RQ2*: What are the metrics to define how sustainable the business process is?*

RQ3*: How can Green BPM be supported with process mining?*

1.2 Research Methodology

The Design Science Research (DSR) is used as a research methodology. The aim of DSR is to generate design knowledge, such as methods, frameworks, technology, tool, concepts, or combination of any of those (Venable and Baskerville, 2012). The research has objective-centered entry point, because it is driven by the clear goal of creating the framework.

According to Peffers et al. (2007) the DSR approach consists of six stages:

1. **identification** of the problem, defining the research problem and justifying the value of a solution;
2. **definition** of aim of the research;
3. **design** and **development** of artefacts;
4. **demonstration** how the solution (artefact) solve the problem;
5. **evaluation** of the solution, comparing the objectives and the actual observed results from the use of the artefact;
6. **communication** of the problem, the artefact, its utility and effectiveness to other researches and practitioners.

Figure 1 shows the research process of creating the artefact according to **DSR**. Firstly, the need for framework to assess the sustainability of business process through process mining tools and the importance of the framework are identified, using the literature study. Then, the objectives and corresponding research questions are set. In the third step, the framework is designed. In order to demonstrate and evaluate the framework, the **Case Study** in manufacturing is performed, utilising the **Data Collection** and **Data Analysis**. Finally, the research findings and conclusions are communicated in the thesis, fulfilling the last step of the design science process.

It should be noted that even though the research process is depicted as straightforward, in reality the steps can be performed in any possible order (Peffers et al., 2007). In this research, for instance, while designing the framework, there was a need to refer to the literature study to ensure alignment with existing knowledge. Additionally, during the case study, certain insights caused a revisit and refinement of the framework. This iterative nature allows for a more comprehensive and refined approach to achieving the research objectives.

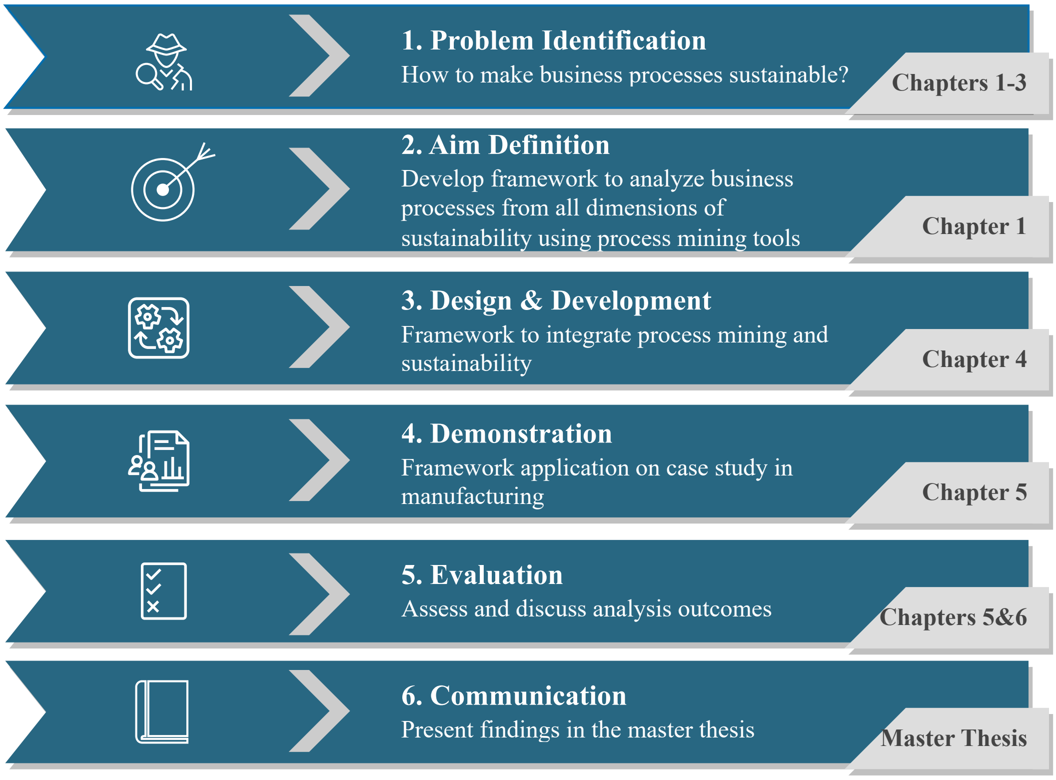


Figure 1: Research phases according to DSR approach

1.3 Delimitation

The current research is interdisciplinary and exploratory in nature; therefore, it should not be constrained by any limitations in order to discover innovative solutions. However, considering the given time, resources and other factors, some possible limitations could be accounted.

The main pitfall of this research is the availability and quality of data. The case study's success relies on the availability of process data and the willingness of the organization to share it. Since the real-life data are not accessible, the research is done on publicly available event log enriched with generated attributes. For this, various estimates and assumptions are required and may prove to be wrong, biased and have misleading analysis outcomes. Paired with absence of subject-matter experts, the quality of data has impacted the accuracy and reliability of the analysis.

Another limitation of this study lies in its exclusive focus on sustainability aspects, rather than conventional performance metrics. While this approach showcases new analysis techniques, it may not provide comprehensive insights into the process's overall efficiency and effectiveness.

Moreover, the generalizability of the findings might be influenced by the specific characteristics and context of the chosen case study, thereby limiting the broader applicability of the framework. The case study is done only on the core manufacturing process, therefore the defined metrics and analysis approaches can be not suitable for other processes. Additionally, the employed process mining tool Celonis has features that are not available in other tools, making the analysis tool-specific.

1.4 Structure of Thesis

The research work is divided into seven chapters.

Chapter 1: Introduction presents the overview of the research, describing the motivation, objectives, research methodology and structure of the work.

Chapter 2: Background familiarises the reader with the context of sustainable development, sustainability reporting, the frameworks to assess the sustainability of business process (ISO Standards, LCA, Green BPM), the concept of process mining, and current green approaches in manufacturing.

Chapter 3: Related Work explores the research conducted in the field of process mining for sustainability.

Chapter 4: Development of the Framework focuses on the description of novel approach to process mining analysis. The definition of sustainable business process, mapping Global Reporting Initiative (GRI) indexes to business processes, analysis approaches are described in this chapter.

Chapter 5: Case Study in Manufacturing presents the evaluation of the framework. This includes data collection to form the event log, the development of the application to analyse the manufacturing process, as well as the analysis itself.

Chapter 6: Discussion comments on the findings, compares them to the prior studies, concludes the answers to the research questions and shows, how the limitations of the work have been taken into account.

Chapter 7: Conclusion provides an assessment of the extent to which the research objectives were achieved, presents the key findings and their implications in a broader context, and suggests the area for future research.

2 BACKGROUND

This chapter focuses on key theories and concepts related to sustainability in business processes. At the beginning, the sustainable development and sustainability reporting are opened a little, after which the frameworks to assess the sustainability of business processes (ISO Standards, LCA, Green BPM), the concept of process mining, and current green approaches in manufacturing are discussed.

2.1 Sustainable Development

The concept of sustainability has its roots in the environmental movement of the 1960s and 1970s, which brought attention to issues such as pollution, resource depletion, and the loss of biodiversity. In 1987, the United Nations published the Brundtland Report, which defined sustainable development as ”development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Imperatives, 1987, p. 43).

Sustainability has since evolved to encompass not only environmental concerns, but also economic and social considerations. The widely used and well-known three-dimensional UN commissioned sustainability assessment model (UN, 2021; Imperatives, 1987) defines each pillar as follows:

- **Environmental sustainability** means the protection of natural resources, reduction of pollution and waste, and protection of biodiversity. Climate change, loss of biodiversity, and resource depletion is the major global challenges that can only be addressed by taking a long-term and holistic approach.

- **Social sustainability** ensures that everyone has access to basic needs such as food, water, healthcare, and education, and that they have the opportunity to live a fulfilling and healthy life. It also means creating a society that is inclusive, equitable, and just, where everyone has the opportunity to participate in decision-making and have their voices heard.

- **Economic sustainability** ensures that economic growth is inclusive and equitable, and that it creates jobs and prosperity for all. By promoting sustainable business practices, reducing resource depletion, and addressing poverty, a more stable and resilient economy can be created.

In the corporate world, CSR has emerged as a trend over the past few years, which has been included in the strategy of almost all companies. The idea of CSR is to consider the economic, social and environmental perspective by including them in business and communication with stakeholders (Van Marrewijk, 2003). Considering these three concerns is also known as the Triple Bottom Line (TBL) framework (Slaper, Hall, et al., 2011), where all have got interfaces which each other (Figure 2). Consumers and other stakeholders who are more aware than before demand socially responsible activities from companies, so companies must meet the demands of the stakeholders.

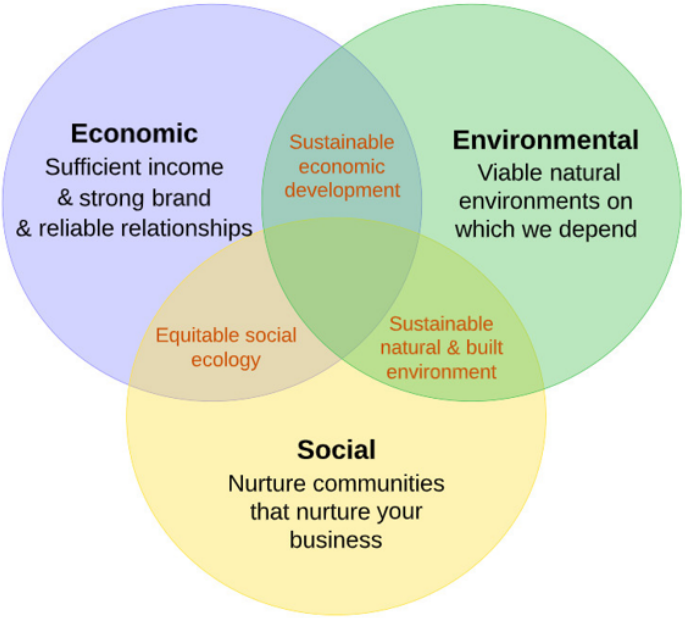


Figure 2: Triple bottom line framework

The TBL framework aligns closely with the United Nations' Sustainable Development Goals (SDG) by promoting a holistic approach that integrates all three dimensions to achieve sustainable development and address global challenges. The United Nations' SDG were adopted in 2015 as a universal call to action to end poverty, protect the planet, and ensure that all people enjoy peace and prosperity by 2030 (UN, 2015). The SDGs is a set of 17 goals and 169 targets. These goals serve as a blueprint for businesses to align their strategies, operations, and processes with the broader sustainability agenda.

2.2 Sustainability Reporting

Sustainability reporting is the practice adopted by companies and organizations to be accountable to their stakeholders and follow sustainability disclosure regulation (Erkens, Paugam, and Stolowy, 2015). Organizations disclose and report publicly on its economic, environmental, and/or social impacts, and hence report its contributions—positive or negative—, as well as how the company progress towards them and towards sustainability (GRI, 2021). A sustainability report enables companies to collect data across the organizations about their economic, environmental and societal impacts, visualize these impacts, and then transform the organization's strategy towards sustainability. They also transform their business models towards SDGs. The main goal is to inform internal and external stakeholders, thereby improving stakeholder engagement and dialogue, transparency, reputation and trust. Sustainability reports are published annually by private and public organizations. In some countries, such as Finland, CSR reporting is mandatory for public-listed companies according to *Directive 2014/95/EU* (2014).

Several frameworks and standards guide organizations in conducting sustainability reporting, ensuring consistency and credibility. One widely recognized framework is GRI (KPMG, 2022). The findings from GRI's 2022 research reveal that adoption of the GRI Standards for reporting among the G250 has increased to 78%, showing growth from 73% in 2020 (*Four in Five Largest Global Companies Report with GRI* 2022). GRI provides comprehensive guidelines and indicators for reporting Environmental, Social and Governance (ESG) performance. It helps organizations structure their reports and disclose relevant information in a systematic manner, enabling stakeholders to gain insights into various sustainability aspects.

The GRI standards are international, non-governmental and independent standards. However, they are developed in accordance with policies in international labor practices and environmental impact (Brown, De Jong, and Lessidrenska, 2009). ISO 14010, ISO 14011, ISO 14012 and ISO 26000 set out a standard for assessing the environmental impact, while ISO 45001 (previously OHSAS 18001) was used for a health and safety risk management system.

The GRI Standards are a modular system comprised of three series of Standards to be used together: Universal Standards, Sector Standards and Topic Standards. The Universal Standards outline the requirements and principles for reporting (GRI 1), disclosure of organizational details (GRI 2), and guidance on determining and managing material topics (GRI 3). The Sector Standards include the most possible material topics for some industries: Oil and Gas (GRI 11), Coal (GRI 12), and Agriculture, Aquaculture and Fishing (GRI 13). The development of a Standard focused on the mining sector (GRI 14) is currently underway. The remaining standards are topic specific: Economic (GRI 200), Environmental (GRI 300), and Social (GRI 400). The corresponding indexes are presented in **Appendix A**.

2.3 ISO Standards

ISO standards guide organizations towards sustainable and responsible practices. These standards provide frameworks for assessing environmental and social impacts, implementing effective management systems, and ensuring compliance with internationally recognized benchmarks. The commonly used standards to assess business processes include ISO 26000, ISO 45001, ISO 1400x, ISO 9001, and ISO 50001.

ISO 26000:2010 Social Responsibility

ISO 26000 offers guidance on social responsibility, emphasizing the need for organizations to operate ethically, contribute to sustainable development, and engage with stakeholders. It outlines principles and practices for organizations to address social, economic, and environmental aspects of their operations. ISO 26000 is a voluntary guidance standard, but not a management system and does not provide any requirements.

ISO 45001:2018 Occupational Health and Safety Management Systems

ISO 45001 is the international standard for occupational health and safety management systems. It helps organizations establish a systematic approach to identify and manage risks, prevent work-related injuries and illnesses, and continuously improve occupational health and safety performance.

ISO 14001:2015 Environmental Management Systems

ISO 14001 provides a framework for implementing effective environmental management systems. It guides organizations in identifying and managing environmental aspects, minimizing their environmental footprint, complying with regulations, and fostering a culture of environmental responsibility.

ISO 14010-14012: Environmental Auditing

ISO 14010-14012 standards provide guidance on environmental auditing, including principles, procedures, and competencies for conducting audits. They support organizations in evaluating their environmental performance, identifying areas for improvement, and ensuring compliance with environmental regulations.

ISO 9001:2015 Quality Management Systems

ISO 9001 sets the requirements for implementing a quality management system. While primarily focused on quality, organizations can integrate environmental and social considerations into their processes to enhance overall performance and meet customer expectations. Standard promotes adopting a process approach in developing, implementing, and improving the effectiveness of a quality management system, with the goal of meeting customer requirements and enhancing customer satisfaction.

ISO 50001:2018 Energy Management Systems

ISO 50001 offers a framework for implementing energy management systems. It enables organizations to improve energy efficiency, reduce energy costs, and minimize their environmental impact by establishing energy policies, setting targets, and implementing energy-saving measures.

Overall, mentioned ISO standards serve as invaluable tools for organizations seeking to assess and improve their environmental and social impacts. They provide guidance, frameworks, and best practices to drive sustainable development, enhance performance, and meet stakeholder expectations.

2.4 Life Cycle Assessment

ISO 14040:2006 defines LCA as the following:

> "LCA studies the environmental aspects and potential impacts throughout a product's life cycle (*i.e.,* cradle-to-grave) from raw materials acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences."

Similarly to GRI Standards, the procedures to perform LCA are retrieved from ISO Standards and regulations. For the environmental management, ISO 14040 provides the framework and principles, while ISO 14044 provides an outline of the requirements and guidelines. With regards to GHG emissions LCA comply with Publicly Available Specification (PAS) 2050 and the GHG Protocol Life Cycle Accounting and Reporting Standard. For the social impacts, Social Life Cycle Assessment (SLCA) is framed by the UNEP/SETAC's Guidelines for social life cycle assessment of products (2009), which, in turn, based on the ISO 26000:2010 Guidelines for Social Responsibility and GRI Guidelines (Garrido, 2017).

Ciroth et al. (2011) proposed the **Life Cycle Sustainability Assessment (LCSA)** framework, that 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 (Hoogmartens et al., 2014).

- **LCA** (or **E-LCA**, Environmental Life Cycle Assessment) takes into account all stages, including the production process, use, and end-of-life phases, and quantifies the energy consumption, resource depletion, emissions, and waste generation associated with each stage (Ilgin and Gupta, 2010). It provides a holistic perspective by considering the entire life cycle, enabling organizations to identify areas for improvement and make informed decisions to minimize environmental burdens.

- **SLCA** is used for social impact assessment. While the guidance were developed by Benoit et al. (2010) and UNEP/SETAC (2009), SLCA is still on its early development level (Sala, Ciuffo, and Nijkamp, 2015).
- **Life Cycle Cost (LCC)** approach addresses the economic dimension and refers to the total cost of owning and operating a product or system throughout its entire life cycle, taking into account acquisition, maintenance, and disposal expenses (Finkbeiner et al., 2010).

While LCA explicitly assesses products, it also takes into account background processes, such as supply chain, production, and distribution of those products (Hoogmartens et al., 2014). **Organizational Life Cycle Assessment (O-LCA)** extends the concept of product LCA even further to encompass the entire scope of an organization's operations. This includes not only the environmental impact of the organization's main products but also various activities, processes, and services (ISO 14072:2014, UNEP/SETAC, 2009). Moreover, as noted by Fritsch et al. (2022), LCA, with its process-oriented perspective, can be integrated with process management.

Nevertheless, there are several reasons why LCA may face challenges when applied to business processes. Firstly, obtaining accurate and comprehensive data for all steps of the process, including upstream and downstream activities, can be time-consuming and resource-intensive (Kim et al., 2015). Secondly, the complexity and variability of business processes make it difficult to capture all relevant environmental impacts and establish consistent assessment boundaries. Thirdly, the lack of standardized methodologies and data availability for specific industries or processes may hinder the application of LCA (Perkins and Suh, 2019). Finally, the dynamic nature of business processes, with changes in technology, materials, and supply chains, poses challenges for conducting LCA studies that reflect the current state of operations accurately (Cerdas et al., 2017).

2.5 Green Business Process Management

Weske (2012, p. 5) defines the business process as ”a set of activities that are performed in coordination in an organizational and technical environment” to achieve a business goal, captured in a business process model. As organizations increasingly recognize the importance of sustainability, the concept of sustainable business processes emerges. Literature does not define the sustainable business process explicitly, but rather focuses on sustainable/green business or business models. Said that, the sustainable business processes go beyond mere operational effectiveness by integrating environmental, social, and economic considerations into their design, implementation, and improvement. This holistic approach ensures that business activities not only contribute to the organization's objectives but also minimize negative impacts on the environment and promote social responsibility.

To effectively manage and optimize business processes, organizations employ BMP methodologies. According to Weske (2012, p. 5) BMP includes ”concepts, methods, and techniques to support the design, administration, configuration, enactment, and analysis of business processes.” However, the pursuit of sustainability has led to the evolution of BPM into Green BPM. Green BPM focuses specifically on integrating sustainable practices into processes.

Table 1: Green patterns for business process optimization (based on Nowak et al. (2011))

Category	**ID**	**Green pattern**	**Application context**	**Relations to other patterns**
Basic	1	Green Compensation	Process (structure, resources, behavior) cannot be changed due to internal policies, laws, regulations or other constraints	2
	2	Green Variant	Conventional process cannot be changed due to green trade-off	8, 9
	3	Resource Change	Keep original process structure by making external changes	4
	4	Green Feature	Add green option to the product	3
Process-centric	5	Common Process Improvement for Environmental Aspects	Process optimization based on KPIs (*e.g.,* time, quality, cost, and flexibility)	6, 7
	6	Process Automation	Automate some activities	3, 4, 7
	7	Human Process Performance	Replace activities performed by machines with humans	3, 6
Sourcing-centric	8	Insourcing	Perform certain activity/process in-house	9
	9	Outsourcing	Perform certain activity/process with green partner	1, 2, 3, 7

Nowak et al. (2011) classifies the green business process practices into three categories (Table 1): (1) *basic patterns* involve optimization methods applied to existing business processes without altering their structure; (2) *process-centric patterns* focuse on modifying the structure and execution of business processes; (3) *sourcing-centric patterns* center around optimizing environmental impact by distributing processes and activities among different partners. The study also provide a decision tree to assist organizations in identifying suitable patterns based on their specific requirements and the structure of business processes.

2.6 Process Mining

This section is dedicated to the process mining. It defines the concept and position of process mining in science. Then the notion of event log is explained, followed by the description of different process mining techniques.

2.6.1 Process Mining Definition

Process mining is a family of techniques connecting the fields of data science and process management to support the analysis of operational processes based on event logs. It acts as a catalyst for merging event data, representing observed behavior, with process models, either manually constructed or automatically discovered. Unlike data science approaches, which often tend to be process-agnostic, process mining considers end-to-end process models and aligns them with the evidence hidden within the data. On the other hand, process science approaches primarily focus on process models rather than getting insights from event data. The unique position of process mining, as illustrated in Figure 3, aims to utilise the vast availability of data to improve end-to-end processes (Van der Aalst, 2016, pp. 15–20).

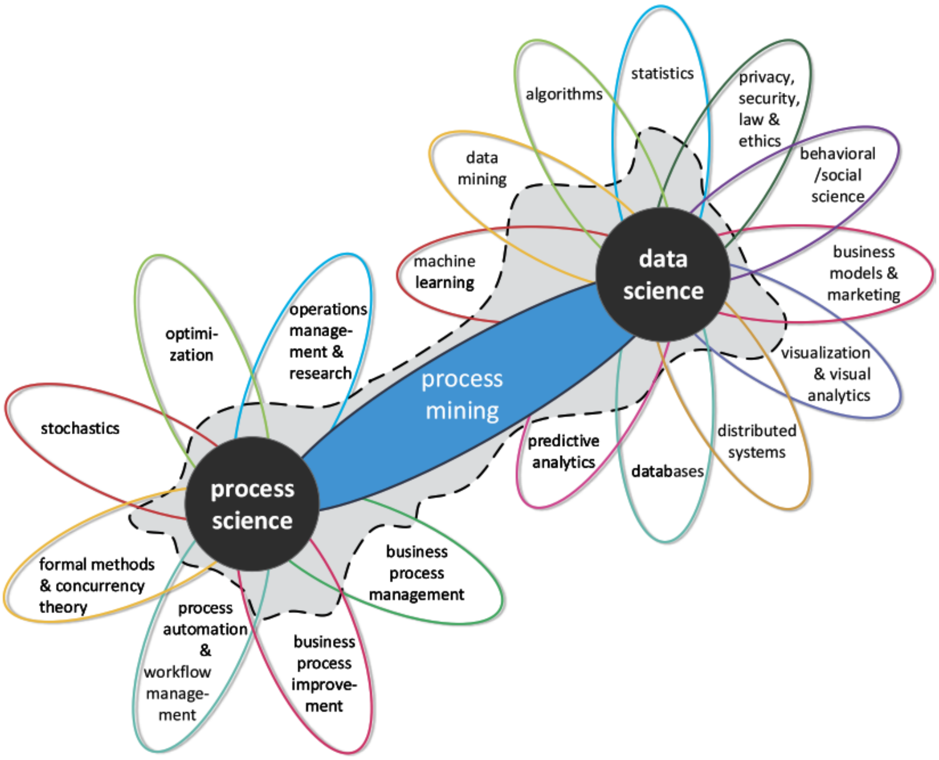


Figure 3: Process mining as the bridge between data science and process science (Van der Aalst, 2016, p. 18)

Although process mining is a relatively recent sub-discipline of both data science and process science (IEEE Task Force on Process Mining, 2023), its techniques can be applied to a wide range of operational processes across organizations and systems. Examples of these applications include analyzing treatment processes in hospitals (Kirchmer, Laengle, and Masías, 2013), improving customer service processes, understanding customer browsing behavior on booking websites (Poggi et al., 2013), and investigating failures in baggage handling systems (Böhm et al., 2022). The common thread among these diverse applications is the need to establish a relationship between dynamic behavior and process models, highlighting the practical implementation of ”data science in action” through process mining (Van der Aalst, 2016, p. 18).

2.6.2 Event Log

An event log is a central concept in process mining. In order to effectively utilize data in any data-driven analysis approach, including process mining, the data should be in the appropriate format. According to Sonawane and Patki (2015) and Van der Aalst (2016) this format is an event log, that represents the chronological record of activities or events that occur within a system or process. It captures detailed information about each event. Event logs serve as the primary source of data for analyzing and understanding the execution of processes.

The data in event logs is typically collected automatically by information systems. As users interact with these systems, they generate a trail of events, which are then logged and stored for future reference. The collection of event data can occur through various mechanisms, depending on the system in question. Some systems directly generate event logs as a built-in feature, while others may require additional configuration or customization to enable event logging. Examples of such systems include but not limited to (Van der Aalst, 2016, p. 32):

- Classical Workforce Management (WFM) systems (Staffware, COSA);
- BPM systems (BPM one, SmartBPM, FileNet, Global 360, and Teamwork);
- Enterprise Resource Planning (ERP) systems (SAP Business Suite, Oracle E-Business Suite, and Microsoft Dynamics NAV);
- Product Data Management (PDM) systems (Windchill);
- Customer Relationship Management (CRM) systems (Microsoft Dynamics CRM, SalesForce);
- Middleware (IBM’s WebSphere, Cordys Business Operations Platform);
- Hospital information systems (Chipsoft, Siemens Soarian).

Even though mentioned above systems offer direct access to event logs, in many cases, information systems store event data in an unstructured format. According to Murillas, Reijers, and Van der Aalst (2019) extracting event logs from real-life systems can be a challenging task, requiring data to be gathered from multiple sources such as ERP systems, flat files, databases or within subsystems that exchange messages. The merging and extraction of event log data can present difficulties due to semantic and syntax issues (Van der Aalst, 2016; Murillas, Reijers, and Van der Aalst, 2019). Furthermore, Van der Aalst, Adriansyah, et al. (2012) propose data quality maturity model, that categorizes event logs into five levels. One-star logs are manually recorded and potentially contain missing or incorrect values, while five-star logs represent the highest maturity level, recorded automatically by systems and being complete and accurate.

Van der Aalst (2016) argues that extracting meaningful data for process mining without clear business questions is problematic. The reason for this is that the event logs may originate from various sources, with each source potentially containing numerous tables. For example, Systems Applications and Products (SAP) contains thousands tables that originate the data flow into event logs (Parthasarathy and Sharma, 2017), making the data hard to navigate and get insights. Therefore it is important to start the process mining project from clear question(s) (Suriadi, Wynn, et al., 2013). Van Eck et al. (2015) argue that further advanced questions may necessitate more advanced data, and if new attributes are required, their availability and integration with existing logs must be carefully defined.

Each event in the log typically contains several attributes that provide information about the event itself. Van der Aalst (2016) highlights that mainstream process modeling notations describe the process instance life cycle through a collection of activities, and process mining follows a similar approach but with event logs representing collections of these instances. Each record in an event log must have at least a ”case id” and ”event id” as basic requirements, but Sonawane and Patki (2015) and Van der Aalst (2016) state that supplementary data, such as timestamps, resource information, and cost-related details, are often used. Additionally, Van der Aalst (2016) claims that for discovering causal dependencies in generated process models, the events within a case must be ordered, making attributes like timestamps necessary. Thus, the timestamp is also seen as mandatory requirement.

The attributes of event log include (Van der Aalst, 2016; Fluxicon, 2020):

- **Case ID**: This attribute identifies the case or process instance to which the event belongs. It helps to group related events together and trace the sequence of events within a specific case.

- **Timestamp**: The timestamp attribute records the date and time when the event occurred. It provides temporal information to analyze the sequence and duration of events.

- **Activity**: The activity attribute indicates the type of activity or task associated with the event. It represents the specific action performed within the process, such as ”order received” or ”invoice generated.”

- **Additional attributes**: Event logs may also include additional data attributes, such as customer ID, product details, transaction amount, or any other data associated with the event. It helps to understand the roles and responsibilities of individuals or entities involved in the process.

While there are three main attributes in the event log, the number of additional attributes may surpass 100. The use of a significant number of additional attributes and indicators in sustainability assessment is driven by the need to comprehensively evaluate the multifaceted nature of sustainability, account for context-specific considerations, involve stakeholders, and align with global sustainability goals.

2.6.3 Process Mining Techniques

There are three main types of process mining techniques.

Discovery is a method that takes an event log as input and produces a representative process model as output (Augusto et al., 2018). This technique helps to understand how processes are actually executed and visualize the sequence of activities, decisions, and interactions. Discovery process mining algorithms—Alpha algorithm or Inductive Miner—generate process models, such as Petri nets, process trees, or Business Process Model and Notation (BPMN) diagrams (Van der Aalst, 2016).

Conformance is “the analysis of the relation between the intended behaviour of a process as described in a process model and event logs that have been recorded during the execution of the process” (Carmona et al., 2018). It assesses how well the recorded events align with the expected process behavior (Jans, Van der Werf, et al., 2011). By comparing the event log against the process model, conformance analysis highlights variations, missing activities, unexpected loops, and other discrepancies (Van der Aalst, 2016).

Enhancement aims to improve existing process models using information from event logs. This technique complements and extends the discovered models by incorporating performance metrics, resource utilization, or other relevant attributes. According to Yasmin, Bukhsh, and Silva (2018) and Van der Aalst (2016) enhancement is further classified into repair and extension. Repair focuses on aligning the model with reality by identifying and correcting deviations between the model and observed behaviors. Extension involves adding new data, such as resources or case-related information, to provide a more comprehensive analysis of the process.

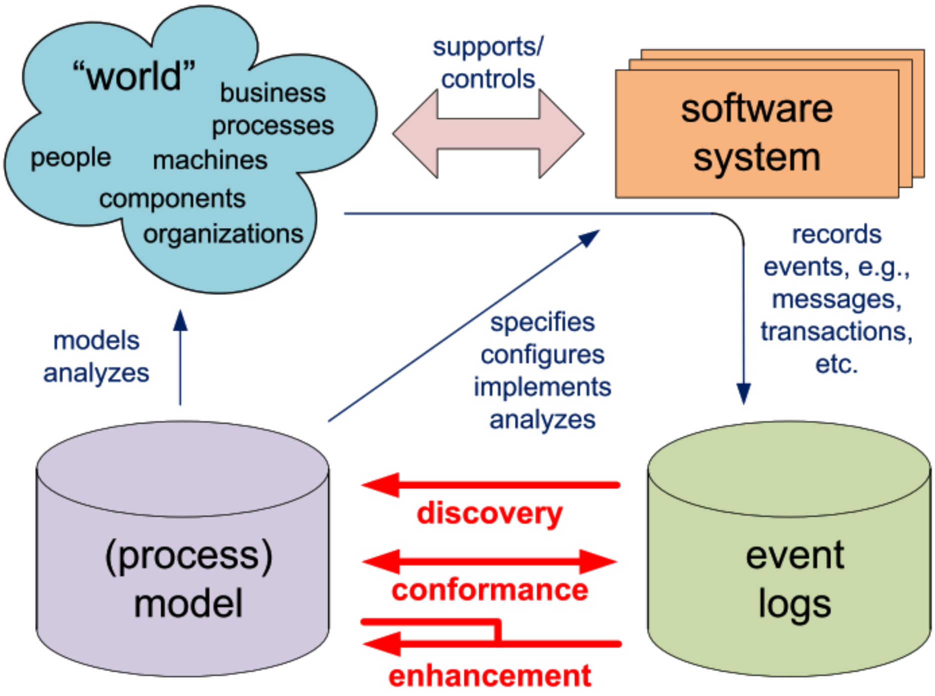


Figure 4: Positioning of the three main types of process mining: discovery, conformance, and enhancement (Van der Aalst, 2016, p. 32)

The overview of the discussed concepts is presented in Figure 4 (Van der Aalst, 2016, p. 32). Process mining establishes links between the actual processes and their data on the one hand and process models on the other hand. The digital universe and the physical universe become more and more aligned. The operations and people in business ”world” are supported and controlled by the different types of software, which, in turn, record all the activities in the form of event log. Through process mining the business models can be discovered, conformed and/or improved. Subsequently, each change in the process model affects the behavior in the business ”world”, leading to changes in data. As a result, the process mining life cycle starts its new circle. Put simply, process management is infinite exercise.

2.7 Sustainable Manufacturing

Being heavily resource-reliant, manufacturing is one of the spheres where the sustainability lenses should be zoomed in. Glavič and Lukman (2007, p. 1883) define sustainable manufacturing as

> “creating goods by using processes and systems that are non-polluting, conserve energy and natural resources in an economically viable, safe and healthy manner, for employees, communities, and consumers, and which are socially and creatively rewarding for all stakeholders for the short- and long-term future,”

while International Trade Administration (2007) states:

> "the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound."

The concept of sustainable manufacturing combines Lean, Green, Six Sigma, and socially sustainable practices (Hariyani et al., 2022). Among others the Lean philosophy is widely adopted, seeking to eliminate waste in the form of muri (overburden), mura (unlevelness) and muda (unnecessary resource use). According to Womack and Jones (2003) Lean is

> "...a way to do more and more with less and less—less human effort, less equipment, less time, and less space—while coming closer and closer to providing customers exactly what they want."

Hawken, A. B. Lovins, and L. H. Lovins (2013) argue that Lean thinking extends beyond enhancing business profitability, and able to foster sustainable growth while minimizing environmental impacts. In response, the academia tries to find the solutions towards sustainable manufacturing. According to Ahmad, Wong, and Butt (2023), past research was focused on the environmental dimension exclusively. However, since 2010 the course of research was changed to comply sustainable manufacturing with TBL, adding social perspective to overall practices.

Clearly, integration of the environmentally friendly practices, social responsibility, and economic viability in industrial processes is of high importance (Stock and Seliger, 2016).

2.8 Overview and Industry Demand

Chapter 2 discussed concepts with regards to sustainability and business processes. Reporting Standards, ISO Standards, LCA, Green BPM, Lean and others are all related to different aspects. They can be integrated or used together to create a comprehensive approach to managing quality, environmental impacts, energy efficiency, and reporting on sustainability performance. Figure 5 shows the connections between frameworks and guidelines.

LCA helps organizations identify opportunities for environmental improvement and make informed decisions regarding sustainability. ISO 14040 and ISO 14044 provide guidelines and principles for conducting LCA. GRI guidelines can be used by organizations to report on their efforts related to ISO 14001, ISO 26000, ISO 50001, and other sustainability initiatives.

ISO 50001, being developed after ISO 9001 and ISO 14001, promotes both the Energy Management System (EnMS) enhancement and the energy performance (ISO 50001, clause 4.2.1

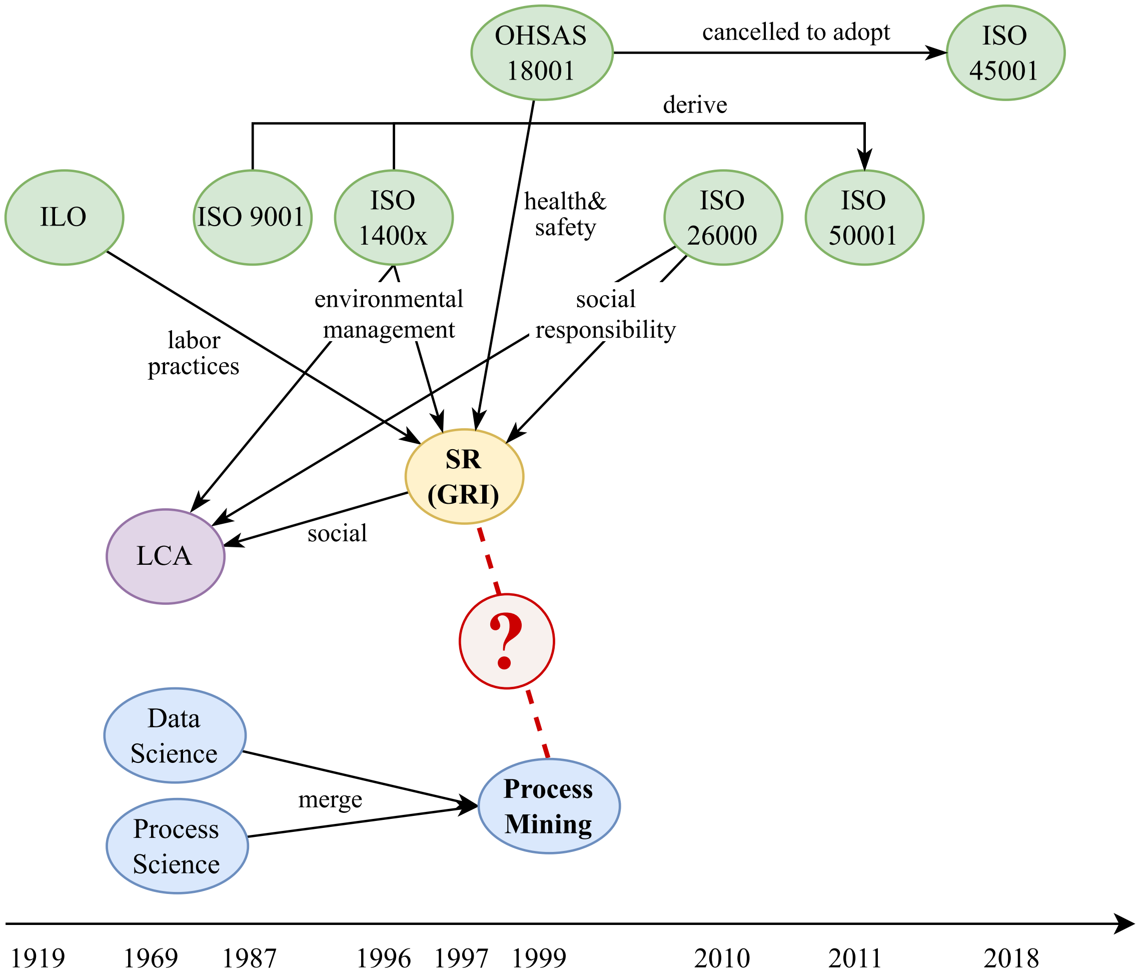


Figure 5: Relations between ISO Standards, LCA, GRI and data analysis tools
Note: (1) Timeline indicates the year when the Standard/Framework was introduced for the first time, but not the latest version of it. (2) There is no exact dates for Data Science and Process Science, as both are broad terms.

c). In contrast, ISO 9001 and ISO 14001 focus on improving the effectiveness of the Management System, but do not explicitly address the quality of the product/service (ISO 9001) or environmental performance (ISO 14001). While it is expected that implementing ISO 9001 and ISO 14001 together would lead to improved quality and environmental performance, the current standards do not mandate this as a requirement.

ISO 45001 uses the management system standard structure guideline Annex SL to allow for simplified integration with other management system standards, such as ISO 9001, ISO 14001 and ISO 50001 (*ISO - Directives and Policies*). All of them follow the *Plan-Do-Check-Act (PDCA)* paradigm (Tague, 2005), where *Plan* refers to defining goals and changes to achieve them, *Do* states for implementation of changes, *Check* refers to measurement, monitoring and reporting, while process improvement performed on the *Act* step. With regards to measurements on *Check* step, ISO 14010, ISO 14011, and ISO 14012 do not provide specific metrics or performance indicators. On the other hand, ISO 9001, ISO 14001, ISO 50001, and ISO 26000 are standards that do provide guidance on establishing metrics and performance indicators within their respective domains. However, there is no ISO Standard that would provide the three-dimensional metrics set.

On the *Check* step the sustainability reporting may be used, as it aims to identify, gather and report Sustainability Key Performance Indicators (SKPIs). GRI reporting, for example, mainly focuses on organization-wide ESG aspects and does not capture the detailed nuances and specific impacts of individual processes within an organization. Additionally, GRI reporting frameworks lack the granular metrics and indicators needed to comprehensively assess the environmental and operational aspects of business processes.

While Lean and Green BPM might support the decision making process on the *Act* step, LCA seems to be a perfect choice to aid ISO Standards on all the stages of PDCA. However, LCA in the current form fails to support business process assessment (see Section 2.4).

Why processes and process mining?

Processes are the arteries of every business (Dumas et al., 2018) and the key to its sustainability performance (Seidel, Recker, and Brocke, 2012). Presently, organizations after completing mandatory reporting face uncertainty about their next steps. Even if sustainability is not a central business value, no company desires to face the embarrassment of non-improving SKPIs in future reports. Thus, there is a need to enhance them. Almost every company is full of business processes that are crucial for business success. But all of those business processes also have very strong sustainability relationship, they have significant impact on those businesses long-term sustainable management (Bocken and Geradts, 2020). Therefore, companies should embed metrics not only at the organizational level, but also into their day-to-day operations.

Metrics are data, and data should be analysed with the proper tools. Data and Process Sciences offer the pool of techniques that can be utilised (Figure 3). Process mining can easily handle both, data and process, perspectives (Van der Aalst and Carmona, 2022, p. 32). What differs process mining from other approaches is the following (Van der Aalst, 2016, pp. 44–52):

- Unlike traditional **BPM** approaches, which typically rely on pre-defined process models, process mining takes a data-driven approach by analyzing event logs to discover, visualize, and improve actual process flows.
- While **Data Mining** focuses on extracting insights from large data sets, process mining specifically targets the analysis of process-related data.

- **Lean** emphasizes waste reduction and process improvement, whereas process mining complements it by providing a data-driven perspective to identify bottlenecks and inefficiencies.

- **Business Process Re-engineering (BPR)** aims to redesign processes from scratch, while process mining provides insights for optimization within existing processes.

- **Business Intelligence (BI)** provides high-level insights into organizational performance, while process mining delves deeper into the details of process execution.

- **Complex Event Processing (CEP)** focuses on real-time event stream analysis, while process mining operates on historical event data.

- **Governance, Risk, and Compliance (GRC)** focuses on regulatory compliance and risk management, whereas process mining contributes by identifying compliance issues and assessing process adherence.

- Process mining also differs from **other process improvement methodologies** such as activity-based process design (ABPD), business process improvement (BPI), and workflow management (WM) by its data-centric approach.

- Process mining can leverage **Big Data** technologies and techniques, but its focus lies specifically in extracting process-related insights rather than the broader scope of big data analytic.

This numerous acronyms used in business consulting emphasize the growing focus on using data for process analysis and decision-making. Process mining can simplify and unify process analysis, providing practical insights and applicability (Van der Aalst, 2016, p. 52).

3 RELATED WORK

This chapter explores the studies conducted in the field of process mining for sustainability. Given the complexity and multidimensionality of the topic, the literature review is done in ”narrative” style (Paré et al., 2015). First, the related works regarding each dimension of sustainability (economic, environmental, and social) are described. Subsequently, articles that embrace a (semi-)holistic approach are presented.

3.1 Search Methodology

Graves, Koren, and Van der Aalst (2023) conducted two literature reviews on process mining for sustainability and circular economy. The findings show that searching for an explicit connection between process mining techniques and sustainable development leads to few results and offers only a partial overview of the potential of process mining in sustainable development. Therefore, the search for related papers is conducted by exploring both, explicit and implicit, connections, ensuring a comprehensive coverage of relevant literature in the field. The search process involves two steps: (1) using keywords such as ”sustainability,” ”sustainable development,” and ”green”; (2) generating additional search terms related to each dimension and application domain based on the TBL framework (Litman, 2021), GRI Standard (GRI, 2021) and related literature (*e.g.,* Börekçi and Kiriş, 2017). The final set of search keywords is presented in Table 2. It should be noted that conducting the proper SLR is outside of the scope of this thesis. Hence, only selected words from Table 2 are used.

Table 2: Keywords and synonyms for literature review search string

Keyword	**Synonyms**
Process Mining	Workflow Mining, Process Discovery, Process Analysis, Process Modeling
Sustainability	sustainable development, Sustainable, Green
Sustainable Process Mining	Green Process Mining, Sustainability and Process Mining
Economic	Economic productivity, Local economic development, Affordability, Operational efficiency, Investment, Economic growth, Financial performance, Economic impact, Business development, Saving, Circular economy, Audit, Fraud
Environmental	Climate change, Air/Noise/Water pollution, Waste, Renewable energy, Energy efficiency, Biodiversity, Ecosystem, Carbon footprint, Greenhouse gas (GHG), Emissions, Environment, Ecology, Recycling, Green, Resource use, Eco-friendly
Social	Equity, Fairness, Trust, Social, Individual, Human rights, Labor rights, Gender, Community, Occupational health and safety, Well-being, Public health, Diversity and inclusion, Employee welfare, Safety and security, Privacy, Cultural heritage, Employment, Ethic, Child labor
Application domain	Manufacturing, Supply Chain, Accounting, Finance, Business Management, Energy Sector, Transportation, Building and Construction, Education, Urban Development, Healthcare

3.2 Process Mining for Economic Sustainability

Jans, Van der Werf, et al. (2011) focus on **internal transaction fraud** and explores the application of process mining as a means to mitigate such fraudulent activities. Through mining event logs in the procurement process of a case company, the study identifies flaws and potential opportunities for fraud. Process mining proves to be a valuable tool in objectively extracting process models from transactions logs without bias, enabling the discovery of non-compliant cases and assisting in monitoring internal controls and business rules. The findings suggest that process mining can aid in fraud detection and compliance checking at an early stage, but further development and automation of process mining tools are needed to enhance its effectiveness for auditing and management purposes.

Several studies aim to improve auditing processes. For example, Werner (2017) presents a novel method for process mining in ERP systems that utilizes accounting data structure dependencies rather than time dependencies between recorded events to infer the control flow. The approach generates sound process models with reduced complexity compared to traditional methods. It has the potential to improve **financial audits** by providing external auditors with efficient and effective information about business processes, freeing up resources for focusing on non-standard transactions with higher audit risk. The method has been evaluated using real-world data from SAP systems, and future research aims to explore its applicability to other ERP systems and real-world organizational settings.

Jans, Alles, and Vasarhelyi (2013) advocate for the use of process mining in **auditing**, highlighting its value-added sources, such as including analyzing the entire data population and meta-data, enabling effective implementation of the audit risk model, conducting unique analyses not possible with existing tools, and identifying social relationships. The authors argue that process mining's potential benefits have not been fully explored in the literature, urging auditors and researchers to appreciate its uniqueness to foster its acceptance in auditing practice.

Tu and Song (2016) introduce a method for analyzing and **predicting cost** of manufacturing processes. The approach includes process model-enhanced cost analysis, which breaks down the cost of each activity, and cost prediction, which provides insights into both consumed cost and remaining cost to complete the process. Future work includes conducting a case study with real-life data to validate the proposed method.

3.3 Process Mining for Environmental Sustainability

Brehm, Slamka, and Nickmann (2022) investigate the application of process mining to support **carbon accounting** and decision-making for carbon reduction in organizations. Through a literature review and expert interviews, the study identifies the potential of process mining to enhance carbon accounting practices. The findings highlight three key contributions: (1) Process mining offers end-to-end visibility of carbon impact at various process levels, allowing measurement of carbon footprints per step and throughout process execution. (2) By simulating different process scenarios, carbon accountants can evaluate alternative and less carbon-intensive ways to operate. (3) Aggregated views facilitate comparing ecological factors (CO_2 emissions) with process performance indicators without overlooking actual process execution. The study emphasizes the need for primary event logs and secondary carbon emission data, providing practical insights for future research and suggesting collaborations between process mining experts and carbon accountants for effective carbon reduction strategies.

Graves, Koren, and Van der Aalst (2023) present the PM4S framework, which aims to increase sustainability in business processes with regards to **circular economy**. The framework utilizes essential environmental sustainability elements to build an Object-Centric Process Mining (OCPM) enriched with environmental impact assessment metrics. It enables comprehensive process analysis, end-to-end process management, and facilitates decision-making by comparing alternative practices and assessing process sustainability. PM4S also supports simulations, digital shadows, and identifies deviations from benchmarks, contributing to effective process improvement and environmental sustainability.

Another framework for **circular economy** is introduced by Acerbi et al. (2022). It supports energy-effective Disassembly Sequence Planning (DSP) in manufacturing companies, and combines various techniques and algorithms to find a feasible and energy-effective disassembling sequence. The framework's feasibility is demonstrated through two applications, indicating its data-driven approach and reliance on data gathered from production systems to achieve efficient DSP.

Ortmeier et al. (2021) investigate the use of process mining for **LCA** in manufacturing and demonstrates how it can address barriers to LCA implementation, potentially increasing its adoption in companies. The study evaluates different algorithms and finds the inductive miner to be most suitable for creating LCA process models based on event attributes. Additionally, it suggests enriching event logs with energy and resource data and incorporating cumulative energy consumption as an attribute in the process mining algorithm for visualization and evaluation. Finally, the paper emphasizes the need for direct input of energy and resource data from machines for further analysis.

Similarly, Otto, Vogel-Heuser, and Niggemann (2018) propose to enrich an event log with **energy consumption** data. This paper presents CyberOpt Online, a novel online parameter estimation approach for reusable automation software components in Cyber-Physical Production Systems (CPPS). Unlike traditional mathematical modeling methods, CyberOpt Online does not require predefined models, but instead learns models automatically from data observed during production system operation.

3.4 Process Mining for Social Sustainability

Nakatumba and Van der Aalst (2010) introduce an approach to quantify the **relationship between workload and processing speed** using regression analysis implemented as a new ProM plug-in. The study emphasizes the importance of accurate assumptions in analyzing business processes and aims to extract useful information from event logs characterizing resource behavior. The results show that the relationship described by the ”Yerkes-Dodson Law of Arousal” exists, but more sophisticated regression techniques are needed to capture the inverse U-shape effectively. Similarly, Park et al. (2015) offer a method for analyzing manufacturing processes in make-to-order production, including **workload and delay analysis**. The proposed approach is validated through a case study, helping identify problem causes by comparing planned and actual processes.

The vast majority of studies are related to **healthcare** process improvement. Dunkl et al. (2011) present an approach that combines workflow modeling, process simulation, process mining, and statistical methods to compare **guideline-based treatment** processes with empirical treatment processes, with a specific application to the Cutaneous Melanoma use case. Ganesha, Dhanush, and SM (2017) apply fuzzy process mining on computed tomography (CT) tests as a baseline scenario to generate and check effective process models for future implementation, aiming to enhance **resource utilization** and **reduce patient waiting times**.

Some papers explore the application of process mining techniques in healthcare to analyze patient flow variations and clinical processes in different hospitals. Suriadi, Mans, et al. (2014) focus on cross-organizational benchmarking, using clustering, process discovery, and performance analysis to measure differences in the **treatment of patients** with chest pain symptoms across multiple South Australian hospitals. Partington et al. (2015) highlight the challenges and potential benefits of process mining in healthcare, presenting a case study that applies process mining techniques to **administrative and clinical data for patients** with chest pain symptoms in four public hospitals. Mans et al. (2009) demonstrate the applicability of process mining in healthcare, using a real case of a gynecological oncology process in a Dutch hospital to provide new insights that improve existing **care flows** from control, organizational, and performance perspectives.

Fernandez-Llatas et al. (2015) demonstrate the successful application of process mining techniques in conjunction with Indoor Localization Systems (ILS) to provide an easy-to-use and comprehensive view of deployed processes in a real **medical environment**. The algorithm effectively captures process features, aiding medical staff and managers in identifying current problems and improving protocols for increased efficiency and success rates. The application not only infers general process characteristics, but also detects specific rare cases that deviate from the usual protocol, allowing for the creation of contingency plans and system corrections. The web-based approach integrated into the users' workflow received positive feedback, indicating good acceptance and utility perception.

Security issues is of high interest of process mining researches. Van der Aalst and Medeiros (2005) advocate using process mining techniques, particularly the α-algorithm, to analyze audit trails for **security violations**. The application of this algorithm enables the detection of anomalous process executions and facilitates process conformance checking by comparing process fragments with the discovered workflow net (WF-net). The study emphasizes the versatility of the α-algorithm in supporting security efforts at various levels, ranging from low-level intrusion detection to high-level fraud prevention. Considering the increasing focus on Corporate Governance and governmental regulations, such as the Sarbanes-Oxley Act, the use of process mining techniques can aid organizations in enforcing and checking security at the level of business processes by storing and monitoring audit trails effectively.

Myers et al. (2018) introduce a novel process mining anomaly detection method that utilizes conformance checking analysis with Industrial Control Systems (ICS) data logs to identify **anomalous behavior** and **cyber-attacks**. The contributions of the study include experimentally derived logging practices recommendations for ICS devices, a formalized approach for pre-processing and transforming device logs for process mining analysis, and guidance on creating a process model for ICSs to identify anomalies through conformance checking analysis. The method has proven effective in detecting ICS cyber-attacks that widely used IDS Snort fails to identify, using logs from industry standard ICS devices.

Accorsi, Stocker, and Müller (2013) investigate the use of process discovery for **security auditing** in the business layer of the enterprise architecture metamodel, assuming well-structured and semantically defined logs. The study demonstrates that process discovery can extract structures from log files that are sufficient for testing organizational security requirements. To improve widespread adoption, the paper highlights the importance of consolidating and leveling logs, explores the extraction of structures considering both control and data flow, and suggests exploring non-repudiation or accountability mechanisms. Additionally, the paper emphasizes the potential of process discovery and security analytics as a powerful basis for risk analysis, which requires further research and development.

Pohl, Qafari, and Van der Aalst (2022) focus on **fairness and discrimination** in process mining, presenting various fairness definitions and a structured taxonomy. It discusses potential key contributions of fairness in process mining, providing an approach to map fairness definitions using situation feature tables. The main consideration is whether differences between groups or individuals stem from unjust bias requiring correction. Justifying selected fairness measurements from a moral perspective and considering associated assumptions are crucial. Enhancing processes with fairness objectives may involve immediate costs and less tangible, delayed benefits.

Qafari and Van der Aalst (2019) propose a fair classifier to avoid making obvious or **unfair judgments**, which may lead to **discriminatory** conclusions. The use of classifier helps to reveal less frequent causes by removing the dependency between the sensitive attribute and the class attributes from the classifier, keeping the acceptable level of accuracy.

Studies related to privacy mainly focuses on the improving process mining algorithms. The importance of privacy regulations and EU GDPR compliance is highlighted in several studies. Mannhardt, Petersen, and Oliveira (2018) explore **privacy challenges** in human-centered industrial environments where wearable technologies provide sensor data for process mining analysis aimed at improving operators' well-being. Mannhardt, Koschmider, et al. (2019) address the impact of **privacy regulations** on process mining, particularly for event data recorded by information systems in domains like e-commerce or healthcare, which may expose sensitive information. It proposes a protection model based on differential privacy to safeguard event data privacy during process mining. The approach is demonstrated through its application to publicly available real-life event logs, showcasing its general feasibility in ensuring privacy compliance.

Another line of research in privacy areas is dedicated to the anonymity of private data. **Log sanitation** is addressed by Fahrenkrog-Petersen, Van der Aa, and Weidlich (2019) by introducing PRETSA algorithm to avoid disclosure of employee identities and sensitive attributes while maintain high utility for process model discovery. Rafiei, Von Waldthausen, and Van der Aalst (2018) propose an approach using abstraction and encryption to **support confidentiality** in process mining, enabling the hiding of sensitive information. Rafiei and Van der Aalst (2021) discuss group-based **privacy preservation** techniques, addressing the challenges of applying existing techniques and introducing an effective privacy preservation technique covering control-flow, time, case, and organizational perspectives. Elkoumy et al. (2020) introduce Shareprom, a tool using secure multi-party computation to enable independent parties to execute process mining operations without revealing data other than the output of the analysis, ensuring **privacy protection**.

3.5 Process Mining for Integrated Sustainability

Safitri, Sarno, and Budiawati (2018) classify business processes based on **sustainability indicators** and establishes benchmarks for sustainability duration in process models. Results indicate that leveraging sustainability indicators for classification can lead to substantial business process improvements. Moreover, the research contributes to calculating sustainability gaps in business processes and guiding improvements based on sustainability indicators, encompassing economic, environmental, social, and corporate governance aspects.

Hakim (2020) highlights the importance of understanding real business processes to uncover hidden problems and enhance the **quality of healthcare services** while **reducing costs**. By applying process mining on activity logs in a cardiology hospital, the study aims to provide objective insights into the patients' treatment process. The process flow model generated from event logs reveals valuable information about delays, inconsistencies, and bottlenecks in patient care flow. As the healthcare industry in Pakistan grows rapidly, efficient resource utilization becomes crucial for maximizing benefits. This research serves as the pioneering attempt to apply process mining tools and technologies in Pakistan, opening new avenues for optimizing healthcare processes in the country.

4 DEVELOPMENT OF THE FRAMEWORK

This chapter describes the proposed Green Process Mining framework. First, the definition of sustainable business process is provided. Subsequently, the enriched process mining methodology is described, including mapping GRI indexes to business processes and analysis approaches.

4.1 Definition of Sustainable Business Process

To assess the sustainability of business process, the definition of it should be given. Sustainable business process is a concept that is widely recognized and discussed across various industries and sustainability initiatives. While there might not be a single ”official” reference defining sustainable business processes, several reputable organizations (United Nations Global Compact (UNGC), World Business Council for Sustainable Development (WBCSD)), frameworks (GRI, TBL), and standards (ISO 14001) provide guidance and principles related to sustainability in business processes.

Based on the principles and guidance, a possible clear definition could be:

> **Sustainable business process** is a set of activities that are performed in coordination within an organizational and technical environment to achieve a business goal while ensuring the responsible and efficient use of resources, minimizing negative environmental impacts, and considering the social and economic well-being of current and future generations.

It is important to note that while this definition attempts to capture the essence of sustainable business processes, individual organizations may interpret and implement sustainability principles in ways that align with their business values and industry contexts. As sustainability is an evolving field, definitions and approaches may continue to evolve over time.

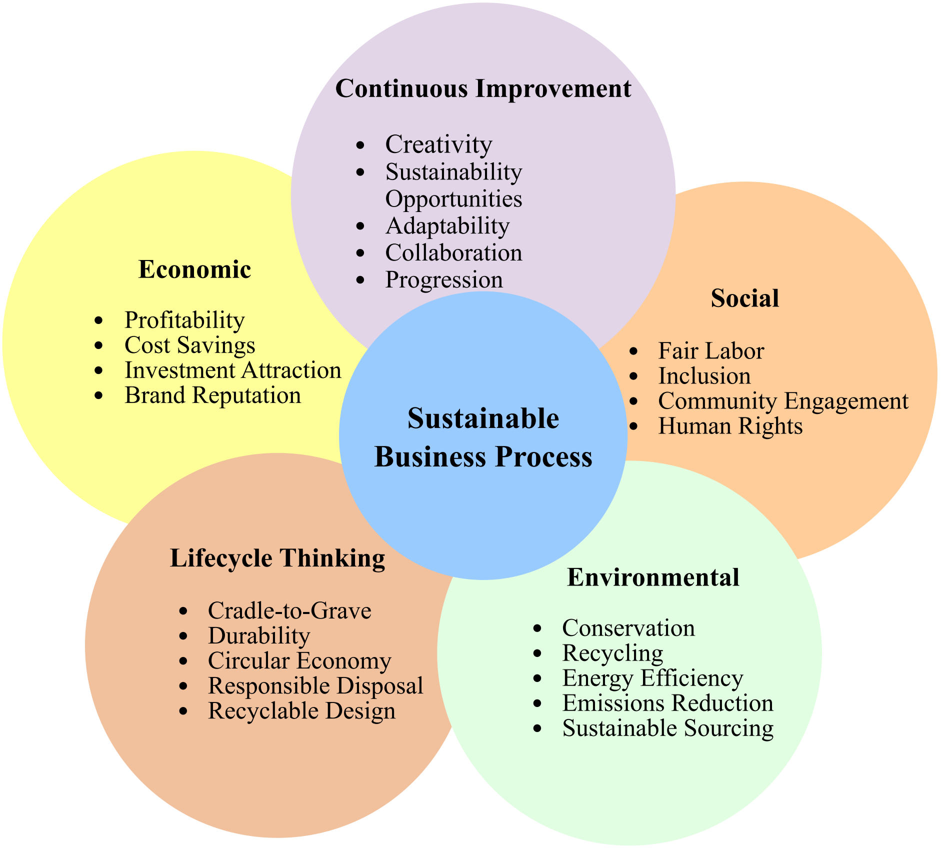


Figure 6: Key characteristics of sustainable business processes

Key characteristics of sustainable business processes include (Figure 6):

- **Environmental responsibility**: Sustainable processes take into account the environmental consequences of business activities, seeking to reduce waste, conserve resources, minimize pollution, and lower GHG emissions. This might involve adopting renewable energy sources, implementing recycling programs, or optimizing transportation and logistics to reduce carbon footprints.
- **Social accountability**: Sustainable business processes consider the well-being of employees, customers, suppliers, and local communities. This includes fair labor practices, safe working conditions, diversity and inclusion efforts, and community engagement initiatives. Companies with a strong social responsibility focus on maintaining positive relationships with stakeholders and supporting the communities in which they operate.
- **Economic viability**: Sustainable business processes are not just about being environmentally and socially responsible; they must also be economically viable. This means that the processes should be efficient and profitable, providing long-term benefits to the company. Sustainable practices can lead to cost savings through reduced resource

consumption and waste, increased employee productivity, and improved brand reputation, which can attract environmentally and socially conscious consumers.

- **Lifecycle thinking**: Sustainable business processes consider the entire lifecycle of products and services, from raw material extraction to disposal or recycling. This approach encourages companies to minimize waste, design products for durability and recyclability, and engage in circular economy practices, where materials are reused and repurposed.
- **Innovation and continuous improvement**: Sustainable business process is the one that constantly being improved and incorporate innovations.

Evidently, sustainable business processes prioritize environmental, social, and economic perspectives, fostering a positive impact on the planet, society, and profitability. The next step is to explore how these aspects can be incorporated into process mining methodology.

4.2 Enhancing PM^2 for Green Process Mining Framework

There are a few methodologies to conduct process mining project: Process Diagnostics Method (PDM) (Bozkaya, Gabriels, and Van der Werf, 2009), the L* life-cycle model (Van der Aalst, 2011), and PM^2: a Process Mining Project Methodology (Van Eck et al., 2015). PDM provides a quick and broad overview of a process, however has limitations in its application for larger projects due to its restricted scope of techniques (Suriadi, Wynn, et al., 2013) and avoidance of domain knowledge (Bozkaya, Gabriels, and Van der Werf, 2009). On the other hand, while L* covers various aspects of process mining and is suitable for structured processes, it lacks an iterative approach (Suriadi, Wynn, et al., 2013). Conversely, PM^2 offers many process mining and analysis techniques, supports both structured and unstructured processes, enables quick analysis iterations, and provides practical guidance through concrete steps (Van Eck et al., 2015). Therefore, PM^2 is selected as the foundational methodology for the development of *Green Process Mining Framework* to better cover sustainability aspects of business processes.

The PM^2 illustrated in Figure 7 consists of six steps (Van Eck et al., 2015). It begins with (1) **planning** and (2) **extraction** stages, where process analysts define initial research questions and extract event data. Following these stages, one or more analysis iterations are carried out, potentially in parallel. Each analysis iteration involves: (3) **data processing**, (4) **mining & analysis**, and (5) **evaluation**. During an analysis iteration, specific research questions are addressed using process mining techniques, and the discovered process models and findings are evaluated. If the results meet the requirements, they can be utilized for (6) **process improvement**.

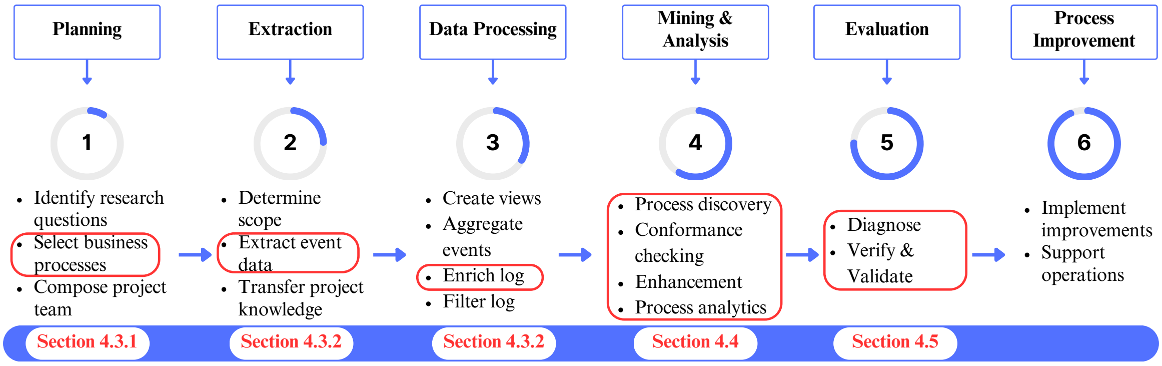


Figure 7: PM^2 and areas for extension (in red)

Figure 7 not only shows the PM^2 methodology, but also highlights the specific *red-bordered* areas where the sustainability aspects are seamlessly integrated, forming *Green Process Mining Framework*. The subsequent sections adhere to the PM^2 structure, while elaborating exclusively on its extension. Which processes to analyse and data to collect are specified in Section 4.3.1 and Section 4.3.2 respectively, while the overview is presented in Section 4.3.3. How process mining and analysis can be done using sustainability-related attributes is described in Section 4.4, finally, the process evaluation with sustainability in mind is addressed in Section 4.5.

4.3 Selection of Business Processes and Event Log Attributes

Janina Nakladal, Director of Sustainability at Celonis, said ”You have the data in your systems already but are not using it for sustainability” (Dignan, 2022). This section aims to investigate which data can be utilised in green process mining.

4.3.1 Selection of Business Processes

According to PM^2, process mining projects begin by selecting business processes for analysis and improvement. R. Bose and Van der Aalst (2009) argue that *process characteristics* and *quality of event data* should be considered on this step, while Van Eck et al. (2015) add that *process changeability* should be also taken into account.

Building upon this foundation, in the context of *Green Process Mining Framework*, an additional essential consideration emerges: the fourth characteristic in selecting business processes should be ***materiality***. It means that processes should align with the organization’s sustainability objectives and reporting requirements. Materiality assessments focus on identifying processes that are critical or have a significant impact on the organization’s overall sustainability performance. For example, in the manufacturing industry, the production process can be material, as it directly influences the environmental and economic aspects of sustainability. In the healthcare sector, patient care and medical waste disposal processes may be material, considering their implications for social responsibility and environmental stewardship. These assessments involve considering the significance of sustainability topics to the organization and its stakeholders, as well as the contribution of the selected processes to the achievement of sustainability goals.

4.3.2 Selection of Event Log Attributes

Extraction is the second step of PM^2, where during the scope determination, one of the questions to be considered is *which data attributes should be extracted*. This is closely related to the enriching event log on the third step *Data Processing*. Van Eck et al. (2015) offer two ways of enriching an event log: (1) derive or computing additional events and data attributes based on the log itself, or (2) adding external data.

Green Process Mining Framework suggests that along with the mandatory attributes (case id, timestamp and activity), additional sustainability-related attributes should be considered. These attributes can be directly related to the sustainability of the process (*e.g.,* energy or water consumption, cost of materials and labor) or used to compute other SKPIs (*e.g.,* emissions intensity is derived from CO_2 emissions and revenue).

Joung et al. (2013) defines a process attribute as a “measure or an aggregation of measures from which conclusions on the phenomenon of interest can be inferred”. This indicators should have a certain qualities to be eligible for application (*Sustainability Measures* 2009; Moss and Grunkemeyer, 2007; Tan et al., 2015):

- **Measurable**: easy and straightforward quantification or assessment within a defined timeframe.
- **Relevant**: direct connection to a significant and meaningful aspect of sustainability in the context of the evaluated business process.
- **Understandable**: easy comprehension and interpretation by the general public and non-experts.
- **Reliable/Usable**: indicator provides trustworthy and accurate information.
- **Data Accessible**: indicator is based on data and information that are readily available and can be accessed.
- **Timely Manner**: collection, calculation, and evaluation of data for an indicator should be conducted in a timely manner to enable informed decision-making.

- **Long-Term Oriented**: future-oriented, ensuring their continuous use, development, and adoption as standards for sustainability in the organization or the process/product.

Section 2.8 discusses different frameworks and practices that could be used to define sustainability-related attributes for event log. None of them suits purpose, apart from sustainability reporting standard. However, according to Joung et al. (2013) there are other indicator sets that might be suitable for measuring sustainability of processes. The summary is presented in Table 3.

Table 3: Summary of sustainability indicator sets (based on Joung et al. (2013))

Indicator set	**Number of indicators**	**Dimensions covered**
Global Report Initiative (GRI)	117	Economy, Environment, Society
Dow Jones Sustainability Indexes (DJSI)	12	Economic, Environmental, Social
2005 Environmental Sustainability Indicators (ESI)	68	Environmental
Environment Performance Index (EPfI)	19	Environmental
United Nations-Indicators of Sustainable Development (UN-CSD)	96	Economic, Social, Environmental
Organisation for Economic Cooperation and Development (OECD) Core Environmental Indicators (CEI)	46	Environmental, Social, Economic
Ford Product Sustainability Index (Ford PSI)	8	Environmental, Economic, Social
International Organization for Standardization (ISO) Environment Performance Evaluation (EPE) standard (ISO 14031)	155	Environmental, Operational, Management
Environmental Pressure Indicators for European Union (EPrI)	60	Various (Air, Climate, Biodiversity, etc.)
Japan National Institute of Science and Technology Policy (NISTEP)	150	Technological Advancement, Personnel Skills
European Environmental Agency Core Set of Indicators (EEA-CSI)	37	Environmental

The selection of suitable set poses challenges. While some sets focus solely on specific dimensions (*e.g.,* ESI, EPfI, NISTEP), others, like UN-CSD, are not tailored to organizations and are designed for top-level sustainable development assessments. Among the available sets the GRI is selected due to its widespread adoption (KPMG, 2022; *Four in Five Largest Global Companies Report with GRI* 2022), comprehensive guidelines, and inclusive coverage of all three dimensions. Additionally, GRI's organization-oriented framework facilitates the alignment of indicators with business processes, making it a favorable choice.

The data that already collected to report on sustainability performance at the organizational level, can also be utilized to create an event log. After performing analysis using process mining tool, there are two benefits: (1) certain indicators can be improved for sustainability reporting, and (2) the application of Green BPM can lead to improvements in business processes. This concept is represented in Figure 8.

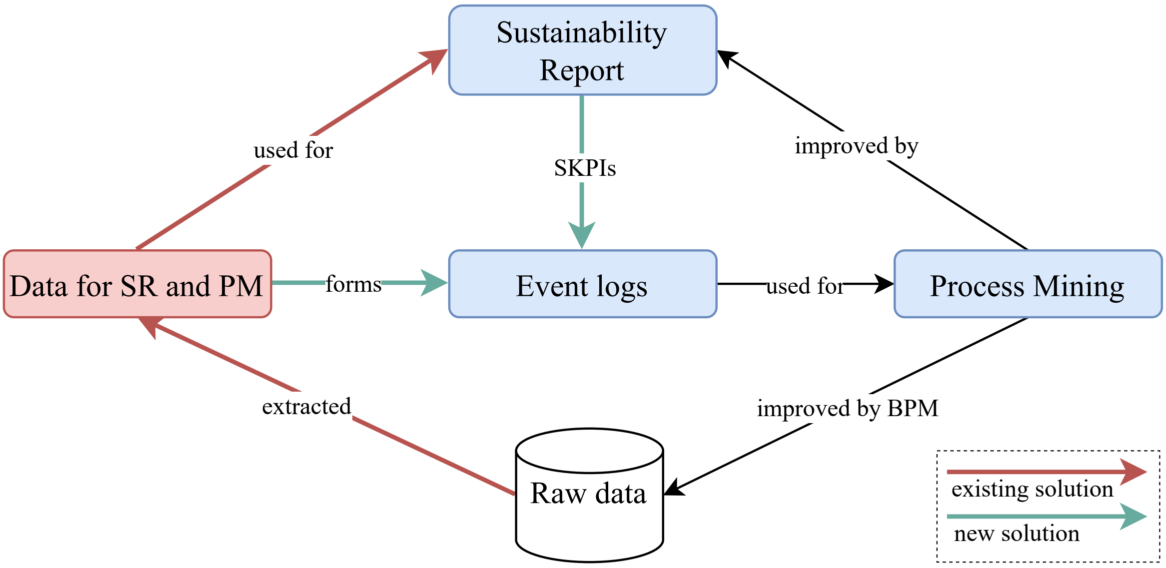


Figure 8: Sustainability-related data flow

Noteworthy, to construct the event log the process-specific data is needed, as well as not all data used for sustainability reporting is applicable to processes. Hence, there is a need for mapping the GRI indexes to business processes, which bridges sustainability reporting with operational aspects.

4.3.3 Mapping GRI Indexes to Business Processes

Considering that organization may contain numerous processes, for the purpose of mapping, only a limited number of processes are chosen. This selection is based on lists of business processes utilized in process mining projects (Santos Garcia et al., 2019; *Celonis Value Trees* n.d.; HSPI, 2021). The inclusion criteria are (1) the substantial quantity of projects, coupled with (2) significant impact on environment, society and economy. The list of selected business processes for mapping is presented in Table 4. As for production process, the detailed mapping procedure is described in Section 5.2.1.

Table 4: Selected business processes for mapping to GRI indexes

Process	**Description**	**Sustainability impact**
Order-to-Cash (O2C)	Involves receiving and processing customer orders, managing inventory, fulfilling orders, and collecting payments from customers	Customer satisfaction, product and service labeling, and supplier environmental assessment
Purchase-to-Pay (P2P)	Includes activities related to procuring goods and services, such as requisitioning, vendor selection, purchase order creation, receipt of goods, and invoice processing	Supplier social practices, human rights assessment, and sustainable procurement
Warehouse Management	Involves the efficient management of inventory and warehouse operations	Resource efficiency, waste management, and environmental impact of logistics
Employee Onboarding (HR)	Process covers activities to integrate new employees into the organization. It includes orientation, training, and familiarization with the organization's culture and processes.	Employee training, diversity and equal opportunity, labor practices and decent work
Supply Chain Management	Involves coordinating the flow of goods, services, and information from suppliers to manufacturers and distributors, and finally to customers	Supplier assessment, responsible sourcing, product and service impacts
IT Service Management (ITSM)	Involves incident management, problem management, change management, and service request handling	Data privacy, cybersecurity, and energy efficiency in IT operations
Claims Management	Involves the registration, processing, and resolution of customer claims or complaints	Customer satisfaction, grievance mechanisms, product and service quality
Customer Journey Experience	The end-to-end interactions and touchpoints a customer has with a company. It includes awareness, consideration, purchase, and post-purchase stages.	Customer satisfaction, leading to brand loyalty and potential long-term environmental benefits
Work Order Management	Involves task execution activities: work request submission, task prioritization, resource allocation, task assignment, progress tracking, and completion validation.	Resource usage, labor practices, and decent work
Internal Audit	Involves audit planning, risk assessment, data collection, analysis, findings evaluation, and recommendation formulation.	Sustainability governance, stakeholder engagement, and public policy advocacy

GRI 3 defines the material topics and offers guidelines, including indicator metrics and their respective calculations (GRI, 2021). Common metrics for each indicator are derived in accordance with GRI guidelines and publicly accessible sustainability reports of various companies. Subsequently, for each selected business process, the relevant metrics are mapped based on predefined in Section 4.3.2 quality criteria of event log attributes.

An overview of selected business processes aligned with GRI indexes is presented in **Appendix A**. The table is organized into four main sections: *GRI Standard*, *Disclosure*, *Metrics*, and *Processes*. The *GRI Standard* column contains the specific GRI index number and its corresponding economic, environmental, or social aspect. The *Disclosure* column provides a brief description of the disclosure related to each GRI index. The *Metrics* column outlines the specific metrics or data points associated with each GRI index. The intersections of the rows and columns in the table contain ”x” marks, indicating the business processes that are relevant to each GRI index. The ”x” marks signify the alignment of GRI indexes with corresponding business processes.

There are two ways to interpret the information in table: GRI indexes and business processes perspectives.

GRI Indexes Perspective

In this approach, the focus is on understanding the disclosure and metrics associated with each GRI index. One can scan through the GRI index column to identify specific GRI indexes. Then, follow the corresponding row to examine the disclosure provided for each GRI index in the *Disclosure* column. The *Metrics* column provides further insights into the specific metrics related to each GRI index. Moving further to the right along the lane, the associated business process can be identified. This approach is used on the *Planning* step, when the business process need to be selected.

For example, if the company is interested in *GRI 301: Materials 2016*, they can find the row corresponding to this index. The *Disclosure* column might provide information about the used materials, recycled input, reclaimed products and their packaging materials. The *Metrics* column provides additional details, such as weight or volume of non-renewable materials used, weight or volume of renewable materials used, percentage of recycled input materials used, percentage of reclaimed products and their packaging materials for each product category. Then, look for ”x” marks in those rows to indicate the respective business processes, such as Order-to-Cash, Purchase-to-Pay, Warehouse Management, Supply Chain Management, Claims Management and Customer Journey Experience.

Business Process Perspective

In this approach, the focus is on understanding how different business processes align with the GRI indexes. One can scan through the columns representing various business processes and look for ”x” marks in each row. An ”x” mark indicates that the respective business process is relevant to the corresponding GRI index. This approach is used on the *Extraction* step, when the business process is already known, and the corresponding metrics need to be identified.

For example, if the company is interested in the *Order-to-Cash* business process, they can find the *Order-to-Cash* column and check for ”x” marks in each row. If there is an ”x” in the row corresponding to *GRI 201: Economic Performance*, it indicates that the *Order-to-Cash* process has a significant impact on economic performance. Contrariwise, if there is no an ”x” mark, for instance, *GRI 303: Water and Effluents*, it does not influence the water discharge-related metrics.

By approaching the table from these two perspectives, companies can identify how different business processes contribute to specific GRI indexes and how the organization’s sustainability performance is measured and disclosed in relation to these indexes. This information can be utilised to make informed decisions, set sustainability goals, and report on their efforts to stakeholders and the public.

4.4 Process Analysis

Process mining & Analysis is the fourth step of PM^2. When the event log is formed, the process analysis begins. Van Eck et al. (2015) define four types of activities: process discovery, conformance checking, enhancement and process analytics.

To integrate the principles of sustainability within the *Green Process Mining Framework*, the focus should be on SKPIs of the process. This can involve identifying inefficiencies, waste, and opportunities for resource optimization, as well as ensuring that processes comply with sustainability goals and standards. Here are some ways to alter the existing methodology:

Process Discovery: Similarly to traditional performance analysis based on throughput times and costs (De Weerdt et al., 2012; Van der Aalst, 2016), the sustainability-related characteristics of the process can be considered. For example, for each activity the carbon emissions, water usage, energy consumption, waste generation, and social impact indicators can be calculated. In this way, the activities that are resource-intensive can be identified.

Conformance Checking: The compliance of processes not only with respect to time, quality, and cost (Rozinat and Van der Aalst, 2008), but also with sustainability goals should be assessed. For example, conformance checking can help identify activities of non-compliance with social responsibilities, ensuring that fair labor practices are maintained throughout the process.

Enhancement: The enhancement activity should not only focus on improving performance (Van der Aalst, 2016), but also on integrating sustainability measures into the process models. For example, process should be optimize to reduce environmental impact (*e.g.,* waste and emissions reduction) or enhance social benefits (*e.g.,* fair wages, incidents reduction).

Process Analytics: Data mining (De Leoni, Van der Aalst, and Dees, 2014) and visual analytics techniques can be used to get insights into sustainability-related patterns and trends. For example, discovered process models of supply chain process can be enriched with graphs that show the spend on local and international suppliers by month. In this way, the spend dynamics can indicate changes in supplier relationships, market conditions, or other significant events.

Benchmarking: Sustainability performance can be compared within different (sub)processes or business units to identify best practices that can be replicated across the organization. For example, the transportation processes with low and high CO_2 emissions can be compared to identify the factors contributing to the variations in CO_2 emissions.

Addressing sustainability in *Process mining & Analysis* step can lead to comprehensive understanding of processes' environmental and social impacts and make data-driven decisions to improve sustainability performance. This will not only result in more responsible and ethical business practice, but also save cost and improve company's brand.

4.5 Process Evaluation

Evaluation step relates analysis findings to improvement ideas, which are used on the final step *Process Improvement & Support* (Van Eck et al., 2015). The improvement of the process is usually done as a separate project, using various approaches, such as process re-engineering (Section 2.5) and Lean (Section 2.7). After changing the process, the improvements can be measured in another analysis project (Van Eck et al., 2015).

Diagnosing the findings obtained on *Process mining & Analysis* step may lead to identifying or refining research questions for possible further iterations, as well as designing ideas for possible process improvements. *Green Process Mining Framework* suggests that the concept of ”green trade-off” and impact assessment should be considered.

4.5.1 Green Trade-off

Even though the traditional process re-engineering approaches shift their focus from economic implications to considering environmental and social implications as well (Weske, 2012; Nowak et al., 2011; Slaper, Hall, et al., 2011), this, in turn, requires shift to multidimensional understanding of processes for better decision making. GRI (2021) states in their guidelines that economy, environment and people are interrelated, and organizations should take into account their impacts on all these dimensions collectively. Balancing the economic benefits with the environmental and social impacts of a decision usually referred as ”Green trade-off” (Nowak et al., 2011).

This perspective also applies to business processes. In Section 4.4 different techniques are discussed how the process analysis can be performed with regards to SKPIs. However, it is important to focus analysis not only on one dimension, but on all three simultaneously.

Impacts of changes in business processes can be both positive and negative. Nevertheless, not all changes for the better necessarily lead to positive outcomes, as positive impacts can sometimes inadvertently result in negative consequences, and vice versa. Examples of green trade-offs during process re-engineering are:

- Implementing energy-efficient equipment that reduces operational costs but comes with a higher upfront investment.
- Optimizing supply chain routes to reduce transportation emissions, which may result in longer delivery times or higher logistics costs.
- Transitioning to sustainable sourcing of raw materials, which might lead to higher prices or potential supply chain disruptions.
- Reducing paper usage through digitalization, which may require staff training and system upgrades.

Consideration of these interconnections may pose new research questions for analysis, as well as help in evaluating improvement opportunities and their potential solutions at the *Evaluation* step.

The next question is whether process mining can assist in evaluating these impacts.

4.5.2 Impact Assessment

Impact assessment is a future-oriented concept, focusing on understanding the consequences of actions or events that have not yet occurred (Nieminen and Hyytinen, 2015). On the other hand, process mining is a retrospective analysis technique that utilizes historical data (Van der Aalst, 2016). Due to this fundamental difference, process mining, in its conventional form, is not inherently suited for predicting the future impact of business processes. Process mining is primarily used for descriptive and diagnostic purposes, helping organizations understand what happened in the past, identify inefficiencies, and optimize current processes. However, process mining can be combined with predictive modeling or forecasting techniques to gain some insight into potential future impacts. Some of these approaches are time series analysis (Koschmider, Oppelt, and Hundsdörfer, 2022), predictive process mining (Mannhardt, Petersen, and Oliveira, 2018), and simulation modeling (Ryabchikov and Ryabchikova, 2022).

GRI (2021) categorize impacts as short-term and long-term. Similarly, Imperatives (1987) distinguish between these two categories as ”...the needs of the present (short-term) without compromising the ability of future generations (long-term)...” However, the exact timeframes are not set, ranging from days to few months for short-term impacts, while can exceed years for long-term impacts.

The event log’s timeframe can be mapped to these levels as follows:

- **Short-Term Impact**: Process mining conducted using event logs from the current process executions to few months, focuses on short-term impact analysis. This approach helps identify immediate inefficiencies and opportunities for quick improvements. For example, through real-time process mining, the organization can identify the energy-intensive activity in their manufacturing process, contributing to a higher carbon footprint. Another example, the analysis of logistic process over six months event log reveals a specific delivery route that causes frequent delays, increased fuel consumption and customer dissatisfaction.

- **Long-Term Impact**: When process mining involves longer event logs or predictive modeling, it relates to long-term impact analysis. This approach allows organizations to project future sustainability implications based on historical data and make informed decisions. For example, if an activity is found to have a significant environmental impact over the long term (*e.g.,* constant hazardous waste disposal), investments in sustainable alternatives or technologies may be warranted.

This concept is presented in Figure 9. Overall, it is possible to assess short-term and long-term impacts with regards to the past. When it comes to predicting future impacts, event logs can potentially be used for predictions.

The exact timeframe of event log depends on several factors. As a general rule in forecasting, the longer timeframe, the better prediction (Grolinger et al., 2016). On the other side, use of longer event log may cause problems due to changes in the process and corresponding noise in data. This, in turn, will affect the prediction, which already inherently uncertain. Van der Aalst (2016, p. 193) states that ”there is no clear relation between the size of a model and its behavior”, in other words, even small event logs may provide precise models. It means that predictions based on small event log can still be accurate. Therefore, the applicability of predictive process mining more depends on the characteristics of the process rather than length of the event log.

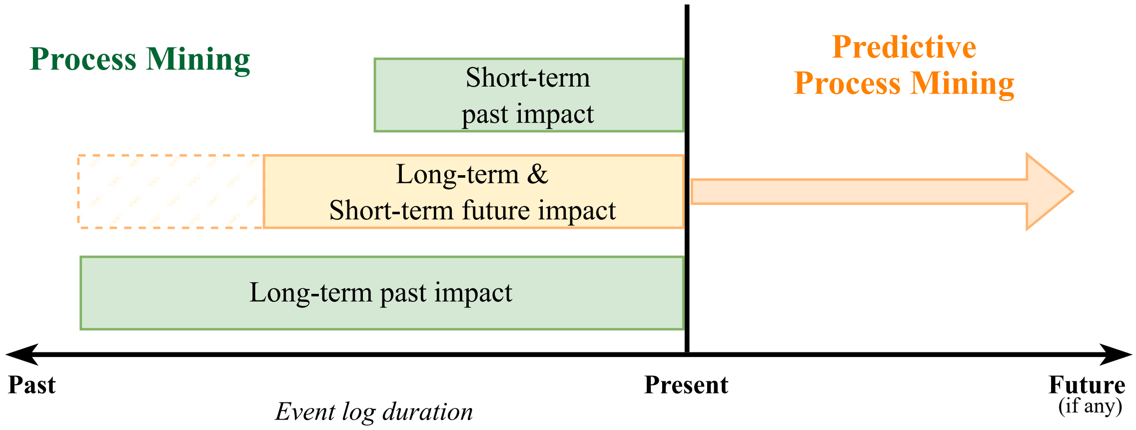


Figure 9: Impact assessment with process mining

In addition to time perspective limitations, there are aspects related to the process mining technology itself. First, process mining provides the quantitative measurements of impact, which should be enhance with additional data and qualitative methods, such as surveys or interviews. For instance, measuring energy consumption alone does not capture environmental impact, and to fully assess effects supplementary data about energy sources is essential (Klöpffer and Grahl, 2014, p. 220). Second, obtaining event logs is already a challenging task, consuming a significant portion of project time, especially in complex environments (Sonawane and Patki, 2015; Van der Aalst, 2016). Adding SKPIs at the activity level further intensifies this challenge, potentially hindering the feasibility of conducting extensive analyses. Furthermore, predictions heavily rely on quality and representativeness of data, modeling approach, and stability of underlying trends (Grolinger et al., 2016).

While measuring and forecasting the sustainability impact at the activity level can be beneficial, it may not always be feasible or necessary to analyze every single activity in a process. Instead, organizations can focus on activities that are resource-intensive, have significant environmental or social implications, or are critical to the overall performance of the process (see process mapping in Section 4.3.3). Additionally, aggregating data at higher levels, such as the process level or organizational level, can provide a broader understanding of the overall sustainability performance.

5 CASE STUDY IN MANUFACTURING

This chapter illustrates how the proposed framework can be used to assess sustainability of manufacturing process. The content is organized in accordance with first five steps of PM^2, where the extensions are made: Planning: Production Process Overview (Section 5.1), Extraction: Data Preparation (Section 5.2), Data Processing: Development of Application (Section 5.3), Mining & Analysis (Section 5.4), and Process Evaluation (Section 5.5).

5.1 Planning: Production Process Overview

On the first *Planning* step there are two main activities: selecting business process and identifying research questions (Van Eck et al., 2015).

The case study is conducted on the production process of spare parts. The choice of production process is motivated by the data quality and high impact of the production process on economy, environment and society (according to process selection criteria in Section 4.3.1.

The blueprint process model consists of seven activities and is shown in Figure 10. The process begins with *Turning & Milling*, where the raw materials are shaped and cut to the required specifications. The products then undergo *quality control (Q.C.)* to ensure they meet the necessary standards. Next, *Laser Marking* is performed to add identifying marks or information to the products. After that, *Lapping* is carried out to achieve a high level of flatness or surface finish. Following *Lapping*, *Round Grinding* takes place to further refine the products' shape and dimensions. A *Final Inspection* is conducted to thoroughly assess the quality of the items before they proceed to the final stage. Lastly, the products are *packed*, ensuring they are protected and ready for distribution to customers or other stages of the supply chain.

Figure 10: Model of production process

The primary goal of the analysis is to assess the sustainability performance of the process. At this point the sustainability-related attributes are not clear as well as their applicability in process mining techniques, thus, the initial research questions are defined on the abstract level with regards to three dimensions of sustainability:

1. *What is the economic performance of the production process?*
2. *What is the environmental performance of the production process?*
3. *What is the social performance of the production process?*

The answers to these questions will be found through an exploratory approach during the fourth step *Process Analysis* (Section 5.4).

5.2 Extraction: Data Preparation

On the second *Extraction* step there are two main activities: determining scope and extracting event data (Van Eck et al., 2015). First, the metrics are selected from the GRI indexes. Then the initial event log is cleaned and enriched with sustainability-related attributes.

5.2.1 Mapping GRI Indexes to Production Process

In order to understand which data attributes to collect, the GRI indexes should be mapped to the production process. In contrast to general mapping in Section 4.3.3 (**Appendix A**), more details are defined for production process. As mentioned in Section 4.3.2, GRI Standard defines indexes on the organizational level, thus not all metrics can be applied to the process *a priori*. Moreover, the production process itself can be categorized into two distinct types. The first type that includes the supply chain, production, sales, and other aspects is referred to as *end-to-end* or *full-scale* production process. The second type that focuses solely on the production process, machine operation, quality control, and packaging is referred to as *core* or *basic* production process. This relation and the amount of possible relevant indexes is illustrated in Figure 11.

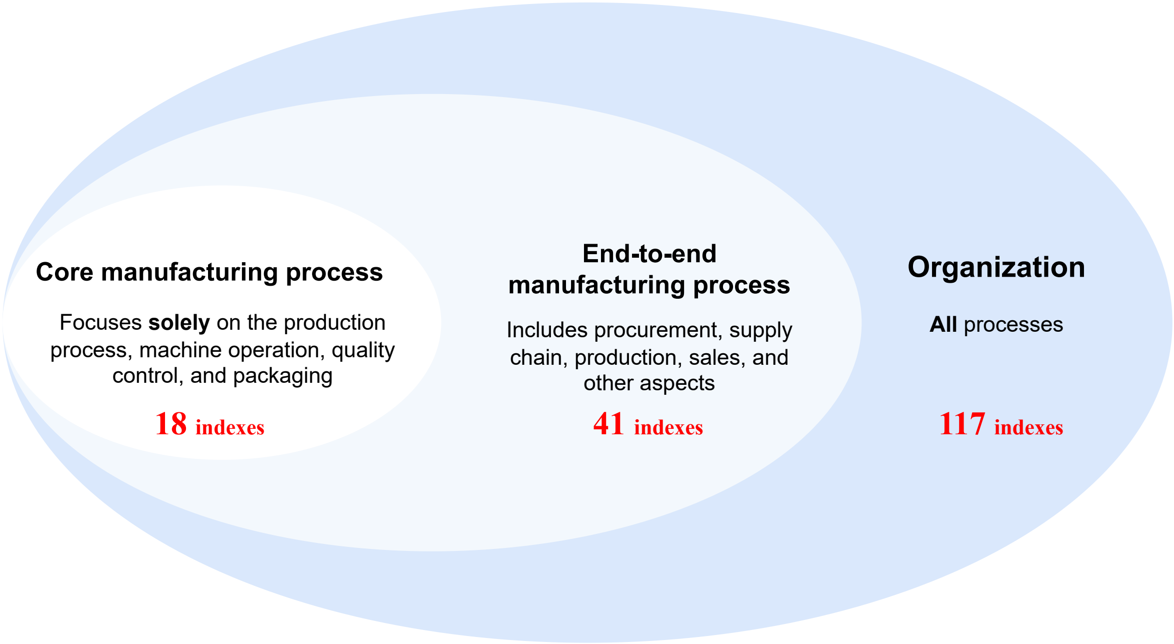


Figure 11: The relation between organizational level, end-to-end and core production process

The selection of metrics is based on predefined in Section 4.3.2 quality criteria of event log attributes and done in several steps:

1. The entire GRI Standard offers disclosure on 117 categories. 30 categories from GRI 2 and three categories from GRI 3 are removed, as they are relevant to the organization in general. For example, disclosure 2-1 Organizational details, 2-22 Statement on sustainable development strategy, or 3-3 Management of material topics.

2. Next, the selection is done among GRI 200 (Economic), GRI 300 (Environmental), and GRI 400 (Social) categories. 48 topics are excluded from consideration due to their irrelevance to the production process or descriptive nature, without any underlying calculations. For example, 201-4 Financial assistance received from government, 305-6 Emissions of ozone-depleting substances (ODS), or 404-3 Percentage of employees receiving regular performance and career development reviews.

3. The final 18 categories are selected from remaining 36 based on the relevance to the core production process. For example, 301-3 Reclaimed products and their packaging materials is related to the end-to-end manufacturing process. In fact, the reclaimed products could be traced back to the time when they were produced and the data can be analyzed to understand the reasons of quality issues.

The selected number of metrics aligns with the sustainability assessment benchmark. A recent study conducted by Ahmad, Wong, and Butt (2023) revealed that the majority of sustainability assessment methods rely on a range of 11-30 indicators, further supporting the validity of the selected metrics.

The final set of disclosures and selected metrics are presented in Table 5. For each metric preference and benchmark are defined. The preference indicates the direction in which the organization seeks to optimize or improve its performance, while the benchmark (or target value) is a measure to achieve for the given disclosure.

Table 5: GRI indexes applied to core production process

GRI Standard	**Disclosure**	**Metrics**	**Preference**	**Benchmark**
GRI 201: Economic Performance 2016	201-1 Direct economic value generated and distributed	Sales Revenue Operating cost per unit/activity	Maximisation Minimisation	Cannot be determined Approaching zero
GRI 204: Procurement Practices 2016	204-1 Proportion of spending on local suppliers	Spend on local suppliers	Maximisation	Cannot be determined
GRI 301: Materials 2016	301-1 Materials used by weight or volume	Total weight of non-renewable materials used Total weight of renewable materials used	Minimisation Maximisation	Approaching zero Cannot be determined
	301-2 Recycled input materials used	Percentage of recycled input materials used	Maximisation	90%
GRI 302: Energy 2016	302-1 Energy consumption within the organization	Energy consumption of activity by type (renewable/non-renewable)	Minimisation	Approaching zero
	302-3 Energy intensity	Energy intensity per unit/product	Minimisation	Approaching zero
GRI 303: Water and Effluents 2018	303-5 Water consumption	Water consumption per activity	Minimisation	Approaching zero

GRI 305: Emissions 2016	305-1 Direct (Scope 1) GHG emissions	CO_2e Emissions per activity	Minimisation	Approaching zero
	305-4 GHG emissions intensity	Emissions intensity per unit/activity	Minimisation	Approaching zero
GRI 306: Waste 2020	306-3 Waste generated	Weight of generated waste	Minimisation	Approaching zero
	306-4 Waste diverted from disposal	Weight of waste directed to reuse/recycling	Maximisation	Cannot be determined
	306-5 Waste directed to disposal	Weight of waste directed to disposal	Minimisation	Approaching zero
GRI 401: Employment 2016	401-2 Benefits provided to full-time employees that are not provided to temporary or part-time employees	Benefits received	Maximisation	Y
GRI 403: Occupational Health and Safety 2018	403-5 Worker training on occupational health and safety	Safety training received	Maximisation	Y
	403-9 Work-related injuries	Injury received	Minimisation	N
GRI 404: Training and Education 2016	404-1 Average hours of training per year per employee	Professional training hours	Maximisation	Cannot be determined

GRI 405: Diversity and Equal Opportunity 2016	405-1 Diversity of governance bodies and employees	Gender Age group	Alternating preferences	33,(3)%
	405-2 Ratio of basic salary and remuneration of women to men	Basic salary Hourly rate	Maximisation	Cannot be determined, but higher than minimum wage in the country

5.2.2 Data Collection

The event log is formed from variety of sources.

1. As the real-life data are not accessible, the event log is selected from publicly available ones. The original event log is located in 4TU.Centre for Research Data repository (Levy, 2014). It consists of 15 attributes, such as Case ID, Activity, Work Station, Start Timestamp, Complete Timestamp, Span, Minutes, Work Order Qty, Product, Worker ID, Report Type, Qty Completed, Qty Rejected, Qty for MRB, Rework. These attributes are suited only for conventional performance analysis with process mining tools.

2. To perform sustainability analysis, another 28 attributes are added and related to activities, products, work stations or workers. These attributes are either the metrics derived in Table 5 or the data utilized in calculating those metrics. This information is taken from online resources, industry benchmarks, or based on certain assumptions. Additional attributes are Sales Price, Revenue, Cost, Supplier Type, Spend on Suppliers, Material Type, Weight NRM, Weight RM, Recycled Input, Energy, Energy Class, Energy Type, Energy Intensity, Water, Emissions, Emissions Intensity, Waste, Waste Recycled, Waste Disposal, Benefits, Safety Training, Injury, Prof Training, Gender, Age Group, Salary, Employment, Hourly Rate.

The detailed description of all attributes of the event log is in **Appendix B**. Table contains names of attributes, their descriptions, source of data and/or calculation method, units used to measure data, and the potential range or categories of values for attributes.

5.2.3 Data Cleaning

Before starting the analysis, the original event log data is cleaned. Data cleaning is crucial as it ensures the accuracy, consistency, and reliability of data, leading to more meaningful insights and informed decision-making processes (Van Eck et al., 2015). Moreover, the original event log comes from third-party source. In this case, data cleaning is especially important because the data comes from external sources and may be more prone to errors, inconsistencies, and inaccuracies (Ilyas and Chu, 2019). However, the original event log requires only minor adjustments:

- Column *Resource* is renamed to *Work Station*.
- Initially columns *Activity* and *Resource* refer to combination of activity and resource that performs this activity, *e.g.,* Turning & Milling - Machine 4. It is decided to leave only activity name as *Activity*, while resources are defined as *Work Station*.
- Duplicates are found in: Case 12 - Flat Grinding Machine 11, Case 87 - Lapping Machine 1, Case 95 - Lapping Machine 1. From one side the duplicate may be a true duplicate which occurred during the data extraction process. On the other side, this duplicates could be registered by the system, and it is better to leave them as is.
- Span is recalculated and changed into the data format duration.
- Report type ”D” is replaced with ”P” which states for production to enhance clarity.
- Rework activities are marked in two different ways: the activity name contains ”rework” or column *Rework* contains ”Y”. For Activities that contains ”rework” in their name (*e.g.,* Grinding Rework, Turning Rework) ”Y” is added to the column *Rework*. Other activities are marked with ”N”.

The data cleaning step finalises the event log preparation, making it ready for further analysis.

5.3 Data Processing: Development of Application

The primary goal of the data processing stage is to generate various perspectives of the acquired event data and to process event logs in an optimized manner for the subsequent mining and analysis stage (Van Eck et al., 2015). This section covers the selection of process mining tool, as well as creating an environment for analysis.

5.3.1 Process Mining Tool Selection

Three most frequently used process mining tools are compared against technical and performance features. The selection criteria include supported platform, ease of use, visualization, flexibility, license, performance and conformance analysis, process analytics, metrics support, benchmarking, and input size.

Table 6: Comparison of process mining tools

Criteria	**Disco 3.5.7**	**Celonis EMS**	**ProM 6.12**
Supported Platform	Mac OS, Windows OS	Web application	Mac OS, Linux, Windows OS
Ease of Use	User-friendly	User-friendly	Technical
Visualization	Rich	Rich	Moderate
Flexibility	Moderate	High	High
License	Commercial, Academic, Demo	Commercial, Academic	Open Source
Performance Analysis	✓	✓	✓
Conformance Analysis	x	✓	✓
Process Analytics	✓	✓	✓
Metrics Support	Limited	Comprehensive	Limited
Benchmarking	✓	✓	✓
Input Size	5 million events	Large datasets up to 1GB, Multi-Event Log	Unlimited

Based on Table 6, ProM and Disco have their respective strengths and limitations compared to Celonis, making Celonis a robust choice to conduct exploratory analysis. ProM 6.12 is a stable release designed for researchers . However, being technically advanced, it may present challenges with regards to a more user-friendly interface and comprehensive metrics support. On the other hand, Disco's limited functionality can hinder in-depth sustainability analysis. Celonis stands out due to its flexibility and custom KPI capabilities. Additionally, according to recent Gartner report, Celonis holds a leader position, Disco is classified as a niche player, and ProM is not included in the Magic Quadrant (Kerremans et al., 2023). Therefore, Celonis is a clear choice not only for technical capabilities, but also for being the industry leader.

Celonis Execution Management System (EMS) is built on process mining technology, serving as the foundation for all other Celonis products. It enables data gathering, exploration, analysis, and solution development across the entire Celonis ecosystem. The data integration methods include Extractor Builder, Data Connections, Data Push API, One Time Extraction from SAP ECC and S/4, and uploading files.

Celonis offers both prebuilt apps and the capability to develop custom apps in Studio for data analysis and exploration. Celonis Studio features a low-code interface, enabling rapid app development, reusing components from successful deployments, seamlessly integrating analytical and execution capabilities, and leveraging template views for various business users.

Celonis app is a set of interactive dashboards with possibility to add the following components: process and variant explorers, charts and tables, graphs, single custom KPIs, machine learning and other design components.

5.3.2 Implementation of Dashboards

Before developing an app, it is essential to define the design elements and parameters for dashboards. A general rule of thumb is to have one theme or question per dashboard. Table 7 contains GRI Indexes defined in Table 5 and corresponding sustainability dimension, as well as which analysis dimensions, relevant KPIs, case dimensions, analysis components should be created on each dashboard.

Based on Table 7, dashboards are implemented in low-code environment. To create custom KPIs, tables and visual components Process Query Language (PQL) is used. PQL is a domain-specific language tailored towards a special process data model. PQL allows to translate process-related business questions into queries, which are executed by a custom-built query engine. It encompasses a wide range of operators, including process-specific functions, aggregations, and mathematical operators. While PQL's syntax draws inspiration from SQL, it is specifically optimized for process-related queries.

Created for each dashboard PQL queries are listed in **Appendix C**. Table contains dashboard names, KPIs and corresponding PQL queries.

The design of developed dashboards is presented in **Appendix D**. It contains descriptions and screenshots for developed dashboards: CSO Dashboard, Costs, Procurement, Supplier, Materials, Resources, Emissions, Waste, Equality, Skills, Gender.

Table 7: Dashboards elements and parameters

GRI Index	**Analysis Dimension**	**Question**	**KPIs (metrics)**	**Case Dimensions**	**Analysis Components**	**Sheet Name**
GRI 201, 204, 301, 302, 303, 305, 306, 401, 403, 404, 405	Economic, Environmental, Social	What is the overall sustainability of production process and check progress in run-time?	Profit, Emissions, Average hourly rate, Cost, Spent on Suppliers, Average recycled input, Weight NRM, Energy consumption, Gender diversity, Number of incidents, Average professional training	N/A	Single KPI, Pie Chart, Bar chart	CSO Dashboard
GRI 201: Economic Performance	Economic	What is revenue and profit margin by product?	Revenue, Profit	Product, Time	Single KPI, OLAP	Costs
GRI 201: Economic Performance	Economic	What is the production cost per unit of product?	Production cost per unit	Product, Time	Single KPI, Column chart, Bar chart, OLAP	Costs
GRI 204: Procurement Practices	Economic	How much does each supplier contribute to costs and how can we reduce procurement costs?	Percentage of local suppliers, supplier cost	Supplier (type), Product, Time	Pie chart, OLAP, Bar chart	Procurement
GRI 204: Procurement Practices	Economic	How much is spend on local and non-local suppliers?	Spend on suppliers	Supplier (type)	Single KPI (Benchmarking)	Supplier
GRI 301: Materials	Environmental	How much recycled materials are used and how to increase usage?	Recycled materials input	Material, Work order, Activity, Product	Pie Chart, OLAP	Materials
GRI 301: Materials	Environmental	How much renewable materials are used and how to increase usage?	Renewable and non-renewable materials input	Material, Work order, Activity, Product	Pie Chart, OLAP	Materials
GRI 302: Energy GRI 303: Water and Effluents	Environmental	How much energy and water is consumed and how to reduce usage?	Energy consumption, water consumption, Energy intensity	Work order, Activity, Product, Resource	Single KPI, Pie Chart, Bar Chart, OLAP	Resources
GRI 305: Emissions	Environmental	What is carbon footprint and how to reduce emissions?	CO_2 emissions, emissions intensity	Work order, Activity, Product, Resource	Single KPI, OLAP	Emissions

GRI 306: Waste	Environmental	How much waste is generated and how to reduce waste?	Waste generated, waste recycled, waste disposal	Work order, Activity, Product, Resource	Stacked bar chart, OLAP	Waste
GRI 401: Employment GRI 405: Diversity and Equal Opportunity	Social	How to ensure fair and living wages for workers and prevent exploitation?	Gender, Age group, Employment type, Hourly wage	Worker (Worker ID)	Pie Chart, Line Chart	Equality
GRI 403: Occupational Health and Safety	Social	How to improve worker safety and reduce the number of accidents in the workplace?	Number of incidents, Safety training	Worker (Worker ID), Activity	Single KPI, Line Chart, Pie Chart	Skills
GRI 404: Training and Education	Social	How to improve the skills and knowledge of workers and promote lifelong learning?	Professional training hours per worker, Ratio of trained workers	Worker (Worker ID)	Single KPI, Line chart	Skills
GRI 405: Diversity and Equal Opportunity	Social	How to ensure fair and equitable treatment of workers and prevent discrimination?	Gender, Age group, Employment type	Worker (gender, age, employment type)	Single KPI, Pie Chart	Equality
GRI 405: Diversity and Equal Opportunity	Social	How to ensure fair and equitable treatment of workers and prevent discrimination?	Number of incidents, Professional training, Age group, Gender	Gender	Single KPI (Benchmarking)	Gender

5.4 Process Analysis

In this section the process mining techniques are applied on event log to answer questions defined in Section 5.1 and gain insights into production process sustainability performance.

5.4.1 Process Overview

Event log contains 3166 events for 153 cases with 147 case variants. Figure 12 shows variant-based filtering using Celonis ”Variant Explorer”. The top five variants (3% of all variants) are kept, which covers only 11 cases (7% of all cases) out of 153 cases.

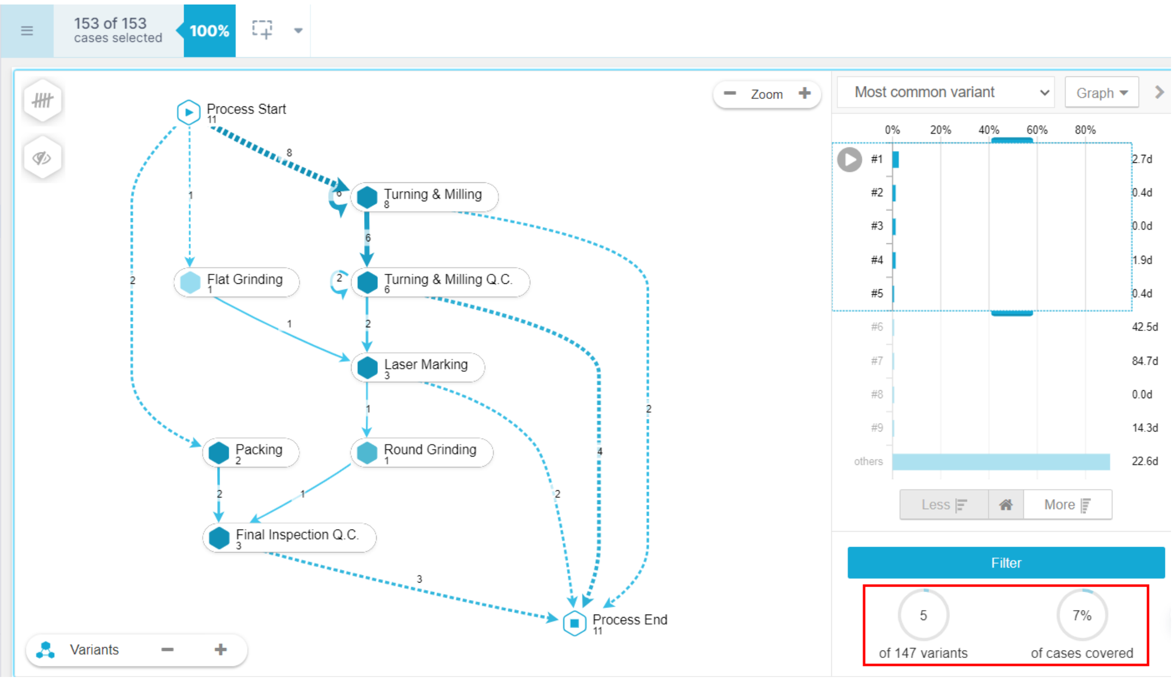


Figure 12: Process map filtered on top five variants in Celonis Variant Explorer

Clearly, that the distribution of cases over variants does not follow a Pareto distribution. In such unstructured process, activity-based filtering is more suitable option for process discovery combined with the bottom-up and top-down approaches (Van der Aalst and Carmona, 2022, pp. 48–50; Fluxicon, 2020). Process discovery paired with process analytics and benchmarking are further used to analyse process.

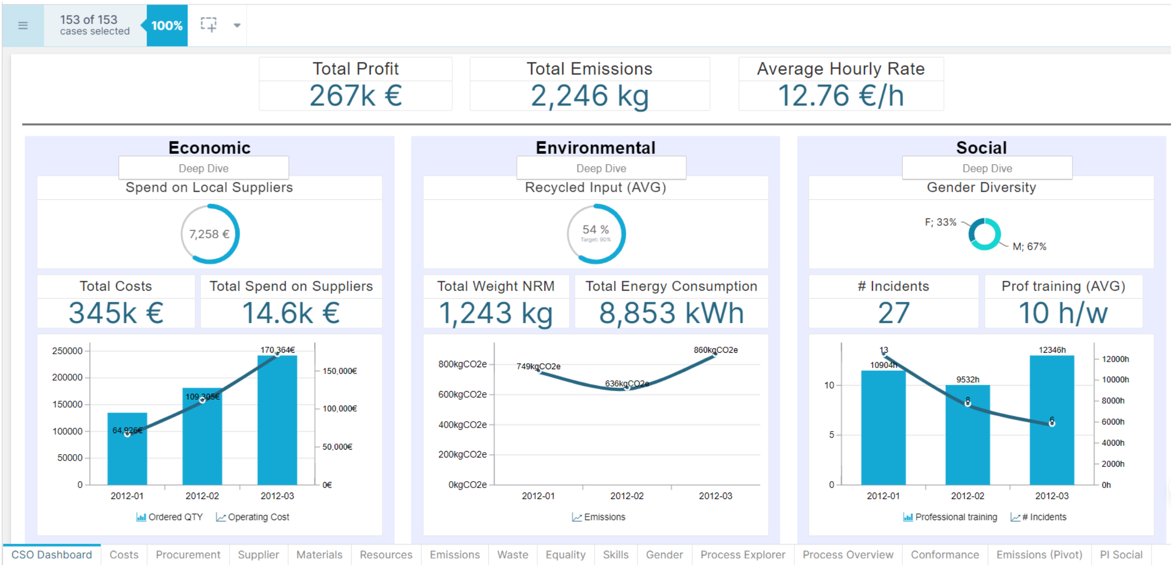


Figure 13: CSO dashboard

Figure 13 displays the main dashboard of Chief Sustainability Officer (CSO) that provides an overview of economic, environmental and social performance of the production process. In cases where certain SKPIs deviate from the norm, the CSO can investigate further to identify potential root causes.

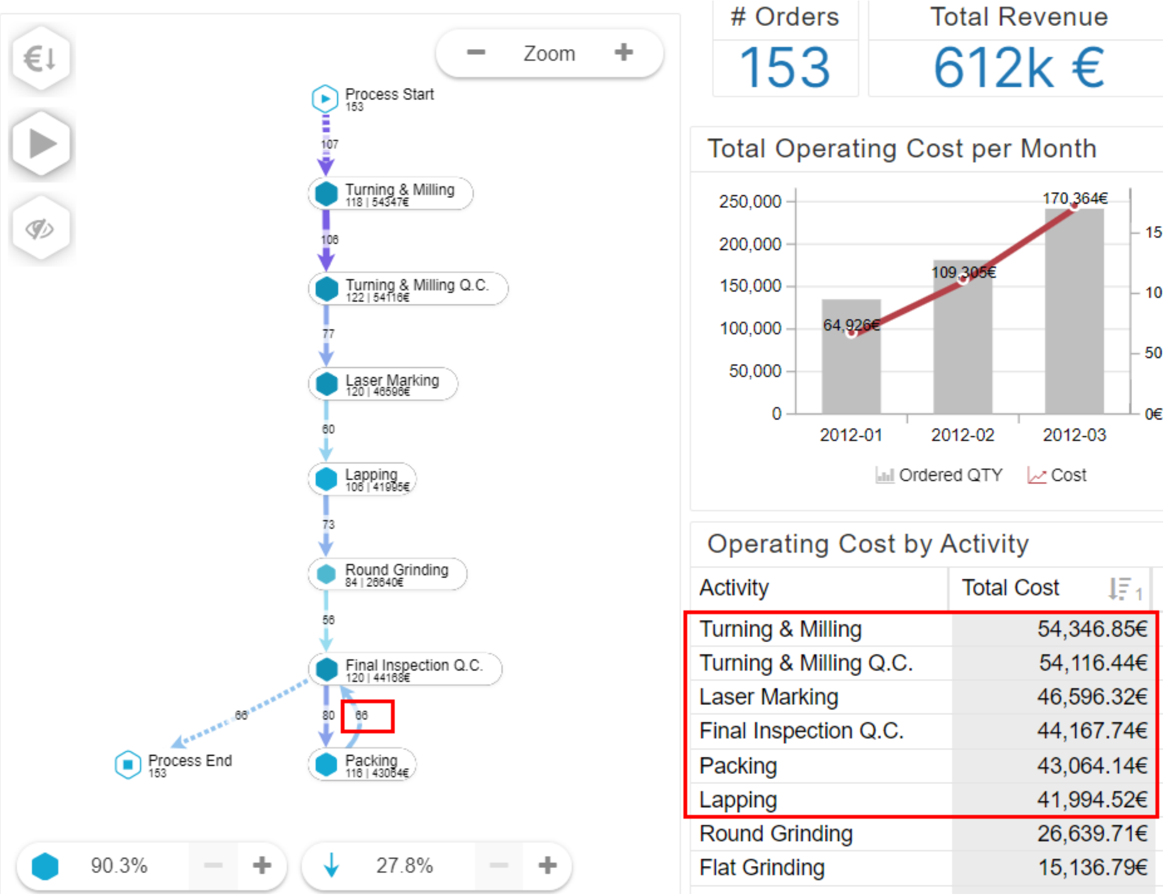
5.4.2 Economic Dimension

This section provides key findings of analysis of the economic dimension, including metrics such as operating costs, spend on suppliers and supplier type.

Operating cost

The aim of operating cost analysis is to identify activities on the process map that are known to have a significant impact on operating costs. These activities could include resource-intensive processes, complex tasks, or those involving expensive materials or equipment.

The process map in Figure 14 shows the number of cases and total operating costs for each activity. The process map and OLAP table depict the activities with the higher operating cost: *Turning & Milling*, *Turning & Milling Q.C.*, *Laser Marking*, *Final Inspection Q.C.*, *Packaging* and *Lapping*. Those activities are the main production process for any product (Figure 10), thus, it is expected that the total operating cost for each of them is high.



Activity	Total Cost
Turning & Milling	54,346.85€
Turning & Milling Q.C.	54,116.44€
Laser Marking	46,596.32€
Final Inspection Q.C.	44,167.74€
Packing	43,064.14€
Lapping	41,994.52€
Round Grinding	26,639.71€
Flat Grinding	15,136.79€

Figure 14: Process map in Cost dashboard (no filters)

Looking at the most common path, the first inefficiency related to **compliance checking** can be easily spotted (Figure 14). For 66 cases the final steps of the process are *Final Inspection Q.C.*, *Packing* and again *Final Inspection Q.C.*. The blueprint of the process does not require quality control after packing (Figure 10). Therefore, the last step can be considered as an undesired activity. To find out the operating cost of additional quality control after packing, activities are cropped starting from *Packing* (Last occurrence) and then filtered on "*Packing* directly followed by *Final Inspection Q.C.*". This results in 61 cases with operating cost of 14662€ (Figure 15). The identified inefficiency presents an improvement opportunity for reducing operating costs.

66.0 of 153 cases selected 43%

Crop activities between Packing - Process end

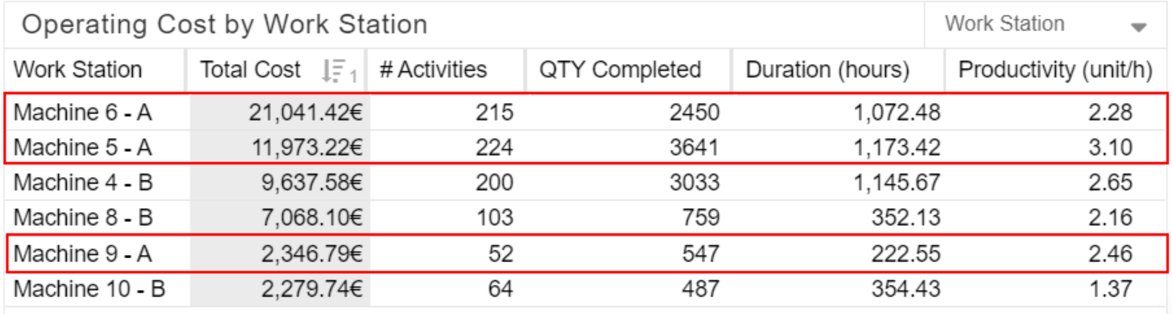
Directly followed by Packing - Final Inspection Q.C.

Figure 15: Process map filtered on 66 cases with undesired quality control

The activity with the highest operating cost of 54347€ is *Turning & Milling*, which occurs in 118 cases (or 77%) (Figure 14). Further analysis can be focused on the cost components within the *Turning & Milling* activity, such as labour, materials, equipment, or overhead costs to determine which cost components contribute the most to the overall operating cost. This breakdown can help identify specific areas where cost-reduction efforts can be focused.

Since the detailed cost breakdown is not available, the **work station utilization** is investigated. Filtering on activity *Turning & Milling*, it is seen that only six work stations perform this operation (Figure 16). All machines execute only turning and milling, however, the number of performed activities, operating time and completed quantity differ. *Machine 5* has the highest productivity accounting for 3.10 units per hour, while the most frequently used *Ma-*

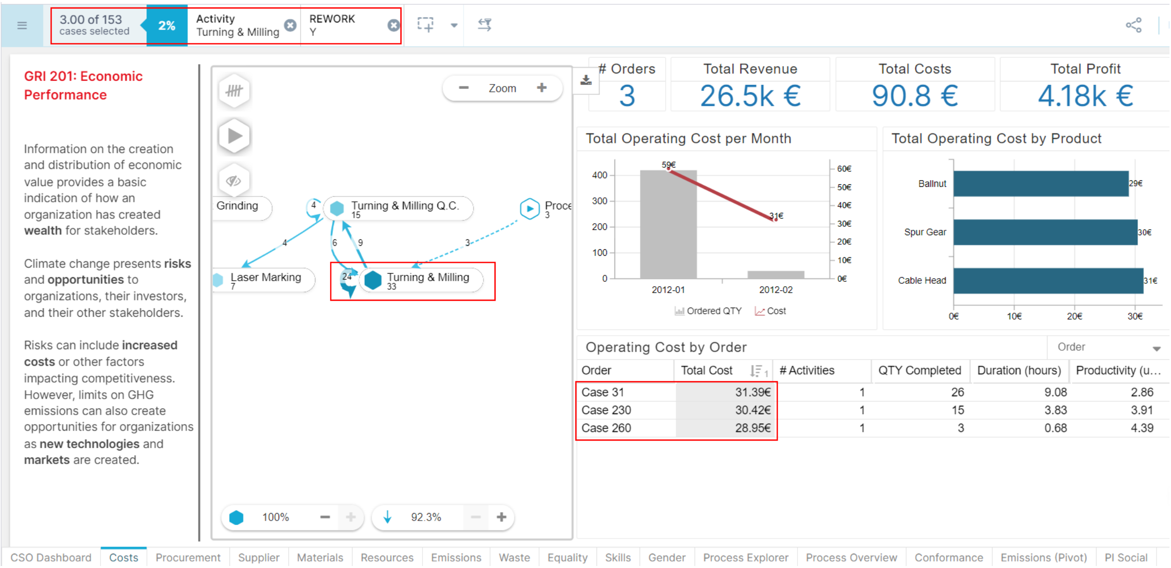
chine 6 produces only 2.28 units per hour. Moreover, *Machine 9*, with the productivity of 2.46 units per hour, which is the third highest, is utilized only for 6.1% of activities. The work stations utilization is not optimal.



Work Station	Total Cost	# Activities	QTY Completed	Duration (hours)	Productivity (unit/h)
Machine 6 - A	21,041.42€	215	2450	1,072.48	2.28
Machine 5 - A	11,973.22€	224	3641	1,173.42	3.10
Machine 4 - B	9,637.58€	200	3033	1,145.67	2.65
Machine 8 - B	7,068.10€	103	759	352.13	2.16
Machine 9 - A	2,346.79€	52	547	222.55	2.46
Machine 10 - B	2,279.74€	64	487	354.43	1.37

Figure 16: Operating cost by work station for *Turning & Milling*

The **looping** instances within the *Turning & Milling* activity account for 69% (594 out of 858 activities) and affect 71% of cases. These instances represent activities that repeated multiple times within a single case. It can lead to increased resource consumption, additional processing time and operating costs. One of the reasons for this can be rework. However, there are only three cases that include rework status "Y" for *Turning & Milling* activity (Figure 17). That means 570 looping activities have different nature. Case-by-case exploration shows that repeating activities refer not only to production but also to setups and breakdowns, which is natural process behaviour. Additionally, several records in a row related to partial order completion. Running machines for smaller quantities are not economically friendly, hence, it is necessary to consult the specialists in the factory.



3.00 of 153 cases selected 2%

Activity: Turning & Milling

REWORK: Y

GRI 201: Economic Performance

Information on the creation and distribution of economic value provides a basic indication of how an organization has created **wealth** for stakeholders.

Climate change presents **risks** and **opportunities** to organizations, their investors, and their other stakeholders.

Risks can include **increased costs** or other factors impacting competitiveness. However, limits on GHG emissions can also create opportunities for organizations as **new technologies** and **markets** are created.

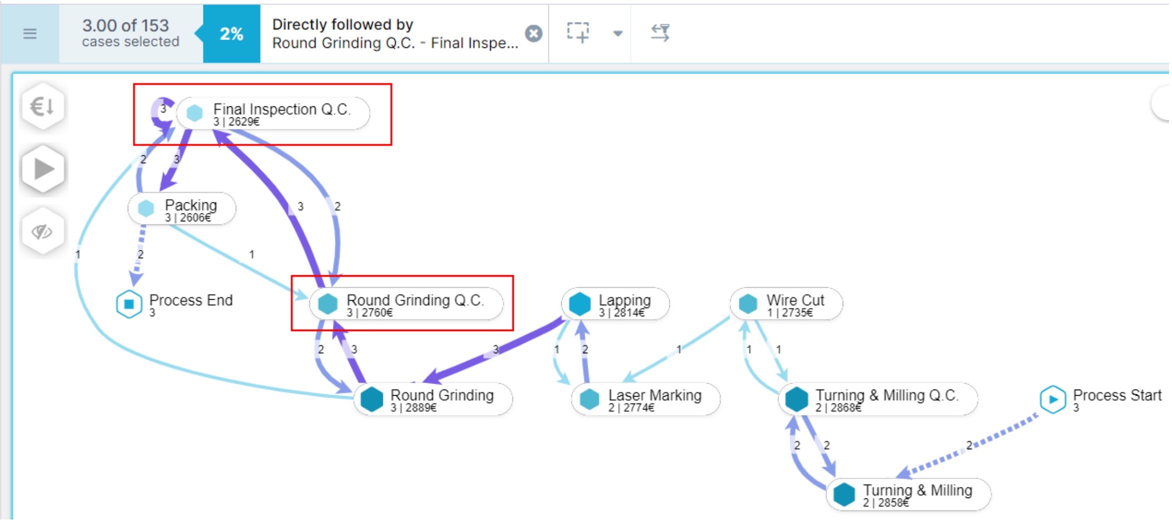
# Orders	Total Revenue	Total Costs	Total Profit
3	26.5k €	90.8 €	4.18k €

Operating Cost by Order

Order	Total Cost	# Activities	QTY Completed	Duration (hours)	Productivity (u…
Case 31	31.39€	1	26	9.08	2.86
Case 230	30.42€	1	15	3.83	3.91
Case 260	28.95€	1	3	0.68	4.39

Figure 17: Looping activities with rework for *Turning & Milling*

The **non-value-added activities** on the process map are activities that do not directly contribute to the production or customer value. Non-value-added activities often consume resources and add unnecessary costs to the process. By identifying and eliminating or optimizing these activities, operating costs can be reduced. One of the examples of such non-value-added process flow is repeating quality control. Cases 102, 231 and 267 have *Final Inspection Q.C.* directly after *Round Grinding Q.C.* (Figure 18). Removing unnecessary quality control after round grinding can save 2760€.



3.00 of 153 cases selected 2%

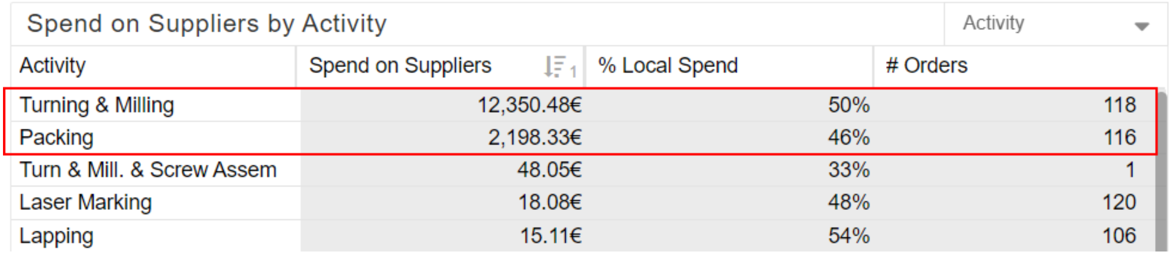
Directly followed by: Round Grinding Q.C. - Final Inspe...

Figure 18: Non-value-added control flow (*Round Grinding Q.C.* followed by *Final Inspection Q.C.*)

Supplier type and Spend on suppliers

Moving on to the procurement indicators—supplier type and spend on suppliers—they can indeed affect the process map and are factors that can be analyzed in a process mining analysis.

The supplier type, specifically whether the supplier is local or non-local, can have an impact on the throughput time of a process. Local suppliers are generally closer in proximity to the manufacturing facility, which can result in shorter lead times for material delivery. Non-local suppliers, on the other hand, may require longer lead times due to transportation distances and potential customs or border-related delays. The variation in lead times between local and non-local suppliers can directly impact the throughput time of the process, as it affects the availability of inputs for production. However, only the core manufacturing process is subjected to the analysis, thus the lead time is unknown.



Spend on Suppliers by Activity

Activity	Spend on Suppliers	% Local Spend	# Orders
Turning & Milling	12,350.48€	50%	118
Packing	2,198.33€	46%	116
Turn & Mill. & Screw Assem	48.05€	33%	1
Laser Marking	18.08€	48%	120
Lapping	15.11€	54%	106

Figure 19: Spend on suppliers by activity (no filters)

Nonetheless, investigating only throughput time can still have some insights. The average throughput time for all cases is 22 days (or 527 hours), while for local and non-local suppliers 22 days (or 531 hours) and 23 days (or 548 hours) respectively. Not significantly, but there is a difference in throughput time between the two supplier types. However, this information should be treated with care, as there are several factors that contribute to the throughput time, such as setup time, resource utilization, process bottlenecks, capacity constraints or scheduling of process activities. As a result, comparing the throughput times for units sourced from local suppliers and non-local suppliers requires additional information.

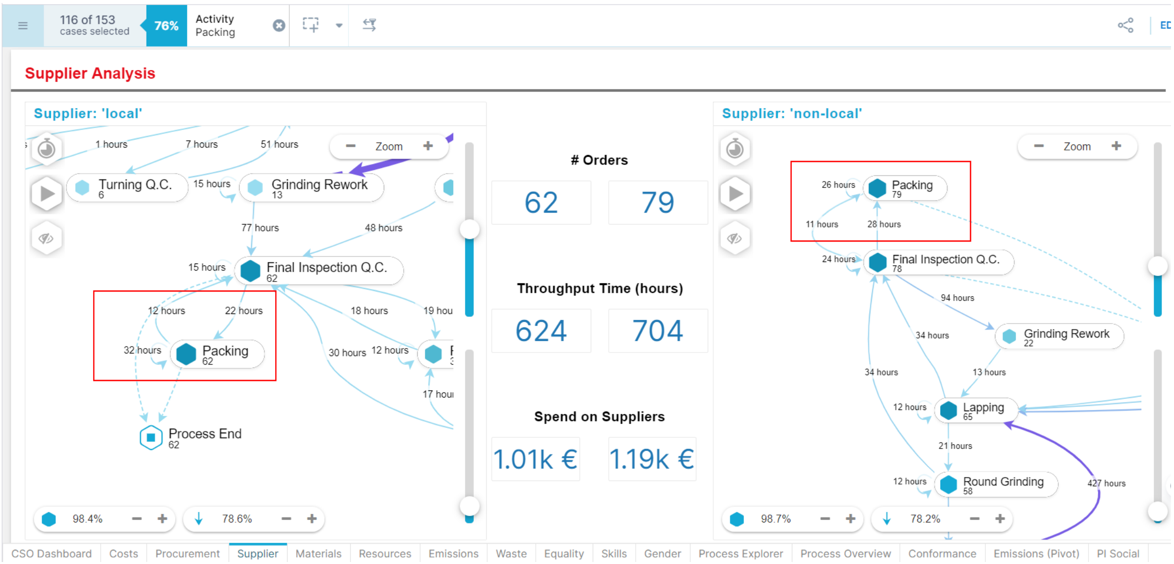


Figure 20: Benchmarking analysis by supplier type (local/non-local) filtered on *Packing*

The supplier type can also be analysed with regards to spend on suppliers. Figure 19 shows that the highest spend on suppliers is on *Turning & Milling* and *Packing*. As *Turning & Milling* activity is the first in most cases and requires input of main materials for the product, it has the significant amount of 12350.48€, half of which is spent locally. Another activity that contributed to Spend on Suppliers is *Packing* with 2198.33€, 46% of which is spent on local suppliers. Filtering the cases that go through the activity *Packing* and using benchmarking analysis, it is seen that the average throughput time from *Final Inspection Q.C.* to *Packing* is 22 hours for local suppliers, while for non-local 28 hours (Figure 20). Among all possible reasons for this bottleneck, there could be a packaging material shortage.

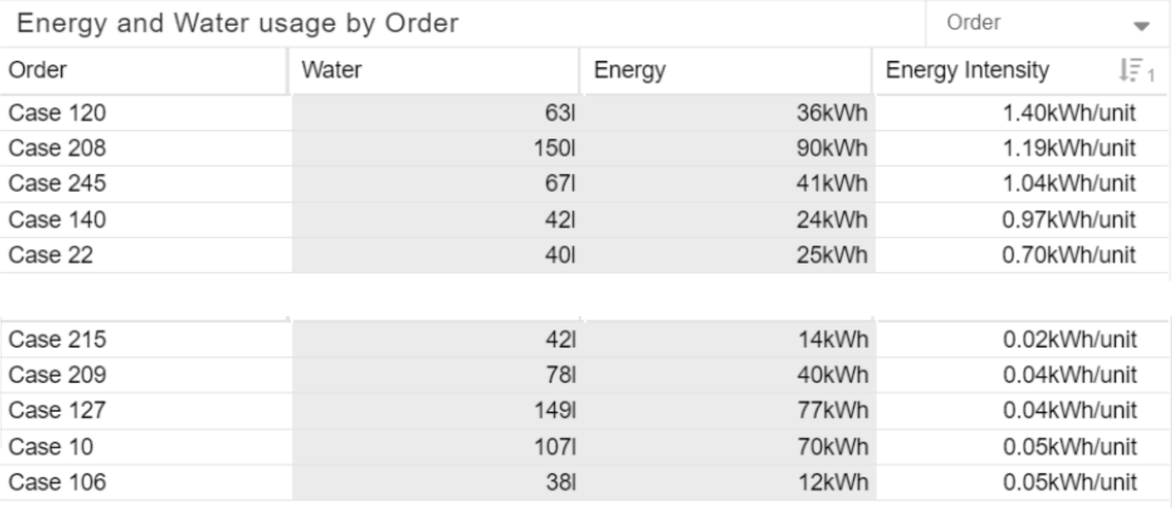
5.4.3 Environmental Dimension

This section provides key findings of analysis of the environmental dimension, including metrics such as material type, weight of non-renewable materials, weight of renewable materials, recycled input, energy, energy class, energy type, energy intensity, water, emissions, emissions intensity, waste, waste recycled, waste disposal.

Similarly to operating cost, the analysis of process flow is done to the following attributes: weight of non-renewable materials, weight of renewable materials, recycled input, energy, water, emissions, waste, waste recycled, waste disposal. For example, (1) the process map is analyzed using the water attribute to identify water-intensive activities and potential opportunities for water conservation. (2) Emissions and emissions intensity are directly analysed on the process map to identify the activities that contribute the most to emissions and assess emissions reduction opportunities. (3) Waste and its types (recycled, disposal) are explored on the process map to understand the generation, management, and disposal of waste throughout the process. Regarding material type and energy type, these attributes are used for additional process analytics.

Energy-efficient patterns

As for energy, energy class, energy type, and energy intensity, these attributes are analyzed on the process map to identify energy-efficient patterns. For this, first, the completed cases are selected, that start with activities *Turning & Milling*, *Turning* and *Milling* and finish with *Packing* or *Final Inspection Q.C.*. The total of 89 out of 153 cases are completed cases. Since energy consumption for each case may vary significantly due to different completed quantities, the energy intensity per unit is used as metric to compare the cases. Five cases with highest and five cases with lowest energy intensity are selected for analysis (Figure 21).



Energy and Water usage by Order

Order	Water	Energy	Energy Intensity
Case 120	63l	36kWh	1.40kWh/unit
Case 208	150l	90kWh	1.19kWh/unit
Case 245	67l	41kWh	1.04kWh/unit
Case 140	42l	24kWh	0.97kWh/unit
Case 22	40l	25kWh	0.70kWh/unit
Case 215	42l	14kWh	0.02kWh/unit
Case 209	78l	40kWh	0.04kWh/unit
Case 127	149l	77kWh	0.04kWh/unit
Case 10	107l	70kWh	0.05kWh/unit
Case 106	38l	12kWh	0.05kWh/unit

Figure 21: Five cases with highest and five cases with lowest energy intensity (only completed cases)

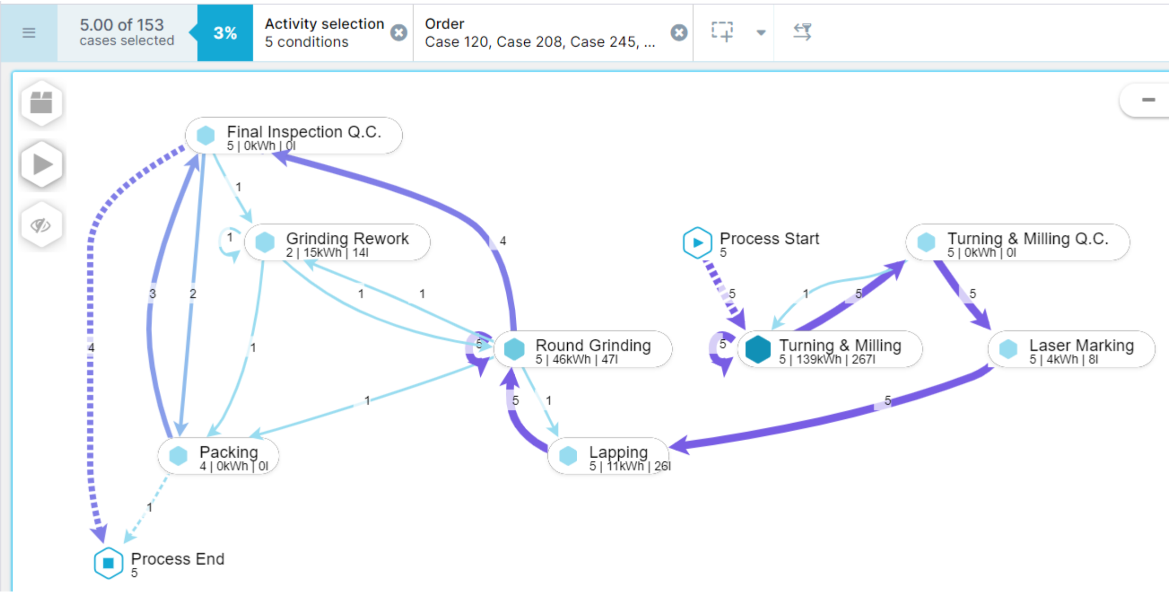


Figure 22: Process map with activity frequency for five cases with highest energy intensity (only completed cases, 100% of activities and 100% of connections)

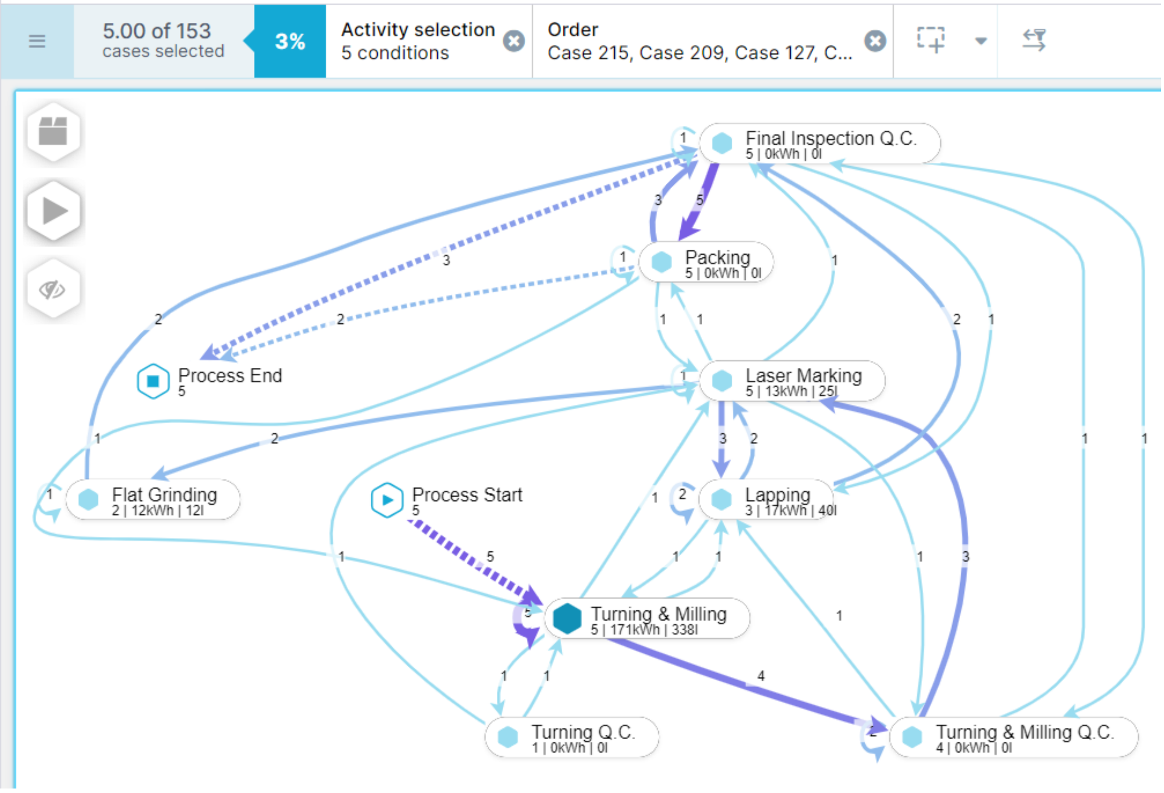
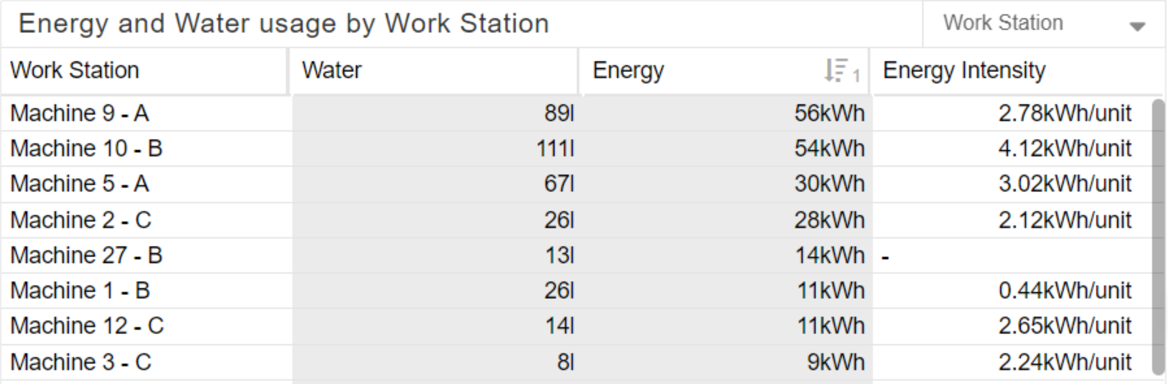


Figure 23: Process map with activity frequency for five cases with lowest energy intensity (only completed cases, 100% of activities and 100% of connections)

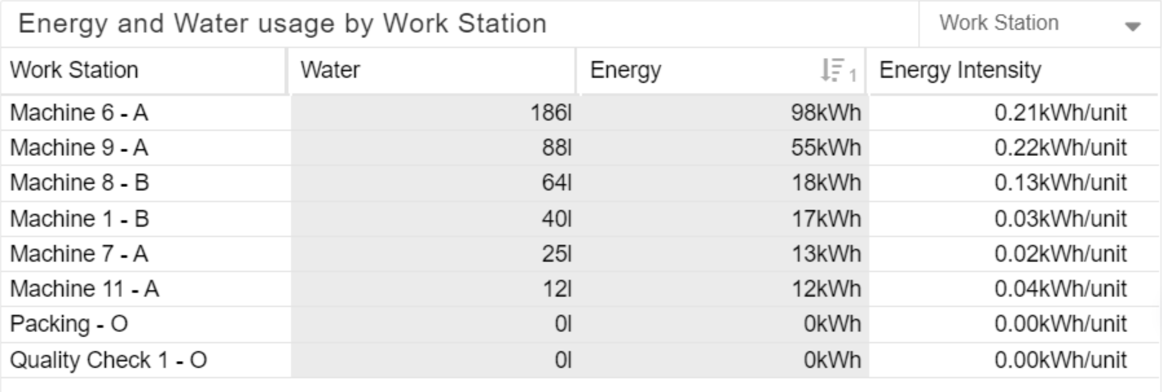
Based on two figures, the process map for less energy-intensive cases (Figure 23) exhibits a higher degree of complexity compared to the energy-greedy cases (Figure 22). Moreover, total energy consumption is 216 kWh and 213 kWh for cases with high and low energy intensity respectively. This implies that the process flow alone cannot be considered as a determining factor for the energy-efficient pattern. Therefore, the energy efficiency of work stations is explored.



Energy and Water usage by Work Station

Work Station	Water	Energy	Energy Intensity
Machine 9 - A	89l	56kWh	2.78kWh/unit
Machine 10 - B	111l	54kWh	4.12kWh/unit
Machine 5 - A	67l	30kWh	3.02kWh/unit
Machine 2 - C	26l	28kWh	2.12kWh/unit
Machine 27 - B	13l	14kWh	-
Machine 1 - B	26l	11kWh	0.44kWh/unit
Machine 12 - C	14l	11kWh	2.65kWh/unit
Machine 3 - C	8l	9kWh	2.24kWh/unit

Figure 24: Work station characteristics used in five cases with highest energy intensity (only completed cases)



Energy and Water usage by Work Station

Work Station	Water	Energy	Energy Intensity
Machine 6 - A	186l	98kWh	0.21kWh/unit
Machine 9 - A	88l	55kWh	0.22kWh/unit
Machine 8 - B	64l	18kWh	0.13kWh/unit
Machine 1 - B	40l	17kWh	0.03kWh/unit
Machine 7 - A	25l	13kWh	0.02kWh/unit
Machine 11 - A	12l	12kWh	0.04kWh/unit
Packing - O	0l	0kWh	0.00kWh/unit
Quality Check 1 - O	0l	0kWh	0.00kWh/unit

Figure 25: Work station characteristics used in five cases with lowest energy intensity (only completed cases)

Evidently, that in high energy-intensive cases (Figure 24), there is a prevalence of work stations belonging to the lower energy classes (primarily B and C). Conversely, less energy-intensive cases mainly employ work stations with A and B energy classes (Figure 25). Furthermore, detailed examination of individual cases reveals that high energy-intensive cases tend to operate machines in small batches, whereas less energy-intensive cases utilize larger batches. These findings highlight that the choice of energy-efficient work stations and production batch sizes determine the energy-efficient pattern, rather than the process flow alone.

5.4.4 Social Dimension

This section provides key findings of analysis of the social dimension, including metrics such as benefits, safety training, injury, professional training, gender, age group, salary, employment, hourly rate.

In fact, there are two ways to continue analysing the production process. (1) Analysing SKPIs individually to explore the possible analysis techniques related to each metric. (2) Delving deeper into the energy-efficient pattern by considering the social dimension. As mentioned in Section 4.5, conducting analysis and evaluating results with process experts may lead to new research questions and iterative analyses, taking into account green trade-offs. To exemplify this, the focus will be on the second way.

In Section 5.4.3 it is discovered that energy efficiency of production process not only depends on the process flow, but also on the work stations utilization and the management of production sizes. Now, a new question arises: *How might workers' performance impact the energy efficiency of the production process?*

The analysis continues on two groups of cases with the highest and lowest energy intensity per unit. Table 8 provides a summary of social metrics for these two groups. Among the social factors analyzed, professional training, gender representation, and age group distribution stand out as potential influencers on energy-efficient process flow. The group with the highest energy intensity shows slightly lower professional training hours per week (11 h/w), a higher percentage of male employees (71%), and a greater proportion of workers above 30 (53%). In contrast, the group with the lowest energy intensity has slightly higher professional training hours (12 h/w), a higher percentage of female employees (47%), and a higher proportion of workers above 30 (66%). Although the data shows potential associations between these metrics and energy efficiency, further statistical analysis and process expert consultancy are needed to validate these relationships.

Table 8: Impact of social metrics on energy efficiency of production process

Metrics	**Energy-intensive cases**	
	Five highest	**Five lowest**
Cases	120, 208, 245, 140, 22	215, 209, 127, 10, 106
Injury	1	1
Professional training	11 h/w	12 h/w
Gender		
M	71%	53%
F	29%	47%
Age group		
<30	47%	33%
30-50	47%	53%
>50	6%	13%
Average hourly rate	13.20 €/h	13.26 €/h
Employment type		
part-time	12%	7%
full-time	88%	93%

Further analysis of process flows of two groups for different age groups, genders, and professional training (0-11 h and 12-19 h) shows no significant difference.

5.5 Process Evaluation

On the fifth *Evaluation* step, the analysis findings along with improvement ideas are presented to the process owners for further validation and verification (Van Eck et al., 2015).

Table 9 presents the summary of discovered inefficiencies in Sections 5.4.2-5.4.4. Since the domain experts are not available, the improvement ideas as well as their implications are based on assumptions. As suggested in Section 4.5 the possible positive and negative impacts on other dimensions are also presented and should be taken into account while conducting further analysis or implement improvement idea(s). The example of such consideration is in Section 5.4.4, where social metrics are taken into account when analyzing energy-efficient patterns.

Table 9: Improvement opportunities and green trade-offs

SKPI	**Analysis technique**	**Analysis findings**	**Improvement idea**	**Green trade-off**
Operating cost	Conformance analysis	Undesired activity *Final Inspection Q.C.* with improvement opportunity of 14662€.	Remove undesired activity	Implementing in-line quality checks can lead to reduced resources usage, contributing to environmental sustainability.
Operating cost	Process discovery	*Turning & Milling* has the highest operating cost (54347€). Requires additional data for further analysis on cost components (e.g., labour, materials, equipment, or overhead costs).	Conduct a detailed cost analysis to identify cost drivers	While conducting a detailed cost analysis may require additional resources, it can lead to more informed decisions and resource optimization, positively impacting the environment.
Operating cost	Process discovery	Work station utilization for *Turning & Milling* is not optimal. Requires clarifications on reasons for such tasks division.	Optimize work station utilization	By optimizing work station utilization, overall energy consumption and resource usage can be minimized.
Operating cost	Process discovery, Conformance analysis	Looping activity *Turning & Milling* (570 out of 858), not related to rework, but to setups, breakdowns and partial order completion. Requires further analysis and additional data.	Implement efficient workflow planning, workforce training	Efficient workflow planning may lead to reduced lead times and transportation requirements, positively impacting the environment. Investments in training may affect budgets, but enhanced workforce skills and overall job satisfaction.
Operating cost	Process discovery	Non-value-added activity with improvement opportunity of 2760€. For example, *Final Inspection Q.C.* directly after *Round Grinding Q.C.*	Remove non-value-added activity	Implementing lean practices to remove non-value-added activities can lead to reduced waste and improved resource efficiency.

Supplier type	Process discovery	Throughput time for all cases is 22 days (or 527 hours), while for local and non-local suppliers 22 days (or 531 hours) and 23 days (or 548 hours). Requires further analysis on lead time	Sourcing from local suppliers	Reduced transportation requirements and emissions by sourcing locally.
Spend on Suppliers	Benchmarking	Average throughput time from Final Inspection Q.C. to Packing is 22 hours for local suppliers, while for non-local 28 hours. Requires further analysis for bottleneck.	Sourcing from local suppliers	Reduced transportation requirements and emissions by sourcing locally.
Energy consumption	Process discovery	Five cases with the lowest energy intensity have more complex process flow compared to cases with highest energy intensity. Requires further analysis on the relationship between complexity and energy intensity.	Conduct new analysis with regards to workers' performance	Additional cost for analysis, but may discover new underlying factors that would lead to better workers' performance.
Energy consumption	Process discovery	Five cases with the lowest energy intensity utilize work stations with B and C energy class, while cases with highest energy intensity mainly utilize A and B class work stations and higher production batch sizes.	Better resource allocation and work order management	Selecting more energy-efficient work stations and optimizing batch sizes can lead to reduced energy consumption and lower operating costs.

Professional training	Process Analytics	Five cases with the lowest energy intensity have an average of 12 h/w, while cases with the highest energy intensity have 11 h/w.	Provide specialized training to the workforce on energy-saving practices and efficient equipment operation	Professional training can lead to enhanced skills and knowledge, potentially improving energy management practices and overall workforce productivity. However, requires further investments and dedicated working hours.
Gender	Process Analytics	Five cases with the lowest energy intensity have 53% male workers, while cases with highest energy intensity have 71% male workers.	Promoting gender diversity	Promoting gender diversity may lead to reduced energy consumption and operating cost.
Age group	Process Analytics	Five cases with the lowest energy intensity have 66% workers above 30, while cases with the highest energy intensity have 53% workers above 30.	Organize knowledge sharing sessions with workers under 30	Such an approach can reduce training costs and improve overall productivity.

Finally, the insights gained from the *Evaluation* step are used on the sixth step *Process improvement & support* to modify the actual process execution (Van Eck et al., 2015). This is often a separate project, and the results of the process mining project serve as fact-based input for process improvement efforts, such as business process reengineering and Six Sigma, allowing for subsequent measurement of improvements in another analysis project.

6 DISCUSSION

This chapter discusses the conducted research. First, the general results are given, followed by how they answer the research questions. Then the contributions to the theory and practice are provided. Finally, how the limitations affected and are avoided, as well as possible research topics that could be dealt with in the future.

This thesis produced a framework to select and analyze business processes using sustainability reporting metrics and process mining tools.

RQ1: What are the existing frameworks to use process mining for sustainable BPM?

The literature study on how process mining is utilized to assess the sustainability of business processes revealed that, despite numerous studies, sustainability is only partially and/or implicitly addressed. The majority of studies are related to the social dimension, primarily focused on privacy and security aspects or patient care flow in the healthcare sector. The environmental dimension is scarcely addressed, with only a few studies proposing the addition of resource-related attributes (*e.g.,* CO_2 emissions, waste, water, energy consumption, etc.) to the event log or using OCPM to track material flow. Similarly, the economic dimension is not a primary focus of process mining studies. Some studies address the auditing process, fraud detection, and cost reduction practices, employing dedicated process mining algorithms.

Certain studies report that conventional performance analysis using process mining leads to economic implications (*e.g.,* reducing operating costs) despite not being the main goal. Lastly, frameworks for overall sustainability assessment are identified. One study offers calculations of the weighted sustainability score based on the process model discovered by process mining. However, such models may not always reflect the actual process flow, especially in unstructured processes. Consequently, the sustainability score may be inaccurate, compounded by the uncertainties introduced by the weighing of sustainability metrics in overall score calculations.

In summary, process mining frameworks for Green BPM focus on two main aspects: (1) a few key metrics, addressed through process mining algorithms or by adding sustainability-related attributes to the event log; or (2) applying process mining in various domains to assess process performance (*e.g.,* throughput time, cost), with sustainability-related implications viewed as ”good-to-have” side effects.

RQ2: What are the metrics to define how sustainable the business process is?

First, a literature study on sustainable business processes and its governance was conducted. The study revealed that there is no ”official” definition for sustainable business processes, despite extensive discussions in academia, industry, and regulations. While there are definitions for sustainability in business, sustainable business models, and products, the concept of sustainable business processes is only partially addressed. For instance, Green BPM focuses on improving processes but relies solely on the blueprint model, without considering real-world deviations from the defined model. Similarly, LCA evaluates the sustainability of products based on basic process flow, leading to situations where the product itself may be claimed sustainable according to LCA, but the production process is not.

In the next literature study on sustainability guidelines, frameworks, reporting, and various ISO Standards to enhance environmental and social performance were examined. For instance, ISO 14010, ISO 14011, and ISO 14012 provide management systems to improve performance but do not offer specific metrics or performance indicators. On the other hand, standards like ISO 9001, ISO 14001, ISO 50001, and ISO 26000 do provide guidance on establishing metrics and performance indicators within their respective domains. However, there is currently no ISO Standard that provides a comprehensive three-dimensional metrics set.

Similarly, several sustainability indicator sets focus solely on specific dimensions (*e.g.,* ESI, EPfI, NISTEP), while others like UN-CSD are not tailored to organizations and are designed for top-level sustainable development assessments. Finally, some sustainability reporting frameworks, such as GRI, cover all dimensions but only on the organizational level, without providing concrete metrics for business processes.

RQ3: How can Green BPM be supported with process mining?

Green BPM utilizes process analysis results for further improvements. However, even though improvement practices already include sustainability aspects (Nowak et al., 2011), the initial process analysis results should also focus on sustainability. In other words, to enhance the sustainability of a business process, its sustainability performance should be assessed. Process mining can be employed for this purpose. Nevertheless, as the findings on *RQ1* demonstrate, process mining only partially addresses sustainability, making the results of such process analysis unsuitable for holistic sustainability assessment.

To support Green BMP, the Green Process Mining framework is developed based on the findings from *RQ1*, *RQ2*, and the existing PM^2 methodology. The sustainability metrics set is derived from GRI Standards and added into the event log as attributes, extending the current process mining methodology. The development and further evaluation of the framework on the production process resulted in several findings.

The first aspect is related to **data collection**. Although GRI Standards provide indexes and related metrics on the organizational level, it is possible to select some that describe the process. The case study shows that out of 117 indexes, 18 are suitable for the process. For each index, one or more metrics can be defined to provide a comprehensive sustainability assessment of the process. A recent study by Ahmad, Wong, and Butt (2023) suggests that the majority of sustainability assessment methods rely on a range of 11-30 metrics.

However, such a broad assessment comes with a cost. In addition to requiring process-related attributes in the event log, some sustainability-related metrics demand additional data for their calculation. For example, operating costs include material cost, labor cost, overhead, etc. Similarly, energy intensity is derived from energy consumption and the number of units produced. Therefore, creating an event log may involve calculating some metrics outside of it or adding all attributes to the event log, especially when certain attributes (*e.g.,* produced quantity) are used to calculate several metrics. The best option may be a combination of both approaches. In any case, this would increase the number of attributes in the event log.

Van der Aalst and Carmona (2022, pp. 221–223) recommend limiting event log attributes to 40. The case study's event log contains 43 attributes, both process- and sustainability-related, which further supports the idea that holistic sustainability assessment can align with the best process mining practices. On the other hand, the case study only presents high-level analysis, and further root-cause analysis would require additional data. As a result, while the lengthy event log may facilitate the assessment of business process sustainability from all dimensions, it could also increase the complexity of the data collection process.

Looking at process mining projects conducted in industry, for sustainability assessment only a few metrics are typically used, primarily due to the difficulty of collecting information. For example, the company Celonis, whose process mining tool is used in the case study, claims to contribute to sustainable procurement and awareness of CO_2 emissions. As for sustainable procurement process, in Celonis EMS one can compare different suppliers based on their scores from Ecovadis platform and opt for the best one. However, assessing the entire procurement process as sustainable based on just one KPI from the GRI Standard (*Disclosure 308-1 About suppliers that were screened using environmental criteria*) is insufficient.

Regarding CO_2 emissions, Climatiq Carbon Calculation Engine integrated with the Celonis EMS enables companies to calculate emissions from their shipments in real-time with industry-approved reporting standards. For example, if needed to compare different delivery options, one calls the add-on, insert the data and receive the average CO_2 emissions for the specified route and means of transportation. Calculations are based on starting address, final address, and shipping type from operational data. However, it does not consider the company’s context, the real-time route, the deviations due to circumstances or force majeure.

Although both examples, CO_2 emissions and supplier ratings, are not directly related to process mining, *Celonis Value Trees* offer more metrics for sustainability-oriented process mining. For example, metrics such as spend compliance, internal control failure, and carbon footprint can assess the purchase-to-pay process, while metrics like energy and water consumption, and waste can be used for the production process. The use of a small number of metrics can be attributed to the general challenges of data collection in process mining projects, which may sometimes make it infeasible and unreasonable to collect and analyze data at the process activity level.

Second aspect is related to **process mining techniques using sustainability-related attributes**. Section 4.4 suggests how sustainability attributes can be incorporated to different process mining approaches, while Section 5.4 explores them in practice. In general, the attributes can be divided into three categories:

1. *Process discovery attributes* are utilized to reveal bottlenecks and resource-intensive activities in the process. Similar to the ”time” attribute in conventional process mining, calculations of ”process discovery” attributes for each activity are added to the process map. Examples of such metrics include operating cost, energy consumption, CO_2 emissions, water usage, and waste generation. However, this approach may not always be the most practical. Classical process analytics and inefficiency analysis based on throughput time and activity frequency can also provide insights into process inefficiencies without the need for calculating attributes for each activity.

2. *Benchmarking attributes* are employed to compare process maps for different categories. The direct impact of these attributes on the process map may not be immediately evident in the traditional process flow diagram, but they can indirectly affect overall process performance and sustainability. For instance, process performance can be compared for different supplier types (local vs. non-local), genders (male vs. female), or levels of professional training (workers with and without training). However, not all ”categorical” attributes may be well-suited for this approach from a process perspective. For example, if the process is conducted by workers of different genders, filtering the process map based on gender may result in the same process map. In such cases, it might be more meaningful to compare specific critical activities identified by process mining techniques, rather than the entire process.

3. *Process Analytics attributes* provide additional information beyond the process mining analysis. Essentially, all attributes in the case study can be categorized under this label. These attributes offer insights into sustainability-related patterns and trends through data mining and visual analytics techniques, enriching the results obtained from process mining.

Overall, these different attribute types complement each other and contribute to a more comprehensive understanding of the sustainability and performance aspects of business processes. It is essential to choose the most relevant attributes based on the specific objectives and constraints of the process mining project.

The third aspect is related to **green trade-offs**. Process mining analysis offers improvement opportunities for Green BPM. However, existing studies and industry projects primarily focus on one dimension or a few KPIs, often overlooking the interconnectedness of the economy, environment, and people. Not all changes made through Green BPM will necessarily lead to purely positive outcomes. Some improvements may inadvertently result in negative consequences, and vice versa. A holistic assessment is needed to understand the trade-offs between different dimensions of sustainability.

The case study highlights that achieving a comprehensive assessment requires exhaustive data collection, while many process mining analysis results could be obtained using conventional process mining techniques. Related studies and industrial projects also indicate that improving process performance often leads to cost reduction, decreased energy consumption, and enhanced social aspects.

Regarding impact assessment, process mining can (1) quantify past impacts and (2) assess future impacts in conjunction with predictive modeling or forecasting techniques. However, the challenges in data collection at the activity level are further intensified when dealing with predictive analysis. Consequently, while measuring sustainability impact at the activity level can be beneficial, it may not always be feasible or necessary to analyze every single activity in a process.

The fourth aspect is related the **evaluation of the proposed framework**, using sustainability in business processes as the assessment criteria. Based on the characteristics of sustainable business processes mentioned in Section 4.1, the proposed framework has achieved four out of five aspects. The assessment of economic, social, and environmental attributes is performed during the *Analysis* step, while continuous improvement is addressed during the process *Evalutation* step and further iterative analysis. However, lifecycle thinking is yet to be fully achieved. The process mining community is actively working towards achieving lifecycle thinking through cross-organizational mining and analysis of process networks within the organization. The OCPM approach is proposed to enable a more comprehensive understanding of processes, considering their interactions and interdependencies across the entire organizational lifecycle.

Overall, based on the analysis of *RQ1*, *RQ2*, and *RQ3*, process mining can indeed assist Green BPM to some extent. The main challenge lies in data collection, which can be addressed through a more targeted approach. A potential solution is to conduct a qualitative impact assessment of the business process first. This involves identifying the possible implications on the environment, economy, and people, as well as understanding their interconnections. By focusing on the most critical aspects, the selection of relevant metrics can be refined.

To exemplify, in a production process, a qualitative impact assessment might reveal that excessive use of certain raw materials and energy-intensive manufacturing techniques has significant environmental implications, leading to high CO_2 emissions and resource depletion. Simultaneously, this process may impact the company's profitability due to increased production costs. Moreover, it could raise social concerns related to worker safety, job satisfaction, and potential health risks to nearby communities or workers. In this case, the relevant metrics to be collected for process mining should include material consumption, energy efficiency, CO_2 emissions, production costs, worker safety incidents, and job satisfaction. By focusing on these key metrics, the sustainability of the process can be thoroughly assessed from all relevant perspectives, without the need for excessive data collection.

This targeted approach ensures that process mining contributes to the assessment of sustainable business processes in a more efficient and effective manner. By using only a few critical metrics, the framework can provide valuable insights to support Green BPM initiatives and foster sustainable practices in organizations.

This thesis has several implications for theory and practice.

Theoretical contributions:

- *Process Mining Domain*: The thesis makes theoretical contributions to the process mining domain by introducing a new framework for the sustainability assessment of business processes. The Green Process Mining framework extends the PM^2 methodology by integrating sustainability aspects. This includes determining which processes to analyze and what data to collect by mapping GRI indexes to specific business processes. It also addresses how process mining analysis can be conducted using sustainability-related attributes. Furthermore, the framework incorporates process evaluation with sustainability in mind, considering green trade-offs and impact assessment. These contributions enhance the understanding and applicability of process mining techniques in the context of sustainability assessment.

- *Green BPM Domain*: The thesis contributes to the Green BPM domain by attempting to provide a clear definition of sustainable business processes. It identifies five characteristics of sustainable business processes: environmental responsibility, social accountability, economic viability, lifecycle thinking, and innovation with continuous improvement. These characteristics help practitioners and researchers in the field of Green BPM to better comprehend the key aspects that contribute to sustainability.

Practical contributions:

- *Support for Practitioners*: The novel process mining methodology proposed in the thesis can be a valuable tool for practitioners seeking to transition to sustainability assessment of their business processes. By incorporating sustainability-related attributes, the Green Process Mining framework offers a structured approach to assess and improve the sustainability performance of processes. This can aid organizations in identifying areas for improvement and implementing sustainable practices.
- *Enhanced Sustainability Reporting*: The mapping of GRI indexes to specific business processes can improve SKPIs for reporting and related initiatives. By establishing a clear connection between metrics and business processes, organizations can enhance their sustainability reporting efforts and provide more accurate and meaningful information to stakeholders.

This thesis has several **limitations**. Firstly, the availability and quality of data represent the main limitation of this research. Reliance on publicly available event logs enriched with generated attributes may introduce estimation errors and biases. Furthermore, the absence of process experts might impact the accuracy and reliability of the analysis. Secondly, another limitation lies in the exclusive focus on sustainability aspects, neglecting conventional performance metrics. While the novel analysis techniques offer valuable insights, a more comprehensive evaluation of overall process efficiency and effectiveness might be beneficial. Thirdly, the chosen case study's specific characteristics and context may limit the generalizability of the findings. The framework developed in this research may require adaptation for different business processes. Additionally, the use of a specific process mining tool (Celonis) may restrict the applicability of the analysis to other tools.

It is worth noting, that mentioned above limitations are not stumbling blocks but rather inherent aspects of the study's design. The primary intention is to introduce and showcase new process mining analysis techniques, but not to delve into the intricacies of the process itself.

Future research in this area should concentrate on addressing the identified limitations. Efforts should be made to enhance data collection and analysis procedures to ensure more reliable results. Moreover, exploring the application of the proposed framework in different industries and diverse business processes would validate its universality and applicability. Additionally, conducting comparative studies between different process mining tools would provide valuable insights into their respective capabilities for sustainability analysis. Such research could aid practitioners in selecting the most suitable tools for their specific sustainability assessment needs. Overall, future research endeavors should strive to overcome the limitations and expand the scope of sustainability assessment in business processes, leading to more robust and widely applicable methodologies.

7 CONCLUSION

This thesis produced a Green Process Mining framework to select and analyze business processes using sustainability reporting metrics and process mining tools. The framework is applied on the case study in manufacturing. For this, mapping GRI indexes to production process, data collection, process analysis and evaluation are done. As the outcome of the research it is reveled that the proposed framework can be use for sustainability assessment of processes to some extend.

The main motivation for this research is curiosity-driven in a way that whether process mining, sustainability reporting and Green BPM can be integrated for Green Deal. In recent years, sustainability has emerged as a critical factor influencing business operations. To report on their sustainability efforts organizations use different guidelines. However, a significant challenge arises when it comes to improving SKPIs and which underlying business processes should be improved. On the other hand, the process mining is well suited for process performance analysis, while Green BMP offers process improvement techniques.

The objective of this thesis is to create a framework to analyze business processes from all dimensions of sustainability using process mining tools. The framework was designed, presented and evaluated. By applying the framework on case study, its effectiveness is tested. As a result, framework helps to analyse production process from economic, environmental and social perspective. Thus, the research objective is fulfilled.

The existing process mining frameworks address sustainability partially and/or implicitly, while present sustainability indicators sets focus on specific dimension or defined on the organizational level. Therefore, in this study, the sustainability metrics are tailored for processes, and then added to the event log as attributes to be analysed by process mining tools to get insights in the sustainability performance of the business process.

Future research in this area should focus on addressing identified limitations and risks, enhancing data collection and analysis procedures for more reliable results, validating the proposed framework's universality and applicability across different industries and business processes, and conducting comparative studies to investigate the capabilities of different process mining tools for sustainability analysis.

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A APPENDIX: MAPPING GRI INDEXES TO BUSINESS PROCESSES

GRI Standard	Disclosure	Metrics	Order-to-Cash (O2C)	Purchase-to-Pay (P2P)	Warehouse Management	Employee Onboarding (HR)	Supply Chain Management	IT Service Management (ITSM)	Claims Management	Customer Journey Experience	Work Order Management	Internal Audit
GRI 201: Economic Performance 2016	201-1 Direct economic value generated and distributed	- Sales Revenue - Operating costs - Profit - Employee wages and benefits - Payments to providers of capital - Payments to government (taxes, penalties) - Community investments	x	x			x		x		x	
	201-2 Financial implications and other risks and opportunities due to climate change	- Financial implications of climate change risks and opportunities - Costs of actions taken to manage the risk or opportunity	x	x			x					
	201-3 Defined benefit plan obligations and other retirement plans	- Value of liabilities - Percentage of salary contributed by employee or employer										
	201-4 Financial assistance received from government	- Monetary value of financial assistance received by the organization from any government										
GRI 202: Market Presence 2016	202-1 Ratios of standard entry level wage by gender compared to local minimum wage	- Entry level wage - Local minimum wage										
	202-2 Proportion of senior management hired from the local community	- Percentage of local senior management										x
GRI 203: Indirect Economic Impacts 2016	203-1 Infrastructure investments and services supported	- Cost of infrastructure investment or service supported	x	x	x			x	x	x	x	
	203-2 Significant indirect economic impacts	- Number of jobs supported in the supply or distribution chain - Economic value retained in the local communities - Taxes paid by the company and its suppliers in each country of operation					x					
GRI 204: Procurement Practices 2016	204-1 Proportion of spending on local suppliers	- Procurement spend on local suppliers - Number of local/non-local suppliers used - Percentage of total procurement spend on local suppliers	x	x			x	x				

GRI Standard	Disclosure	Metrics	Order-to-Cash (O2C)	Purchase-to-Pay (P2P)	Warehouse Management	Employee Onboarding (HR)	Supply Chain Management	IT Service Management (ITSM)	Claims Management	Customer Journey Experience	Work Order Management	Internal Audit
GRI 205: Anti-corruption 2016	205-1 Operations assessed for risks related to corruption	- Number and percentage of operations assessed for risks related to corruption	x	x								x
	205-2 Communication and training about anti-corruption policies and procedures	- Number of employees trained on anti-corruption				x						
	205-3 Confirmed incidents of corruption and actions taken	- Number of confirmed incidents of corruption - Number of confirmed incidents that led to the dismissal of an employee - Number of confirmed incidents that led to the contract termination with business partners - Number of legal cases										x
GRI 206: Anti-competitive Behavior 2016	206-1 Legal actions for anti-competitive behavior, anti-trust, and monopoly practices	- Number of legal actions pending/completed	x	x								x
GRI 207: Tax 2019	207-1 Approach to tax	N/A										
	207-2 Tax governance, control, and risk management	N/A										
	207-3 Stakeholder engagement and management of concerns related to tax	N/A										
	207-4 Country-by-country reporting	N/A										
GRI 301: Materials 2016	301-1 Materials used by weight or volume	For each material type: - Weight or volume of non-renewable materials used - Weight or volume of renewable materials used	x	x	x		x					
	301-2 Recycled input materials used	- Percentage of recycled input materials used			x		x			x		
	301-3 Reclaimed products and their packaging materials	- Percentage of reclaimed products and their packaging materials for each product category			x				x			

GRI Standard	Disclosure	Metrics	Order-to-Cash (O2C)	Purchase-to-Pay (P2P)	Warehouse Management	Employee Onboarding (HR)	Supply Chain Management	IT Service Management (ITSM)	Claims Management	Customer Journey Experience	Work Order Management	Internal Audit
GRI 302: Energy 2016	302-1 Energy consumption within the organization	- Fuel consumption from non-renewable sources - Fuel consumption from renewable sources - Electricity consumption/sold - Heating consumption/sold - Cooling consumption/sold - Steam consumption/sold - Energy consumption			x		x	x			x	x
	302-2 Energy consumption outside of the organization	- Energy consumption outside of the organization										
	302-3 Energy intensity	- Energy intensity for products, services, sales	x	x	x		x	x	x		x	
	302-4 Reduction of energy consumption	- Amount of reductions in energy consumption achieved as a direct result of conservation and efficiency initiatives										x
	302-5 Reductions in energy requirements of products and services	- Reductions in energy										x
GRI 303: Water and Effluents 2018	303-1 Interactions with water as a shared resource	N/A										
	303-2 Management of water discharge-related impacts	N/A										
	303-3 Water withdrawal	For freshwater and other water: - Water withdrawal from all areas - Water withdrawal from all areas with water stress					x			x	x	
	303-4 Water discharge	For freshwater and other water: - Water discharge from all areas - Water discharge from all areas with water stress - Percentage of suppliers with significant water-related impacts										
	303-5 Water consumption	- Water consumption from all areas - Water consumption from all areas with water stress - Change in water storage										

GRI Standard	Disclosure	Metrics	Order-to-Cash (O2C)	Purchase-to-Pay (P2P)	Warehouse Management	Employee Onboarding (HR)	Supply Chain Management	IT Service Management (ITSM)	Claims Management	Customer Journey Experience	Work Order Management	Internal Audit
GRI 304: Biodiversity 2016	304-1 Operational sites owned, leased, managed in, or adjacent to, protected areas and areas of high biodiversity value outside protected areas	N/A										
	304-2 Significant impacts of activities, products and services on biodiversity	N/A										
	304-3 Habitats protected or restored	N/A										
	304-4 IUCN Red List species and national conservation list species with habitats in areas affected by operations	Number of species by type: - critically endangered - endangered - vulnerable - near threatened - least concern										
GRI 305: Emissions 2016	305-1 Direct (Scope 1) GHG emissions	- Gross direct (Scope 1) GHG emissions	x	x	x		x	x		x	x	
	305-2 Energy indirect (Scope 2) GHG emissions	- Gross indirect (Scope 2) GHG emissions										
	305-3 Other indirect (Scope 3) GHG emissions	- Gross other indirect (Scope 3) GHG emissions										
	305-4 GHG emissions intensity	- Emissions intensity for products, services, sales	x	x		x	x	x	x		x	
	305-5 Reduction of GHG emissions	- Emissions reduced										x
	305-6 Emissions of ozone-depleting substances (ODS)	- Production of ODS										
	305-7 Nitrogen oxides (NOx), sulfur oxides (SOx), and other significant air emissions	- Air emissions										
GRI 306: Waste 2020	306-1 Waste generation and significant waste-related impacts	N/A									x	
	306-2 Management of significant waste-related impacts	N/A										
	306-3 Waste generated	- Weight of waste generated and breakdown by type			x							

GRI Standard	**Disclosure**	**Metrics**	**Order-to-Cash (O2C)**	**Purchase-to-Pay (P2P)**	**Warehouse Management**	**Employee Onboarding (HR)**	**Supply Chain Management**	**IT Service Management (ITSM)**	**Claims Management**	**Customer Journey Experience**	**Work Order Management**	**Internal Audit**
	306-4 Waste diverted from disposal	- Weight of waste diverted from disposal - Weight of hazardous waste diverted from disposal (reuse, recycling, other recovery operations) - Weight of non-hazardous waste diverted from disposal (reuse, recycling, other recovery operations)			x							
	306-5 Waste directed to disposal	- Weight of waste directed to disposal - Weight of hazardous waste directed to disposal (incineration, landfilling, other disposal operations) - Weight of non-hazardous waste directed to disposal (incineration, landfilling, other disposal operations)			x							
GRI 308: Supplier Environmental Assessment 2016	308-1 New suppliers that were screened using environmental criteria	- Percentage of new suppliers that were screened using environmental criteria	x	x			x	x				
	308-2 Negative environmental impacts in the supply chain and actions taken	- Number and percentage of suppliers assessed for environmental impacts - Number and percentage of suppliers with negative environmental impacts	x	x			x					x
GRI 401: Employment 2016	401-1 New employee hires and employee turnover	- Number and rate of new employee hires by age group, gender and region - Number and rate of employee turnover				x						
	401-2 Benefits provided to full-time employees that are not provided to temporary or part-time employees	- Number of full-time employees receiving benefits - Types of benefits provided to full-time employees (e.g. health insurance, retirement plans, parental leave, etc.)				x	x				x	
	401-3 Parental leave	Number of employees by gender: - entitled to parental leave - took parental leave - returned to work - Retention rate				x						
GRI 402: Labor/Management Relations 2016	402-1 Minimum notice periods regarding operational changes	- Number of weeks' notice				x						
GRI 403: Occupational Health and	403-1 Occupational health and safety management system	N/A										

GRI Standard	Disclosure	Metrics	Order-to-Cash (O2C)	Purchase-to-Pay (P2P)	Warehouse Management	Employee Onboarding (HR)	Supply Chain Management	IT Service Management (ITSM)	Claims Management	Customer Journey Experience	Work Order Management	Internal Audit
Safety 2018	403-2 Hazard identification, risk assessment, and incident investigation	N/A										
	403-3 Occupational health services	- Service effectiveness metrics (utilization, availability, response time, satisfaction, etc.)				x		x	x	x	x	
	403-4 Worker participation, consultation, and communication on occupational health and safety	N/A										
	403-5 Worker training on occupational health and safety	- Number of workers trained on occupational health and safety - Training cost coverage - Paid working hours allocated for trainings - Training effectiveness metrics			x	x		x	x			
	403-6 Promotion of worker health	- Services and programs effectiveness metrics				x						x
	403-7 Prevention and mitigation of occupational health and safety impacts directly linked by business relationships	N/A										
	403-8 Workers covered by an occupational health and safety management system	- Number and percentage of workers										
	403-9 Work-related injuries	- Number and rate of fatalities as a result of work-related injury - Number and rate of high-consequence work-related injuries (excluding fatalities) - Number and rate of recordable work-related injuries - Main types of work-related injury - Number of hours worked				x						
	403-10 Work-related ill health	- Number of fatalities as a result of work-related ill health - Number of cases of recordable work-related ill health - Main types of work-related ill health										

GRI Standard	Disclosure	Metrics	Order-to-Cash (O2C)	Purchase-to-Pay (P2P)	Warehouse Management	Employee Onboarding (HR)	Supply Chain Management	IT Service Management (ITSM)	Claims Management	Customer Journey Experience	Work Order Management	Internal Audit
GRI 404: Training and Education 2016	404-1 Average hours of training per year per employee	- Average training hours per employee, gender, employee category				x					x	x
	404-2 Programs for upgrading employee skills and transition assistance programs	N/A				x					x	
	404-3 Percentage of employees receiving regular performance and career development reviews	- Percentage of employees by gender, employee category										
GRI 405: Diversity and Equal Opportunity 2016	405-1 Diversity of governance bodies and employees	- Percentage of employees by gender, age group, other indicators	x	x	x	x	x	x	x	x	x	x
	405-2 Ratio of basic salary and remuneration of women to men	- Ratio of the basic salary of women to men for each employee category				x						
GRI 406: Non-discrimination 2016	406-1 Incidents of discrimination and corrective actions taken	- Number of incidents of discrimination by status				x						x
GRI 407: Freedom of Association and Collective Bargaining 2016	407-1 Operations and suppliers in which the right to freedom of association and collective bargaining may be at risk	N/A				x						
GRI 408: Child Labor 2016	408-1 Operations and suppliers at significant risk for incidents of child labor	- Operations and suppliers related to child labor				x	x					x
GRI 409: Forced or Compulsory Labor 2016	409-1 Operations and suppliers at significant risk for incidents of forced or compulsory labor	- Operations and suppliers related to forced or compulsory labor				x	x					
GRI 410: Security Practices 2016	410-1 Security personnel trained in human rights policies or procedures	- Percentage using the total number of security personnel				x						x
GRI 411: Rights of Indigenous Peoples 2016	411-1 Incidents of violations involving rights of indigenous peoples	- Number of incidents by status										

GRI Standard	Disclosure	Metrics	Order-to-Cash (O2C)	Purchase-to-Pay (P2P)	Warehouse Management	Employee Onboarding (HR)	Supply Chain Management	IT Service Management (ITSM)	Claims Management	Customer Journey Experience	Work Order Management	Internal Audit
GRI 413: Local Communities 2016	413-1 Operations with local community engagement, impact assessments, and development programs	- Percentage of operations with implemented local community engagement	x	x					x	x		
	413-2 Operations with significant actual and potential negative impacts on local communities	- Operations with impact on local level - Impact type (severity, likely duration, reversibility, scale)										
GRI 414: Supplier Social Assessment 2016	414-1 New suppliers that were screened using social criteria	- Percentage of new suppliers that were screened using social criteria			x	x	x					
	414-2 Negative social impacts in the supply chain and actions taken	- Number and percentage of suppliers assessed for social impacts - Number and percentage of suppliers with negative social impacts			x	x	x					x
GRI 415: Public Policy 2016	415-1 Political contributions	- Monetary value of financial and in-kind political contributions										x
GRI 416: Customer Health and Safety 2016	416-1 Assessment of the health and safety impacts of product and service categories	- Percentage of products and services assessed			x			x	x	x	x	x
	416-2 Incidents of non-compliance concerning the health and safety impacts of products and services	- Number of incidents by type							x			
GRI 417: Marketing and Labeling 2016	417-1 Requirements for product and service information and labeling	- Number and percentage of products or services requiring environmental or social labeling or information - Number of products or services with label on safe use and disposal					x		x	x		x
	417-2 Incidents of non-compliance concerning product and service information and labeling	- Number of incidents by type					x		x	x		
	417-3 Incidents of non-compliance concerning marketing communications	- Number of incidents by type					x			x		
GRI 418: Customer Privacy 2016	418-1 Substantiated complaints concerning breaches of customer privacy and losses of customer data	- Number of complaints - Number of leaks, thefts, or losses of customer data			x		x	x	x	x		x

B APPENDIX: EVENT LOG ATTRIBUTES DESCRIPTION

Name in event log	**Description**	**Data source for case study**	**Units of measurement**	**Possible values**
Case ID	Unique identification for each case, corresponds to the work order in ERP system	Original event log (Levy, 2014)	N/A	Case 1, Case 277
Activity	Operation in manufacturing and event in a case	Original event log	N/A	Turning & Milling, Packing
Work Station	Machine on which the operation was executed	Original event log	N/A	Machine 3, Quality Check 1
Start Timestamp	Start date and time for each activity	Original event log	N/A	12-01-2012 08:20:00
Complete Timestamp	End date and time for each activity	Original event log	N/A	12-01-2012 09:35:00
Span	Duration of an activity	Original event log	duration	01:15:00
Minutes	Duration of an activity	Calculation: Minutes = Span*24*60	minutes	75
Work Order Qty	Quantity of product part being manufactured in a case	Original event log	unit	50
Product	Product part being manufactured	Original event log	N/A	Cable Head, Ballnut
Worker ID	Unique identification of an employee performing each activity	Original event log	N/A	ID4618
Report Type	Type of particular event	Original event log	N/A	P - Production, S - Setup, B - Break
Qty Completed	Quantity of manufactured products	Original event log	unit	1, 17
Qty Rejected	Quantity of rejected products	Original event log	unit	2
Qty for MRB	Quantity of parts for the selected part that are in Material Review Board (MRB) locations	Original event log	unit	0
Rework	Rework indicator	Original event log	N/A	Y - Yes, N - No
Sales Price	Sales prices per unit of the production parts are found in the online shops. The exact links are not provided due to marketing policy. The market prices are valid as of 19 May 2023. Then 10% as profit margin of online shop is deducted from the market price. This resulted in the sales price of the manufacturing company.	Calculation: Sales Price = Market Price - 10%	€	13.64
Revenue	Revenue is the amount of gross income produced through sales of products.	Calculation: Revenue = Sales Price * Work Order Qty	€	9818.18
Cost	If organization is using ABC method to calculate Operating cost per unit, then the cost will be ABC*Number of units produced. Operating cost per unit = Total manufacturing cost / Number of units produced = (Material + Labor + Overhead) / Number of units produced As no data available for the case study, to calculate the operating cost, sales price and revenue the reverse method is used. To calculate operating cost the 15% as profit margin of manufacturing company is deducted from the sales price. The operating cost per activity per unit is calculated as the sales prices per unit divided by seven, which corresponds to the number of activities in the blueprint business model (Figure 10). As event log contains also the information about the quantity, the total operating cost per activity is calculated as the operating cost per activity per unit multiply by the sum of quantity completed, rejected and for MRB. If the total quantity is equal to 0, then the the operating cost per activity per unit multiply by 1. This is due to the fact, that even though no details were proceeded, the activity still was performed.	Calculation: Revenue = Sales Price - 15%	€	11.86
Supplier Type	Type of supplier	Random	N/A	Local, non-local
Spend on Suppliers	The cost of materials depend on the supplier and material, and thus should be calculated accordingly based on the data from Finance module. However, such detailed calculations are outside of the scope of the thesis. Therefore, the cost of materials is calculated as total weight of non-renewable and renewable materials multiply by 0.01 €.	Calculation: Spend on Suppliers=Weight NRM/RM*0.01	€	3.86

Name in event log	**Description**	**Data source for case study**	**Units of measurement**	**Possible values**
Material Type	Material type is taken from product specification	As per product specification	N/A	Aluminum, Carton
Weight NRM	Total weight of non-renewable materials used. If activity is Milling, Turning, Turning & Milling or Setup Turning & Milling, then the total weight is calculated as weight of the production part plus 0.2 g as associated process materials. The latter are the materials that are needed for the manufacturing process but are not the part of the final product, such as lubricants for manufacturing machinery. If activity is Flat Grinding, Grinding Rework, Lapping, Laser Marking, Nitration Q.C., Round Grinding or Turning Rework, then the total weight of non-renewable materials is the weight of the associated process materials and equal to 0.2 g. As for other activities, the weight of non-renewable materials is assumed to be 0. Finally the total weight of non-renewable material is calculated as the weight per unit multiply by the sum of quantity completed, rejected and for MRB.	Calculation: Total Weight NRM=Weight NRM*(Qty Completed+Qty Rejected+Qty for MRB)	g	80.78
Weight RM	Total weight of renewable materials used. In this case study the only renewable material is carton for packaging. As it is done manually, it is assumed that there is no associated process materials. The product dimensions are considered to define the box size. Then added extra 5% for folding parts.	Calculation: Weight RM=Volume*Density*1.05	g	385.56
Recycled Input	Percentage of recycled input materials used = Total recycled input materials used/Total input materials used * 100	Carton: 100% Other materials: random between 0% and 90%	%	95
Energy	Energy consumption of activity is defined for each work station. For each activity, the time of operation is multiplied by the energy consumption of work station that performed the activity. Energy consumption of work station is assumed to be between 1.0 and 1.5 kWh, for manually performed activities (Quality Check and Final Inspection) the energy consumption is 0.	Energy=Energy consumption of work station*Span	kWh	3.69
Energy Class	Energy class is defined for each work station. Unlike for home appliances, for CNC machines there is no aggregated label to refer to energy consumption of machine. There is a research offering such method and which metrics should be included to the label. However, it does not offer any classification. Even though the energy consumption for each work station is already defined, for visualisation purposes, the energy class also is assigned. The following rules are used: A - 1.0 B - 1.1-1.2 C - 1.3-1.5 O - 0.0 (for manual operations)	Labeled based on energy consumption of work station	N/A	A, B, C, O
Energy Type	Type of the energy source (renewable, non-renewable) can be specified separately based on overall organization data. For this case study, the energy type is assigned randomly between renewable and non-renewable.	Random	N/A	renewable, non-renewable
Energy Intensity	Energy intensity per unit produced = Total energy consumed / Total quantity of products manufactured	Calculation: Energy Intensity=Energy consumption per activity/(Qty Completed+Qty Rejected+Qty for MRB)	kWh/unit	35.87
Water	Water consumption of activity = Total water withdrawal - Total water discharge Water consumption in l/h is defined for each work station. For each activity, the time of operation is multiplied by the water consumption of work station that performed the activity.	Water=Water consumption of work station*Span	l	4.8

Name in event log	Description	Data source for case study	Units of measurement	Possible values
Emissions	CO_2eq Emissions = Energy Consumption * Carbon Intensity * GWP factor For this case, only CO_2 is considered. For non-renewable energy source the total CO_2eq Emissions is calculated by total energy consumption per activity multiply by Carbon Intensity. For renewable energy sources and manual operations such as Packaging, Settings and Quality Control, the total CO_2eq Emissions is equal to 0. Carbon Intensity is taken for Germany 2021 and equals to 380 gCO_2e/kWh (https://www.nowtricity.com/country/germany).	Packaging, Settings and Quality Control: 0 Calculation for other activities: Emissions=Energy*380	gCO_2e	313.5
Emissions Intensity	Emissions intensity = Emissions per unit produced = Total emissions / Total quantity of products manufactured Total emissions per activity divided by the sum of quantity completed, rejected and for MRB.	Calculation: Emissions Intensity=Emissions/(Qty Completed+Qty Rejected+Qty for MRB)	gCO_2e/unit	14.07
Waste	Weight of generated waste. The percentage of generated waste is defined per each activity based on the industry standards and ranges between 0.05-1.5%. Then percentage is calculated from the total weight of renewable and non-renewable materials.	Calculation: Waste=(Weight NRM+WeightRM)*waste percentage	g	3.86
Waste Recycled	Weight of waste directed to reuse/recycling. It is assumed that only carton waste is sent to the recycling point. The percentage of waste is taken as 1%.	Calculation: Waste=(Weight NRM+WeightRM)*1%	g	8.35
Waste Disposal	Weight of waste directed to disposal is obtained by subtracting Weight of waste directed to reuse/recycling from the weight of generated waste.	Calculation: Waste Disposal=Waste-Waste Recycled	g	3.64
Benefits	Benefits received by the employee. It is assumed that full-time workers receive benefits, while part-time do not.	Assigned based on employment type	N/A	Y - for full-time, N - for part-time
Safety Training	Safety training received for each worker	Random	N/A	Y - Yes, N - No
Injury	Injury received by the worker for each event	Random	N/A	Y - Yes, N - No
Prof Training	Total hours of professional training per year for each worker	Random between 0 to 19 h	h	15
Gender	Gender of employee	Random	N/A	M - male, F - female
Age Group	Age group as per GRI Standard: <30, 30-50, <50	Random	N/A	<30, 30-50, <50
Salary	Average monthly salary for reporting year for each employee. Full-time workers range 1700-2600€, part time workers range 900-1000€.	Random	€	2100
Employment	Employment type (full-time or part-time)	Random	N/A	PT - Part-time, FT - Full-time
Hourly Rate	Hourly rate per worker is basic salary divided by 160h for full-time or 80h for part-time.	Calculation: Hourly Rate (full-time)=Salary/160 Hourly Rate (part-time)=Salary/80	€/h	12.5

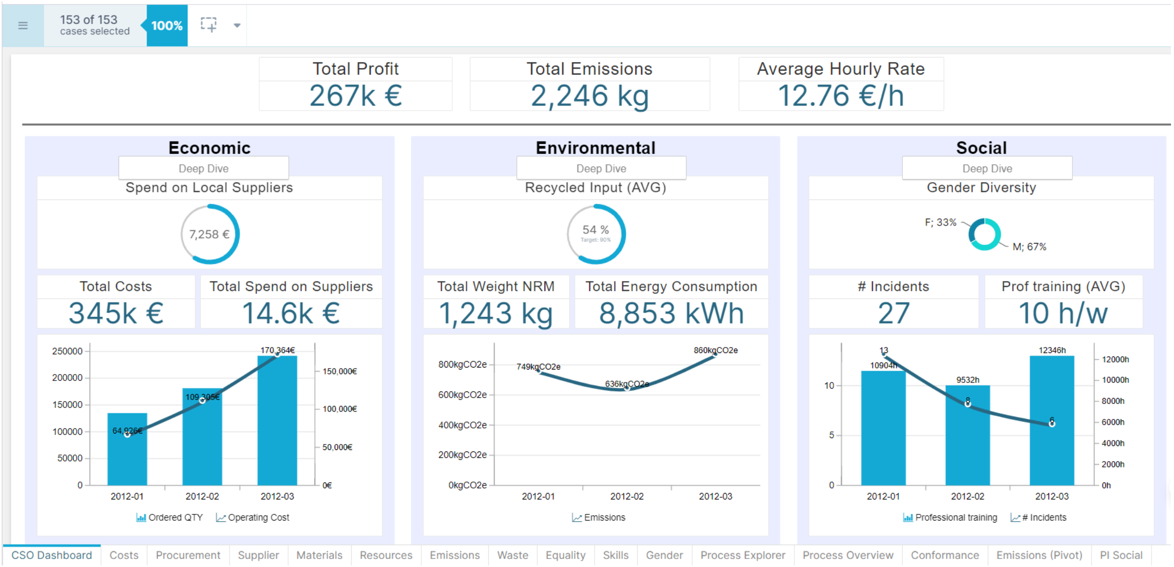
C APPENDIX: PQL QUERIES FOR DASHBOARDS COMPONENTS

Dashboard	**KPI**	**PQL query**
Costs	Total Revenue	SUM(PU_min("Production_Data_CASES", "Production_Data"."REVENUE"))
	Total Costs	SUM("Production_Data"."COST")
	Total Profit	SUM (PU_FIRST("Production_Data_CASES", "Production_Data"."REVENUE"))-SUM (PU_SUM ("Production_Data_CASES", "Production_Data"."cost"))
	Productivity (unit/h)	SUM("Production_Data"."QTY COMPLETED")/(SUM("Production_Data"."MINUTES")/60)
Procurement	Total Spend on Suppliers	SUM("Production_Data"."SPEND ON SUPPLIERS")
	% Local Spend	SUM(CASE WHEN "Production_Data"."SUPPLIER TYPE" = 'local' THEN "Production_Data"."SPEND ON SUPPLIERS" ELSE 0 END) / SUM("Production_Data"."SPEND ON SUPPLIERS")
Supplier	Component filters	FILTER "Production_Data"."SUPPLIER TYPE" = <%=Supplier1%> FILTER "Production_Data"."SUPPLIER TYPE" = <%=Supplier2%>
	Throughput Time	AVG(CALC_THROUGHPUT(ALL_OCCURRENCE['Process Start'] TO ALL_OCCURRENCE['Process End'], REMAP_TIMESTAMPS("Production_Data"."START TIMESTAMP", HOURS)))
Materials	Total Weight NRM	SUM("Production_Data"."WEIGHT NRM")/1000
	Total Weight RM	SUM("Production_Data"."WEIGHT RM")/1000
	Recycled Input (AVG)	AVG("Production_Data"."RECYCLED INPUT")
Resources	Total Water Usage	SUM("Production_Data"."WATER")
	Total Energy Consumption	SUM("Production_Data"."ENERGY")
	Energy Intensity	SUM("Production_Data"."ENERGY")/(SUM("Production_Data"."QTY COMPLETED")+SUM("Production_Data"."QTY REJECTED"))
	Energy Intensity (OLAP)	SUM("Production_Data"."ENERGY")/(SUM("Production_Data"."QTY COMPLETED")+SUM("Production_Data"."QTY REJECTED"))
Emissions	Total Carbon Emissions in Trees	SUM("Production_Data"."EMISSIONS")/1000/<%= CO2_Tree%>
	Total Emissions	SUM("Production_Data"."EMISSIONS")/1000
	Emissions Intensity	SUM("Production_Data"."EMISSIONS")/SUM(PU_FIRST("Production_Data_CASES", "Production_Data"."WORK ORDER QTY"))
	Emissions Intensity (Revenue)	SUM("Production_Data"."EMISSIONS")/SUM(PU_FIRST("Production_Data_CASES", "Production_Data"."REVENUE"))
Waste	Total Waste	SUM("Production_Data"."WASTE")/1000
	Waste to Recycle	SUM("Production_Data"."WASTE RECYCLED")/1000
	Waste to Landfill	SUM("Production_Data"."WASTE DISPOSAL")/1000
	Waste to Recycle Rate	SUM("Production_Data"."WASTE RECYCLED") / SUM("Production_Data"."WASTE")

Dashboard	KPI	PQL query
Equality	# Activities	COUNT("Production_Data"."ACTIVITY")
Skills	# Incidents	SUM(CASE WHEN "Production_Data"."INJURY " = 'Y' THEN 1 ELSE 0 END)
	Prof training (AVG)	AVG("Production_Data"."PROF TRAINING")
	Prof training (Total)	SUM("Production_Data"."PROF TRAINING")
Gender	Component filters	FILTER "Production_Data"."GENDER " = <%=Gender1%> FILTER "Production_Data"."GENDER " = <%=Gender2%>
Costs (example of Dynamic Analysis in OLAP)	Button dropdown	<%= ButtonDrilldown1== '"Production_Data"."ACTIVITY"' ? 'Activity': ButtonDrilldown1== '"Production_Data"."PRODUCT"' ? 'Product': ButtonDrilldown1== '"Production_Data"."Work Station" || \' - \' || "Production_Data"."Energy Class"' ? 'Work Station': ButtonDrilldown1== '"Production_Data"."CASE ID"' ? 'Order':''%>
	Table title	Operating Cost by <%= ButtonDrilldown1== '"Production_Data"."ACTIVITY"' ? 'Activity': ButtonDrilldown1== '"Production_Data"."PRODUCT"' ? 'Product': ButtonDrilldown1== '"Production_Data"."Work Station" || \' - \' || "Production_Data"."Energy Class"' ? 'Work Station': ButtonDrilldown1== '"Production_Data"."CASE ID"' ? 'Order':''%>
	Dimension title	<%= ButtonDrilldown1== '"Production_Data"."ACTIVITY"' ? 'Activity': ButtonDrilldown1== '"Production_Data"."PRODUCT"' ? 'Product': ButtonDrilldown1== '"Production_Data"."Work Station" || \' - \' || "Production_Data"."Energy Class"' ? 'Work Station': ButtonDrilldown1== '"Production_Data"."CASE ID"' ? 'Order':''%>

D APPENDIX: DASHBOARDS DESIGN

The **CSO Dashboard** provides real-time monitoring of economic, environmental, and social sustainability metrics related to the production process, including profit, emissions, cost, supplier spending, energy consumption, gender diversity, incident numbers, and professional training, through single KPIs, pie charts, and bar charts.



153 of 153 cases selected 100%

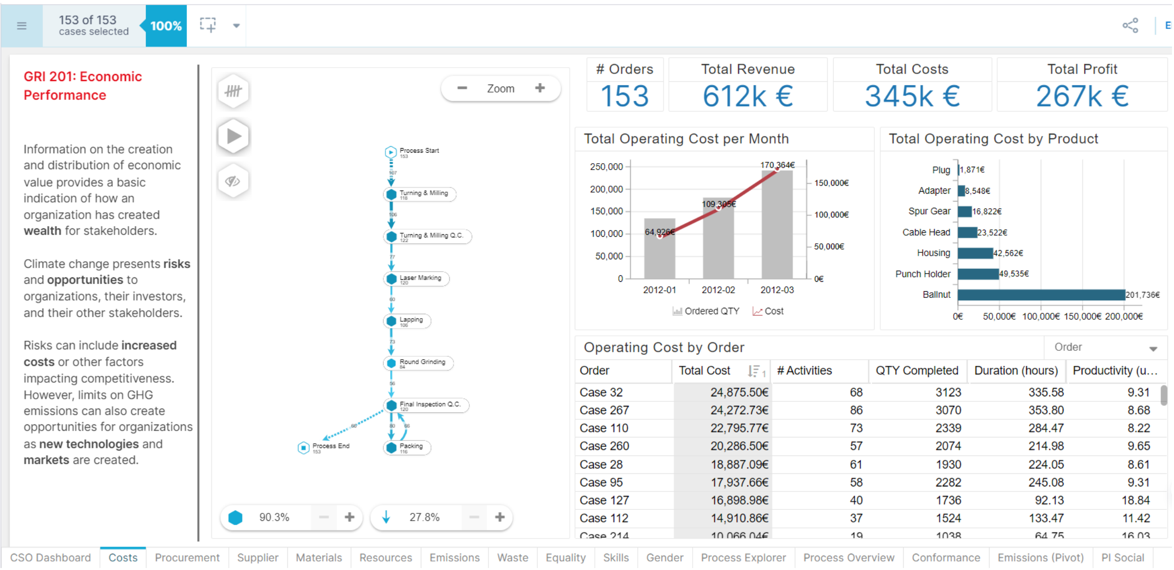
Total Profit: 267k €
Total Emissions: 2,246 kg
Average Hourly Rate: 12.76 €/h

Economic
Spend on Local Suppliers: 7,258 €
Total Costs: 345k €
Total Spend on Suppliers: 14.6k €

Environmental
Recycled Input (AVG): 54 % (Target: 90%)
Total Weight NRM: 1,243 kg
Total Energy Consumption: 8,853 kWh

Social
Gender Diversity: F; 33% M; 67%
Incidents: 27
Prof training (AVG): 10 h/w

The **Costs** dashboard (GRI 201: Economic Performance) provides insights into revenue, profit and production cost per unit of product, using single KPIs, OLAP, column charts, and bar charts for effective analysis of costs over time periods.



153 of 153 cases selected 100%

GRI 201: Economic Performance

Information on the creation and distribution of economic value provides a basic indication of how an organization has created **wealth** for stakeholders.

Climate change presents **risks** and **opportunities** to organizations, their investors, and their other stakeholders.

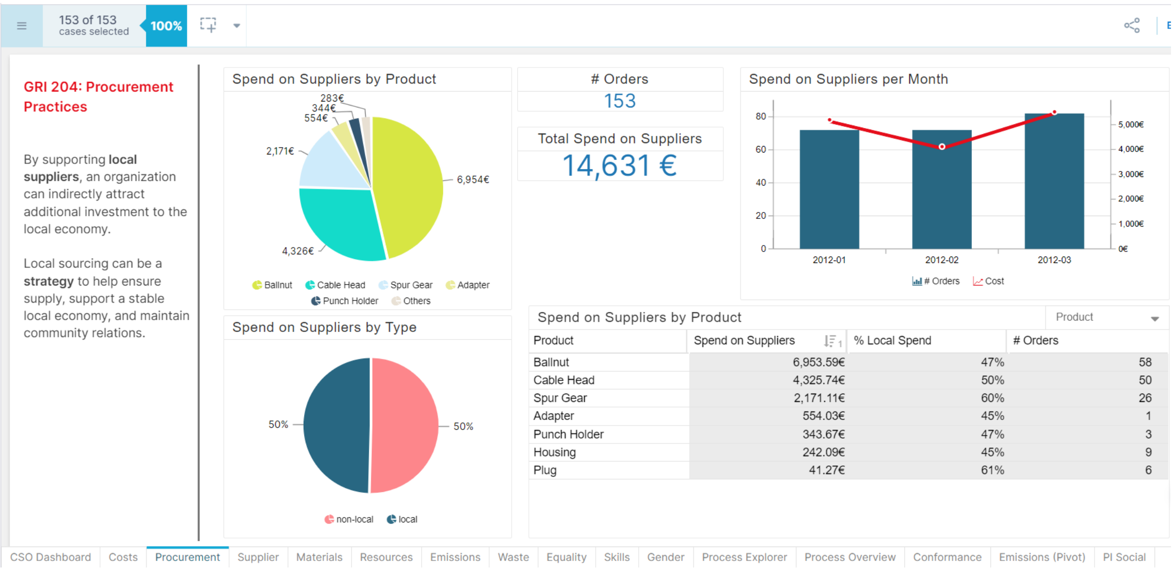
Risks can include **increased costs** or other factors impacting competitiveness. However, limits on GHG emissions can also create opportunities for organizations as **new technologies** and **markets** are created.

Orders: 153
Total Revenue: 612k €
Total Costs: 345k €
Total Profit: 267k €

Operating Cost by Order

Order	Total Cost	# Activities	QTY Completed	Duration (hours)	Productivity (u…
Case 32	24,875.50€	68	3123	335.58	9.31
Case 267	24,272.73€	86	3070	353.80	8.68
Case 110	22,795.77€	73	2339	284.47	8.22
Case 260	20,286.50€	57	2074	214.98	9.65
Case 28	18,887.09€	61	1930	224.05	8.61
Case 95	17,937.66€	58	2282	245.08	9.31
Case 127	16,898.98€	40	1736	92.13	18.84
Case 112	14,910.86€	37	1524	133.47	11.42
Case 214	10,066.04€	19	1038	64.75	16.03

The **Procurement** dashboard (GRI 204: Procurement Practices) allows monitoring of supplier contributions to costs and offers insights on reducing procurement costs by displaying the percentage of local suppliers, supplier costs based on supplier type, product, and time, using pie charts, OLAP, and bar charts for effective analysis of procurement data.



GRI 204: Procurement Practices

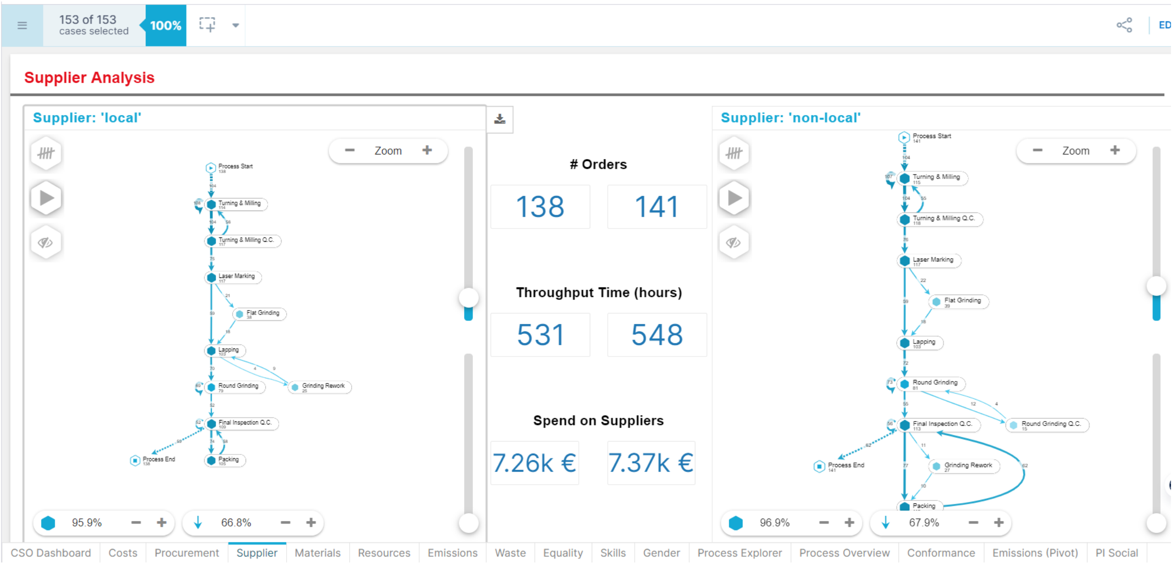
By supporting **local suppliers**, an organization can indirectly attract additional investment to the local economy.

Local sourcing can be a **strategy** to help ensure supply, support a stable local economy, and maintain community relations.

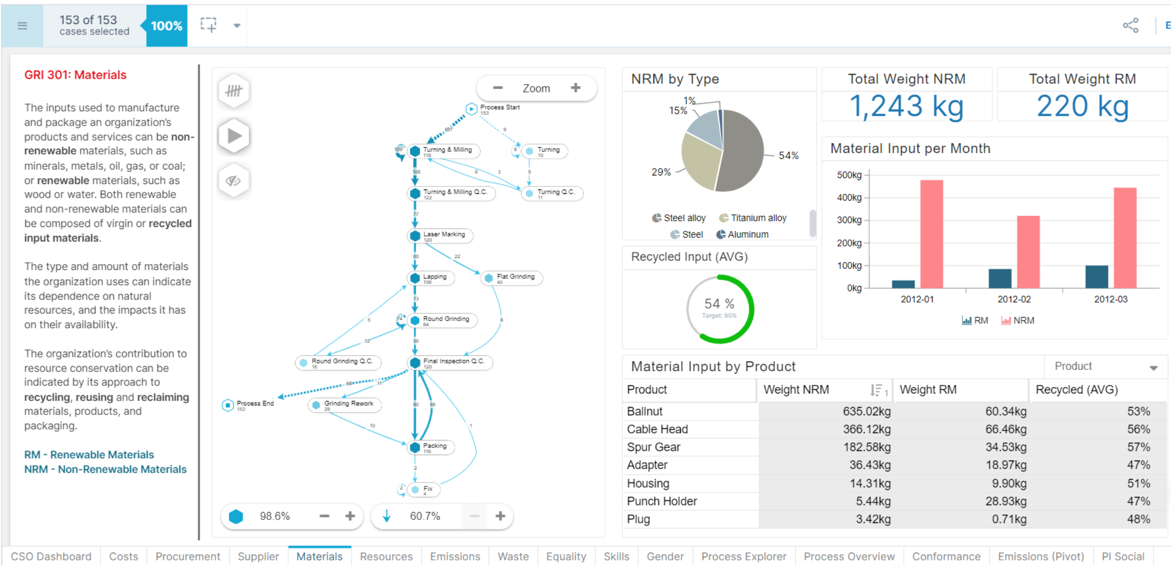
Spend on Suppliers by Product

Product	Spend on Suppliers	% Local Spend	# Orders
Ballnut	6,953.59€	47%	58
Cable Head	4,325.74€	50%	50
Spur Gear	2,171.11€	60%	26
Adapter	554.03€	45%	1
Punch Holder	343.67€	47%	3
Housing	242.09€	45%	9
Plug	41.27€	61%	6

The **Supplier** dashboard (GRI 204: Procurement Practices) provides benchmarking view of the processes, where local and non-local suppliers involved, allowing for a clear comparison of the expenses related to different supplier types.



The **Materials** dashboard (GRI 301: Materials) provides insights on the usage of recycled and renewable materials, by displaying data related to recycled materials input and renewable/non-renewable materials input based on material, work order, activity, and product using pie charts and OLAP for effective analysis of material usage patterns.



GRI 301: Materials

The inputs used to manufacture and package an organization's products and services can be **non-renewable** materials, such as minerals, metals, oil, gas, or coal; or **renewable** materials, such as wood or water. Both renewable and non-renewable materials can be composed of virgin or **recycled input materials**.

The type and amount of materials the organization uses can indicate its dependence on natural resources, and the impacts it has on their availability.

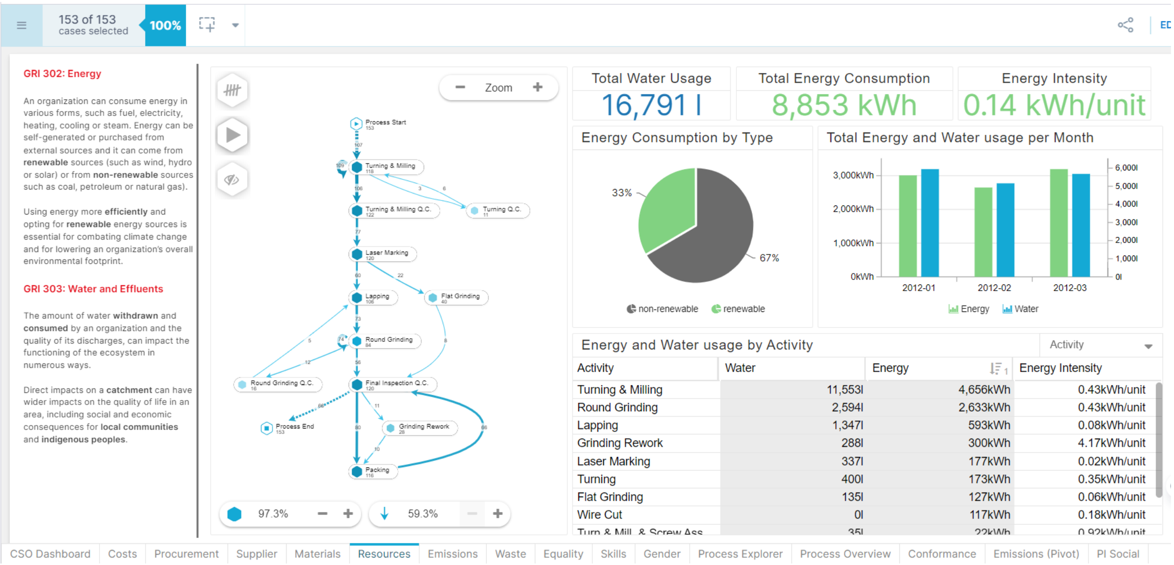
The organization's contribution to resource conservation can be indicated by its approach to **recycling**, **reusing** and **reclaiming** materials, products, and packaging.

RM - Renewable Materials
NRM - Non-Renewable Materials

Material Input by Product

Product	Weight NRM	Weight RM	Recycled (AVG)
Ballnut	635.02kg	60.34kg	53%
Cable Head	366.12kg	66.46kg	56%
Spur Gear	182.58kg	34.53kg	57%
Adapter	36.43kg	18.97kg	47%
Housing	14.31kg	9.90kg	51%
Punch Holder	5.44kg	28.93kg	47%
Plug	3.42kg	0.71kg	48%

The **Resources** dashboard (GRI 302: Energy, GRI 303: Water and Effluents) provides key insights into energy and water consumption, including energy intensity. It visualizes data based on work orders, activities, products, and resources using single KPIs, pie charts, bar charts, and OLAP for effective resource management.



GRI 302: Energy

An organization can consume energy in various forms, such as fuel, electricity, heating, cooling or steam. Energy can be self-generated or purchased from external sources and it can come from **renewable** sources (such as wind, hydro or solar) or from **non-renewable** sources such as coal, petroleum or natural gas).

Using energy more **efficiently** and opting for **renewable** energy sources is essential for combating climate change and for lowering an organization's overall environmental footprint.

GRI 303: Water and Effluents

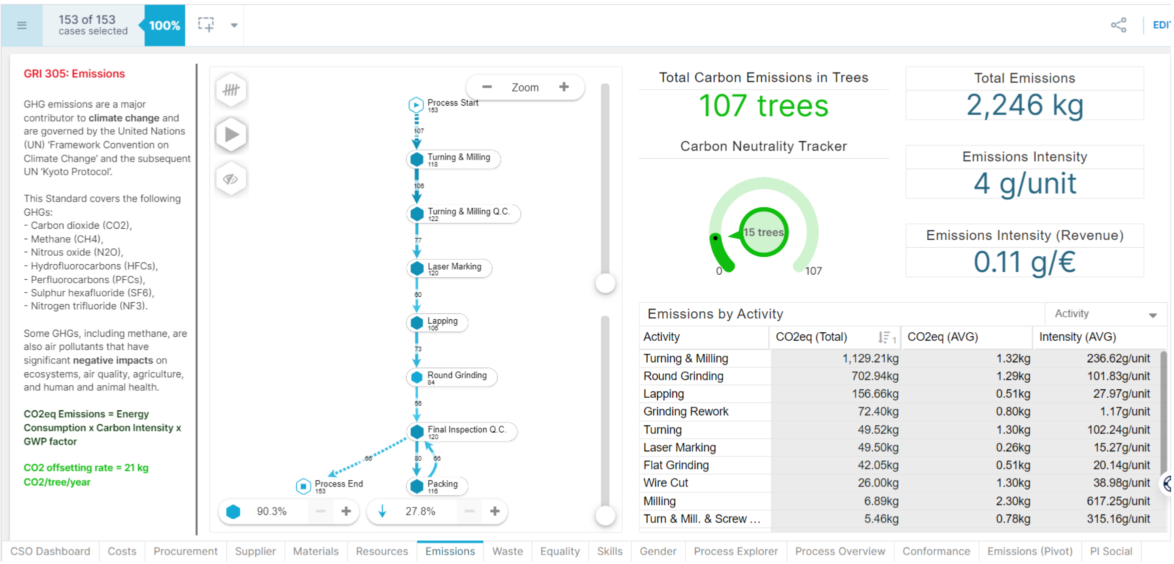
The amount of water **withdrawn** and **consumed** by an organization and the quality of its discharges, can impact the functioning of the ecosystem in numerous ways.

Direct impacts on a **catchment** can have wider impacts on the quality of life in an area, including social and economic consequences for **local communities** and **indigenous peoples**.

Energy and Water usage by Activity

Activity	Water	Energy	Energy Intensity
Turning & Milling	11,553l	4,656kWh	0.43kWh/unit
Round Grinding	2,594l	2,633kWh	0.43kWh/unit
Lapping	1,347l	593kWh	0.08kWh/unit
Grinding Rework	288l	300kWh	4.17kWh/unit
Laser Marking	337l	177kWh	0.02kWh/unit
Turning	400l	173kWh	0.35kWh/unit
Flat Grinding	135l	127kWh	0.06kWh/unit
Wire Cut	0l	117kWh	0.18kWh/unit
Turn & Mill. & Screw Ass	35l	22kWh	0.92kWh/unit

The **Emissions** dashboard (GRI 305: Emissions) enables tracking of the carbon footprint by displaying data related to CO_2 emissions and emissions intensity based on work orders, activities, products, and resources, utilizing single KPIs and OLAP for effective emission management.



GRI 305: Emissions

GHG emissions are a major contributor to **climate change** and are governed by the United Nations (UN) 'Framework Convention on Climate Change' and the subsequent UN 'Kyoto Protocol'.

This Standard covers the following GHGs:
- Carbon dioxide (CO2),
- Methane (CH4),
- Nitrous oxide (N2O),
- Hydrofluorocarbons (HFCs),
- Perfluorocarbons (PFCs),
- Sulphur hexafluoride (SF6),
- Nitrogen trifluoride (NF3).

Some GHGs, including methane, are also air pollutants that have significant **negative impacts** on ecosystems, air quality, agriculture, and human and animal health.

CO2eq Emissions = Energy Consumption x Carbon Intensity x GWP factor

CO2 offsetting rate = 21 kg CO2/tree/year

Total Carbon Emissions in Trees
107 trees

Total Emissions
2,246 kg

Carbon Neutrality Tracker

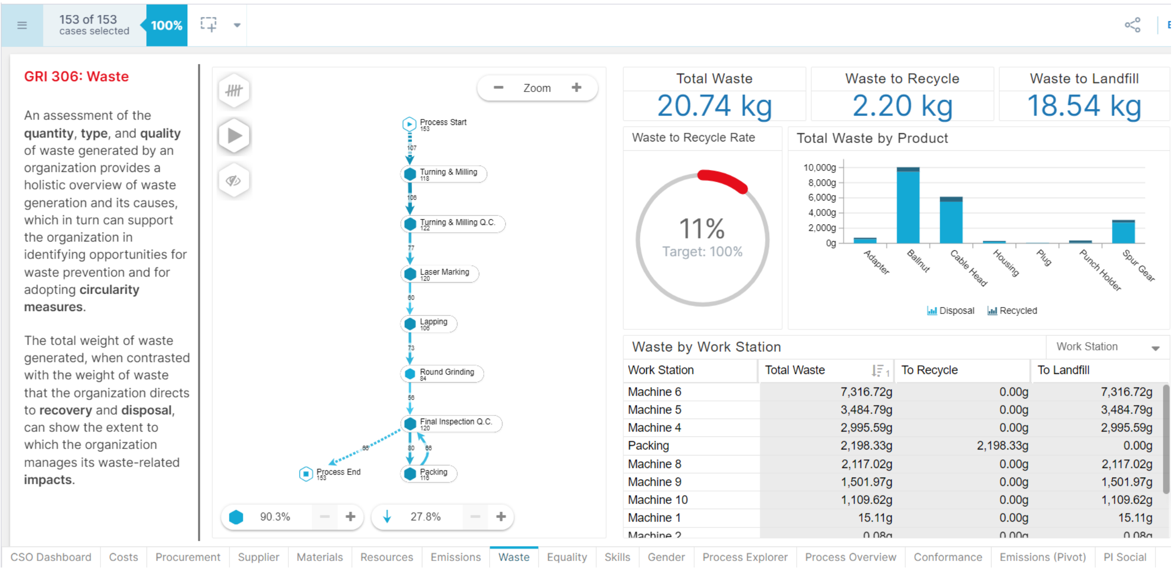
Emissions Intensity
4 g/unit

Emissions Intensity (Revenue)
0.11 g/€

Emissions by Activity

Activity	CO2eq (Total)	CO2eq (AVG)	Intensity (AVG)
Turning & Milling	1,129.21kg	1.32kg	236.62g/unit
Round Grinding	702.94kg	1.29kg	101.83g/unit
Lapping	156.66kg	0.51kg	27.97g/unit
Grinding Rework	72.40kg	0.80kg	1.17g/unit
Turning	49.52kg	1.30kg	102.24g/unit
Laser Marking	49.50kg	0.26kg	15.27g/unit
Flat Grinding	42.05kg	0.51kg	20.14g/unit
Wire Cut	26.00kg	1.30kg	38.98g/unit
Milling	6.89kg	2.30kg	617.25g/unit
Turn & Mill. & Screw …	5.46kg	0.78kg	315.16g/unit

The **Waste** dashboard (GRI 306: Waste) facilitates monitoring of waste generation by presenting data on waste generated, waste recycled, and waste disposal based on work orders, activities, products, and resources, utilizing stacked bar charts and OLAP for effective waste management.



GRI 306: Waste

An assessment of the **quantity**, **type**, and **quality** of waste generated by an organization provides a holistic overview of waste generation and its causes, which in turn can support the organization in identifying opportunities for waste prevention and for adopting **circularity measures**.

The total weight of waste generated, when contrasted with the weight of waste that the organization directs to **recovery** and **disposal**, can show the extent to which the organization manages its waste-related impacts.

Total Waste
20.74 kg

Waste to Recycle
2.20 kg

Waste to Landfill
18.54 kg

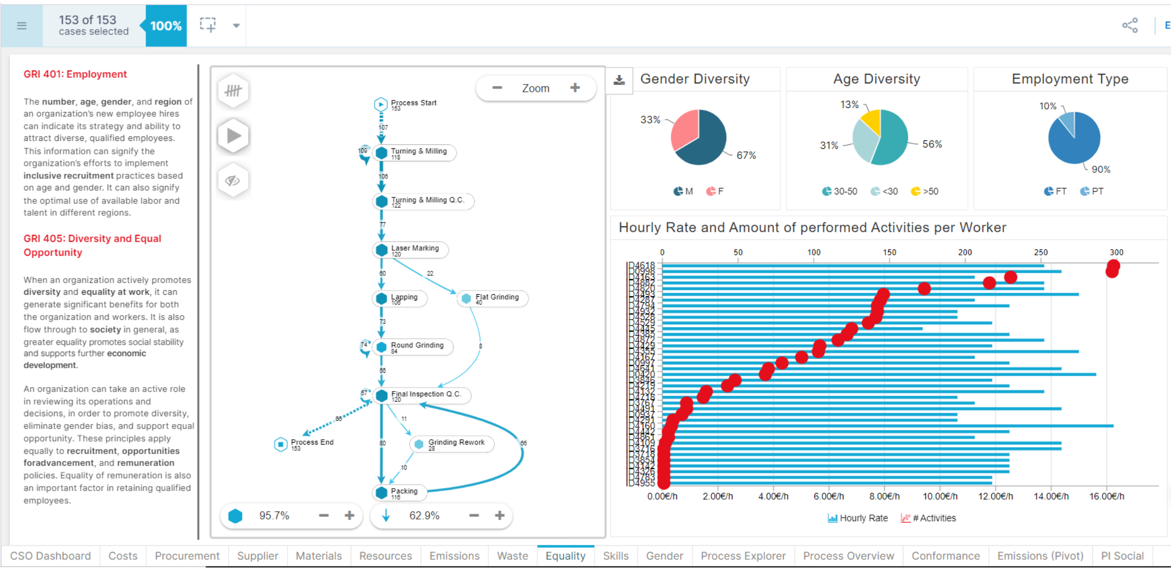
Waste to Recycle Rate
11%
Target: 100%

Total Waste by Product

Waste by Work Station

Work Station	Total Waste	To Recycle	To Landfill
Machine 6	7,316.72g	0.00g	7,316.72g
Machine 5	3,484.79g	0.00g	3,484.79g
Machine 4	2,995.59g	0.00g	2,995.59g
Packing	2,198.33g	2,198.33g	0.00g
Machine 8	2,117.02g	0.00g	2,117.02g
Machine 9	1,501.97g	0.00g	1,501.97g
Machine 10	1,109.62g	0.00g	1,109.62g
Machine 1	15.11g	0.00g	15.11g
Machine 2	0.08g	0.00g	0.08g

The **Equality** dashboard (GRI 401: Employment, GRI 405: Diversity and Equal Opportunity) aims to ensure fair and living wages for workers, prevent exploitation, and promote equitable treatment by providing insights based on gender, age group, employment type, and hourly wage using pie charts and line charts for wage analysis and single KPIs and pie charts for equitable treatment assessment.



GRI 401: Employment

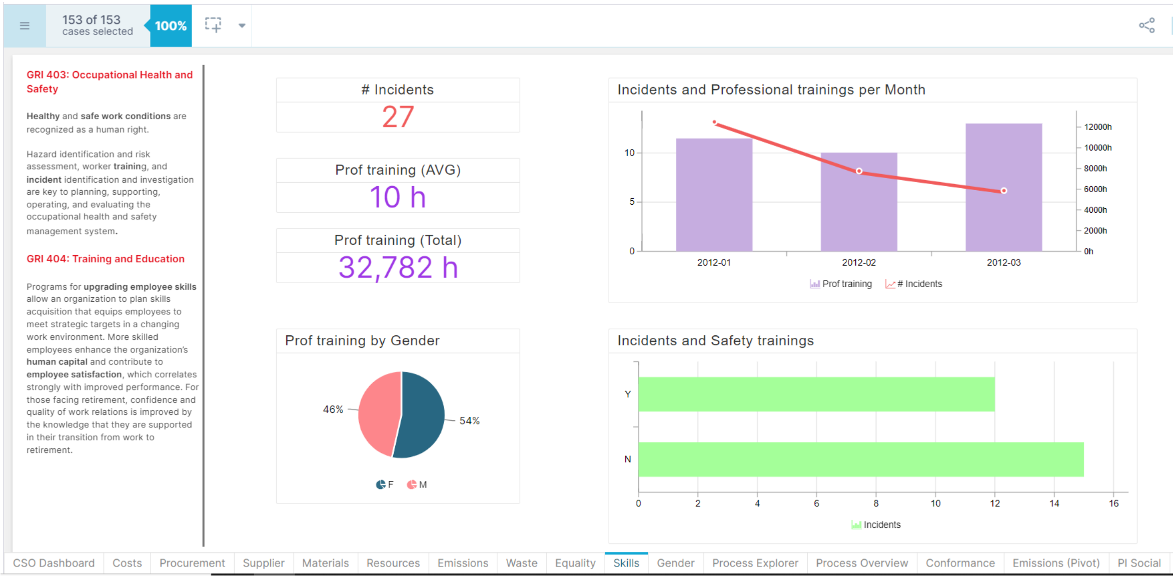
The **number**, **age**, **gender**, and **region** of an organization's new employee hires can indicate its strategy and ability to attract diverse, qualified employees. This information can signify the organization's efforts to implement **inclusive recruitment** practices based on age and gender. It can also signify the optimal use of available labor and talent in different regions.

GRI 405: Diversity and Equal Opportunity

When an organization actively promotes **diversity** and **equality at work**, it can generate significant benefits for both the organization and workers. It is also flow through to **society** in general, as greater equality promotes social stability and supports further **economic development**.

An organization can take an active role in reviewing its operations and decisions, in order to promote diversity, eliminate gender bias, and support equal opportunity. These principles apply equally to **recruitment**, **opportunities foradvancement**, and **remuneration** policies. Equality of remuneration is also an important factor in retaining qualified employees.

The **Skills** dashboard (GRI 403: Occupational Health and Safety, GRI 404: Training and Education) focuses on improving worker safety and reducing workplace accidents by analyzing data on the number of incidents and safety training, while enhancing workers' skills by tracking professional training hours and the ratio of trained workers using single KPIs, line charts, and pie charts for safety evaluation and skill development assessment.



GRI 403: Occupational Health and Safety

Healthy and **safe work conditions** are recognized as a human right.

Hazard identification and risk assessment, worker **training**, and **incident** identification and investigation are key to planning, supporting, operating, and evaluating the occupational health and safety management system.

GRI 404: Training and Education

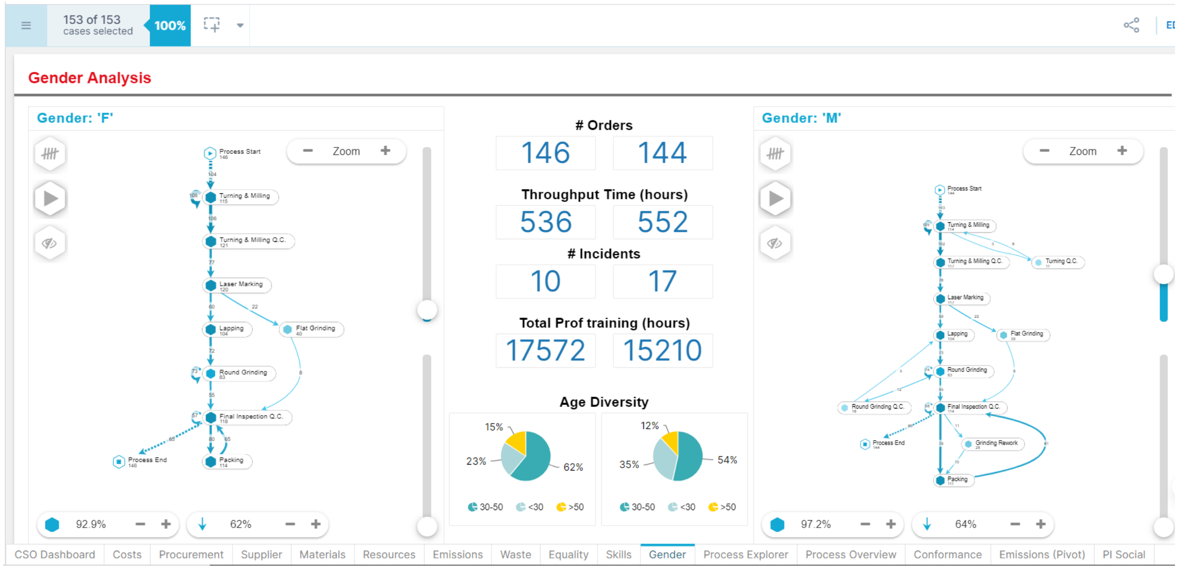
Programs for **upgrading employee skills** allow an organization to plan skills acquisition that equips employees to meet strategic targets in a changing work environment. More skilled employees enhance the organization's **human capital** and contribute to **employee satisfaction**, which correlates strongly with improved performance. For those facing retirement, confidence and quality of work relations is improved by the knowledge that they are supported in their transition from work to retirement.

Incidents
27

Prof training (AVG)
10 h

Prof training (Total)
32,782 h

The **Gender** dashboard (GRI 405: Diversity and Equal Opportunity) provides benchmarking view of the processes, where different genders involved, allowing for a clear comparison of number of incidents, professional training, and age group.



153 of 153 cases selected 100%

Gender Analysis

Gender: 'F'

Gender: 'M'

Orders: 146 | 144

Throughput Time (hours): 536 | 552

Incidents: 10 | 17

Total Prof training (hours): 17572 | 15210

Age Diversity