Process Mining Guidelines for Greenhouse Gas Emission Management in Production Processes

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Abstract. Despite the urgent need for becoming more sustainable and enhancing sustainability reporting induced by, e.g., the Corporate Sustainability Reporting Directive effective from January 2024, there exists a lack in research and industry efforts for integrating sustainability metrics into business processes. One particular reporting requirement entails that large EU companies must disclose their sustainability metrics for greenhouse gas (GHG) emissions across their supply chains. To address this challenging task, this paper presents the Process Mining Guidelines for Greenhouse Gas Emission Management (PMG3), helping companies implement process mining to meet GHG emissions targets in production processes. Thereby, the PMG3 provides detailed steps for defining business and data requirements, analyzing inefficiencies, and formulating recommendations to enhance sustainability reporting. To validate PMG3, a detailed demonstration was conducted using real-world data from a business case in the production process within the consumer goods industry. The utility evaluation revealed high approval for the PMG3's usefulness, ease of use, and practitioners' intention to use it in industry settings. Overall, this paper contributes a structured and applied approach for organizations to report GHG emissions and improve sustainability performance through process mining.

Keywords: green business process management, process mining, sustainability, production processes, design science research

1 Introduction

With the United Nations' 2030 Agenda for Sustainable Development and the European Green Deal aiming for climate neutrality by 2050, businesses are increasingly responsible for minimizing environmental impact [1]. Goal 12 encourages large companies to include sustainability indicators in their reports [2]. The Corporate Sustainability Reporting Directive (CSRD) takes effect in 2024, requiring large or publicly listed EU-based companies to apply new rules for environmental and social sustainability reporting [3]. Reporting must cover the entire value chain, including partners and suppliers, making tracking sustainability metrics, including CO_2e emissions, a high priority. As such, organizations face increasing reporting requirements, adopting IT-based business process management solutions to enhance sustainability performance. Double materiality, a concept in sustainability reporting, recognizes the broader impact of an organization's actions on the economy, society, and environment [4].

In the EU, the manufacturing sector accounts for roughly 35% of total GHG emissions [5]. GHG emission scopes include Scope 1 (direct emissions from company-owned sources), Scope 2 (indirect emissions from purchased energy), and Scope 3 (all other indirect emissions in the value chain). The three-scope classification is the official classification defined by the GHG Protocol [6]. In light of the CSRD, companies must report on emissions originating from their entire value chain, including production processes that generate emissions of various scopes (Scope 1 and Scope 3). Due to Scope 3 emissions being indirect emissions, their calculation is less straightforward. Recent emission reduction efforts in the manufacturing sector led to a decrease in value-added due to high start-up costs of emission reduction initiatives, lack of innovation, and low digital maturity [5]. This indicates challenges in developing and adopting economically efficient environmental sustainability practices in this sector. In the first stages of adopting sustainability practices, such an effect is not unexpected. In line with the devil's pentagon [7], an extension of the devil's quadrangle [8], improvements to the sustainability of processes can come at the cost of the other dimensions – time, flexibility, cost, and quality. In the long run, due to lower operating costs, emission reduction initiatives should turn out to be cost-effective [9].

Sustainability metrics are rarely tracked along business processes [10], posing a problem as the CSRD requires large companies to report on sustainability metrics starting January 1, 2024. The lack of consistent guidelines and industry-specific reporting standards complicates tracking and quantifying sustainability KPIs. Process mining techniques can provide solutions for measuring sustainability KPIs of business processes by achieving full process transparency [11]. Traditional process mining offers transparency into process flow rather than material flow, making it difficult to determine materials' contribution to the carbon footprint of products [12].

Accordingly, the research objective of this study is to *provide guidelines for organizations to implement process mining for GHG emissions goals reporting and improvement in production processes*. To achieve the research objective, a set of Process Mining Guidelines for GHG management (PMG3) is developed following design science research. PMG3 is applied in a business case to demonstrate its applicability in real-life business settings and evaluated for its validity and utility through interviews and focus groups. The result is a set of guidelines for implementing process mining projects for sustainability, particularly GHG reporting in production processes.

2 Related Work on Process Mining and Sustainability

Applying process mining techniques for sustainability is part of the broader research area of Green Business Process Management (Green BPM). Green BPM is a multidisciplinary field that integrates BPM principles with environmental sustainability considerations. Its focus is optimizing business processes in an environmentally responsible manner. The priority is the design, analysis, and improvement of business processes while minimizing their environmental impact, such as reducing resource consumption, waste generation, and carbon emissions [13]. Green BPM strives to strike a harmonious equilibrium between operational efficiency and sustainability goals, ensuring that businesses conduct their operations in an environmentally conscious manner. Recent studies show that a process-oriented strategy allows organizations to enhance their sustainability performance throughout all their operations rather than a narrow focus on the sustainability of end products and services [14].

One existing framework, PM4S, utilizes an object-centric approach to process mining, focusing on individual objects throughout the production cycle. Object-centric event logs enrich data on both the event and object levels, enabling use cases such as waste reduction and emission control. However, PM4S has not been tested in real-world scenarios, leaving its practical applicability unproven. Additionally, it highlights gaps in integrating sustainability with process mining, particularly in data enrichment and compliance checking [12]. The framework by Ortmeier et al. [15] integrates Process Mining Project Methodology (PM2) with Life Cycle Assessment (LCA), as defined by ISO 14044:2006, which evaluates the environmental impact of a product throughout its life cycle [16]. The framework proposes an iterative process for continuous hotspot analysis, while data availability challenges limit its real-life application [15].

To summarize, we observe two studies in the literature that provide methods and techniques for using process mining for sustainability purposes. Both frameworks recognize data availability and quality issues but lack comprehensive guidelines for addressing these issues. This study aims to provide guidelines for implementing process mining for sustainability in production and address related data availability and quality issues by demonstrating the applicability of the guidelines in real-life business settings.

3 Research Design

In developing PMG3, we followed the Design Science Research (DSR) methodology [17], adopting the DSR process by Peffers et al. [18]. The process depicted in Fig. 1 presents the research design that we followed. Accordingly, we identified the problem and defined our motivation, as we presented in Section 1. In the following sections, we describe the remaining research steps we followed.

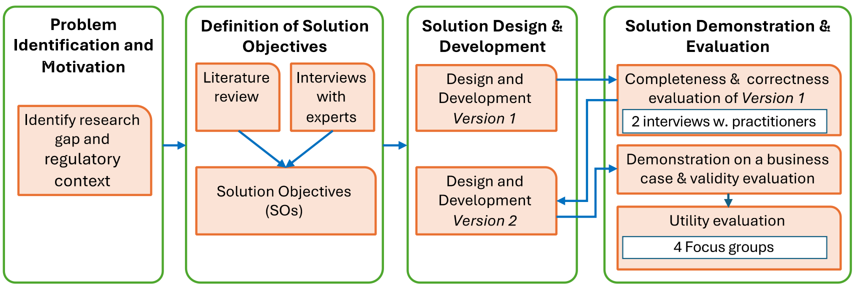

Fig. 1. Research design process.

3.1 Definition of Solution Objectives

The goal of this research step is to identify the objectives for an admissible solution (i.e., PMG3), which acts as the reference for the solution's validity [17]. To this end, we first reviewed the relevant literature on process mining methodologies and guidelines (e.g., [10], [11], [12], [15], [19]) as well as the regulatory aspects in the sustainability context. Due to limited existing research (as discussed in Sec.2), we also performed interviews with two practitioners to gain insights into the success factors and challenges in the industry and the requirements for practical guidance to address them.

We interviewed two experts from different companies operating in the process mining industry. Both experts had over 4 years of experience in process mining consultancy and services, one acting as the 'sustainability lead' in the last 3 years, in charge of managing process mining implementation teams. The semi-structured interviews (recorded and transcribed) involved topics related to opportunity identification, methodologies, challenges, data availability and quality, continuous improvement, risk management, and process mining success factors. The first interview aimed at addressing the aforementioned topics in relation to the manufacturing and production processes, while the second interview focused on the same topics applied to sustainability goals.

Both experts confirmed the relevance of using process mining for sustainability reporting of production processes, particularly the ability of process mining techniques to improve process transparency and uncover hidden inefficiencies. Key challenges in process mining implementation were reported as data availability and quality. Business information systems like ERP and SCM are not designed for tracking sustainability metrics, resulting in fragmented or missing data, especially when combined with machine and sensor data. When available, machine and sensor data is relevant for tracking sustainability metrics, including GHG emissions, as the machines used in manufacturing can monitor not only parameters directly relevant for tracking emissions (e.g., chemical reactions) but also other parameters that can be used as contextual data to enhance the quality of the analysis (e.g., operating temperatures, fuel consumption). Manual input errors and system failures further compromise data quality. Both experts suggested using APIs to integrate external sustainability data, linking various data sources, and enabling change logs to address data challenges. Change logs are event logs that track changes made to the data. When not explicitly logged as activities in the IT systems, change logs serve to signal changes in object attributes (e.g., quantities), crucial for enhancing the quality of the data and of the analysis. Both interviews emphasized the role of process mining in continuous improvement beyond reporting.

Expert 2 noted the risks in process mining for sustainability, mainly related to data quality, which can affect reporting accuracy. Diverse experiences for resistance to the use of process mining were noted. Expert 1 reported resistance from IT departments due to challenges to the status quo and security concerns. Expert 2 noted some resistance and acknowledged that financial goals often precede sustainability goals due to stricter financial reporting guidelines. Based on our literature review and expert interviews, we defined the following solution objectives (SOs) for PMG3:

- SO1 PMG3 should give guidelines to address data availability, quality, and awareness challenges.
- SO2 … align with existing technology and security infrastructure of the organization.
- SO3 … support the integration of various systems and data sources.
- SO4 … be understandable and transparent for the user in terms of design and logic.
- SO5 …support sustainability domain experts in sustainability improvement decision-making processes.
- SO6 …support managerial involvement through feedback, decision-making, and project management
- SO7 …serve to identify carbon emissions throughout the target processes.

3.2 Solution Design & Development

Based on the solution objectives (Sec. 3.1), the first version (Version 1) of the guidelines was designed taking the existing research frameworks (e.g., the process mining project implementation process of [20]) as a basis. Following the evaluation of the first version for its completeness and correctness regarding its content and structure, the final version of the artifact (Version 2) was developed. The final version consists of a number of subprocesses for each step (represented using BPMN) and detailed guidelines for inputs and outputs. Various frameworks, concepts, and classifications (e.g., PPTI framework [21] and GHG emission scopes) have been incorporated to enhance the applicability and utility of the guidelines.

3.3 Solution Demonstration & Evaluation

The objective of this research step was to showcase the application of the artifact and evaluate it for its validity and utility [17], focusing on ex-post (post-design) evaluation [22]. The initial version (ver.1) was evaluated through unstructured interviews with process mining practitioners to refine its structure. Further evaluations of the final version, aligned with DSR guidelines, assessed the artifact's validity and utility through a business case demonstrating its applicability in reporting and tracking GHG emissions. Validity was measured by benchmarking outcomes against predefined objectives, while utility, emphasizing practical benefits, was assessed using the core constructs of the Technology Acceptance Model (TAM) [23], i.e., usefulness, ease-of-use, and target user's intention to use the guidelines. Participants' feedback on additional resources or adjustments needed for ease of use and integration was also collected through a 7-point Likert scale survey questions. The results are presented in Section 5.

4 PMG3: Description & Demonstration

The PMG3 includes a set of steps, each consisting of a subprocess and detailed guidelines for inputs and outputs. The final artifact's description shows how its steps address the solution objectives (SOs). Table 1 presents an overview of the main steps. While these steps are presented in sequence, the process is iterative. A detailed description of the artifact and a demonstration of its applicability can be found in the online Appendix (https://drive.google.com/drive/folders/1YsxzyavURN5IwoT4EIqE5-c6jTRae2Zu).

We demonstrate the application of the PMG3 using a business case in the consumer products industry using synthetic data. The datasets were created based on an anonymized data model used for Bill of Materials (BoM) explosions, preserving the structure of the data model (datasets, columns, and logical relationships) while using the U.S. Lifecycle Inventory database [24] to construct BoM alternatives. The business case aims to compare emissions for different BoM alternatives (ALT1 and ALT2 of product X) to inform future product composition decisions. Since the source database lacks product alternatives, some components and quantities were constructed to complete the comparison. While this approach involves some artificial data creation, it effectively demonstrates the artifact's applicability in guiding emission-related decision-making and showcasing how issues regarding data availability can be dealt with.

Table 1. Overview of PMG3 core process steps.

Step	*Output*	*Involved Org. Roles*	*Tools/Resources*
Step 1. Define business requirements	Business requirements	Process expert, project manager	
Step 2. Define data prerequisites/ requirements	Data requirements	Implementation expert, project manager, sustainability expert	
Step 3. Perform data pooling	Carbon-enriched event logs	Implementation expert, sustainability expert	Data sources, data pool
Step 4. Visualize target relationship	Process model/ visualization	Implementation expert	Visualization tool/ dashboard
Step 5. Analyze results & formulate recommendations	Result analysis, Recommendations	Implementation expert, project manager, sustainability expert	Visualization tool/ dashboard

In Step 1, the business requirements are defined using the Pearson framework, focusing on key dimensions, such as people, processes, technology, and information. The project goal, target process, and sustainability metrics are established, followed by decisions on tracking levels, emission scopes, KPIs, and reporting frequency. Table 2 presents the sub-steps for this step. This step also aims to address SO1-3 (Sec. 3.1).

For the business case on which we applied our model, the goal was to compare CO_2e emissions of two product alternatives (ALT1 and ALT2) within the production process. CO_2e emissions were selected as the sustainability metric, with tracking at the *object level*. Emission scopes included *Scope 1* and *Scope 3.* Scope 2 emissions are also relevant, but are omitted in the absence of data... Resources included a project manager, an implementation, and a sustainability expert.

Table 2. Sub-steps of Step 1. Define business requirements.

Sub-steps of Step 1	*Ouput*	*Involved Org. Roles*
Set project goal	Project goal	Project mng., sustainability expert
Determine target process	Target process	Project manager
Determine sustainability metric	Sustainability metric	Sustainability expert
Determine tracking level	Tracking level	Sustainability expert, project mng.
Determine GHG emission scope	Emission scope	Sustainability expert
Determine KPIs & exp. outcomes	KPIs, Expected outcomes	Project mng., sustainability expert
Determine reporting frequency	Reporting frequency	Sustainability expert
Determine required resources	Resources	Project manager
Determine tasks	Tasks	Project manager
Determine involved business units	Business units, data sources	Project manager
Determine infrastr. requirements	Infrastructure requirements	Project manager

Step 2 involves determining the data fields required for analysis, including process, contextual, and sustainability metrics. Data availability is checked internally, with external sources used if necessary. Quality standards are set, and data is enhanced and validated to meet these standards. Fig. 2 presents a process model (in BPMN) for the sub-steps of Step 2 (more details are available in the online Appendix.)

In the business case, process and contextual data were available internally, while GHG emissions data was sourced externally from databases such as CBAM (https://shorturl.at/PPvCI), GHG (https://shorturl.at/KNn1t), and Climate Trace (https://climatetrace.org/data). The data was then prepared for pooling.

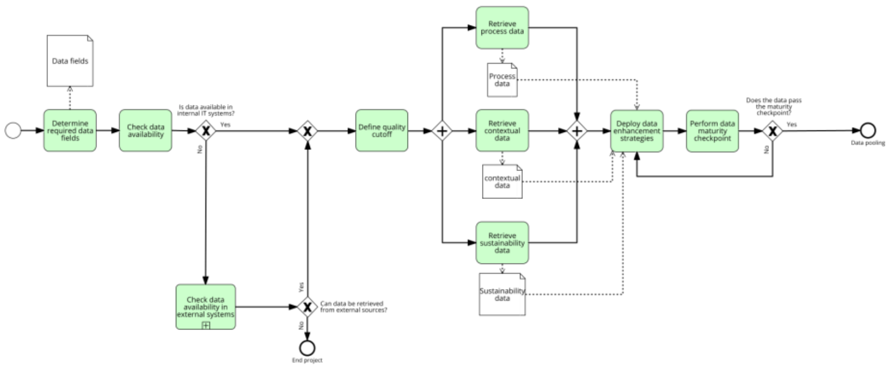

Fig. 2. Process model for the sub-steps of Step 2.

During Step 3, the retrieved data is integrated to form carbon-enriched event logs. These logs are the fundamental data structure for PMG3 and are achieved by mapping the sustainability metric to the process data. They are event logs with an additional event attribute (carbon emissions quantified per event or object). The data flow diagram representing the creation of the carbon-enriched event logs of the data pooling step is represented in Fig. 3. The data is mapped to the appropriate tracking level and adjusted for contextual factors like material weight. This forms the foundation for the analysis. In the business case, the emission factors were mapped to product subcomponents at the object level, ensuring accurate CO_2e calculations. Despite the absence of activity-level emissions data, the approach provided a comprehensive view of the emissions for each product alternative.

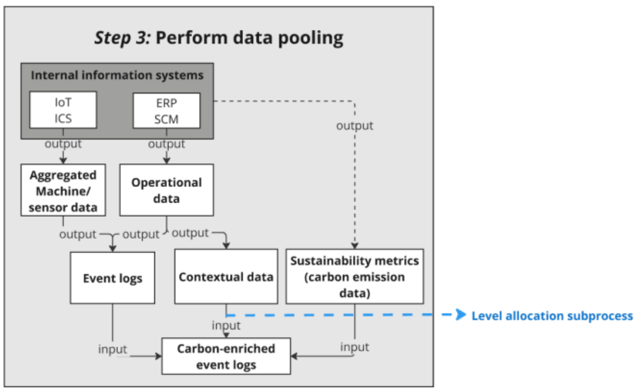

Fig. 3. Data flow of retrieved and pooled data.

In Step 4, relationships between events, objects, and activities related to GHG emissions are visually represented. This helps in understanding material flows, identifying emissions hotspots, and comparing process variants. In the business case, the visualizations were created using Celonis EMS to represent the object-to-object relationships for the two product alternatives, providing insights into which materials contributed most to overall emissions. Fig. 4 presents the final output for both alternatives.

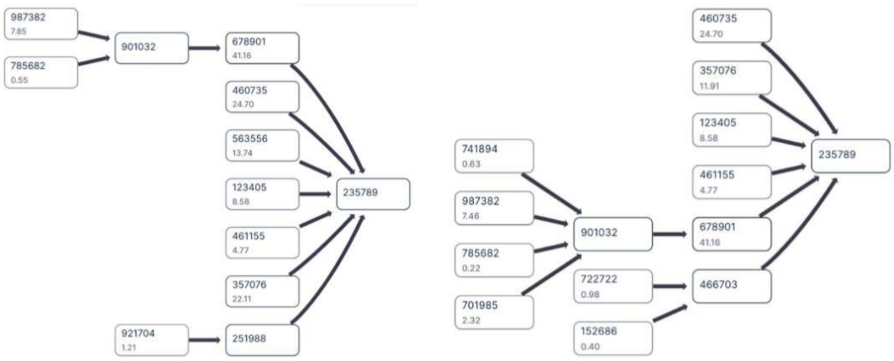

Fig. 4. Network representation of the BoM explosion of the product alternatives (up: material number, down: emissions (CO_2e kg/ kg of material)): ALT1 (left), ALT2 (right).

Aiming to address SO5-6 (Sec. 3.1), Step 5 involves analyzing the pooled data to identify inefficiencies and improvement areas. Process discrepancies and KPI inefficiencies are examined, and recommendations are formulated to improve the process. In the business case, CO_2e emissions for the two product alternatives were calculated, revealing opportunities for improvement, such as reducing component weights and improving waste management. These recommendations were prioritized based on their potential impact on emissions reduction to help address SO7.

5 Evaluation

5.1 Evaluation of Version 1

The evaluation of the first version of PMG3 was conducted through two unstructured interviews with practitioners who were target users of the guidelines, aiming to assess completeness. The first interviewee had 9 years of experience as aaa process improvement manager, and the second interviewee had 3 years of experience as a process intelligence consultant. Subprocesses as a part of the guidelines (detailed in the online Appendix were not yet included and were added following this initial evaluation. Interviewees advised differentiating business and data requirements by type, such as infrastructure and resources, in Steps 1 and 2, and suggested using a sequential representation for defining data maturity requirements. They also recommended providing detailed guidelines for sustainability-specific concepts throughout these steps. Additionally, for Steps 2 and 3, they emphasized the importance of focusing on specific requirements and guidelines for retrieving sustainability data. For Step 3, they advised adopting a sequential approach for selecting and retrieving sustainability data sources.

5.2 Evaluation of the Final Version

The final version was evaluated for its utility through four focus groups (FGs), which included process mining and improvement experts of varying expertise. (FG 1 involved three experts with 1 to 5 years of experience in process mining, FG 2-4 involved three experts with 1 to 3 years of experience in process mining, and one project manager with

4 years of experience. The expertise was assessed through tenure, field experience, and job title, while interest in sustainability was gauged via a pre-focus group survey. Each session began with a walk-through of the main process of the guidelines and specific subprocesses based on participants' interests and qualifications. Questions were asked regarding the method's completeness, ease of understanding, and necessary modifications for adoption. Two focus groups (FG1 and FG3) focused on Steps 1, 2, and 3 of the guidelines, with FG1 also evaluating guidelines for GHG data requirements in detail. FG2 reviewed Steps 1, 2, and 5, and FG4 focused on Steps 3, 4, and 5.

After the focus groups, we asked practitioners to provide a more structured view of the utility of the guidelines through a questionnaire involving the core constructs of the Technology Acceptance Model (TAM) [20]. Accordingly, the questionnaire assessed practitioners' perceived usefulness, ease of use, and intention to use the guidelines. Statements in the questionnaire were crafted based on the extended TAM questionnaire [25] (Table 3). Respondents rated the statements on a 7-point Likert scale, with 1 being 'Completely disagree' and 7 being 'Completely agree'. **Table 4** presents the survey results, including the distribution of ratings, average scores, and standard deviations.

Table 3. Statements in the Questionnaire.

Perceived usefulness	1. I think this method supports a more efficient and effective implementation of Process Mining techniques for sustainability/ GHG emission (reporting) goals? 2. The way this method shows how to conduct a Process Mining for sustainability/ GHG emission (reporting) goals would be difficult for users to understand. (*) 3. Using this approach would make it more difficult to communicate how Process Mining implementation techniques can help organizations achieve sustainability/ GHG emission (reporting) goals. (*) 4. Overall, I find this process useful.
Perceived ease of use	5. Learning to use this method would be easy for me. 6. I found the method unclear and difficult to understand. (*) 7. It would be easy for me to become skillful at using this method. 8. Overall, I find this method difficult to use. (*)
Intention to use	9. I would use this approach to implement a PM project for sustainability/ GHG emission goals. 10. I would intend to use this approach in preference to another approach.

** Reversed questions, marked with an asterisk* had their scores adjusted to mitigate response bias.*

With average scores above 5 for all *Perceived Usefulness* questions, respondents generally find the guidelines beneficial, though two noted some difficulty in understanding them. The method's structured, step-by-step guidance is particularly appreciated by those new to sustainability data, while even experienced experts found it helpful for decision-making on data sources and validation. However, additional sustainability training was suggested despite the guidelines being perceived as flexible.

Perceived Ease of Use received lower scores, though still positive. Two respondents found the artifact challenging, primarily due to difficulties in understanding sustainability concepts, which one attributed to a lack of process or industry-specific knowledge. Respondents recommended more detailed documentation and sustainability training to improve ease of use. Despite these issues, the level of detail in the subprocess steps, as illustrated by BPMN, was considered appropriate.

Table 4. Questionnaire results: # of respondents per rating and rating statistics per question (r).

	Ques.	*Completely disagree ←→ Completely agree*							*Avg*	*Std.Dev.*
Perceived usefulness	1	0	0	0	0	3	9	5	6.1	0.70
	2 (*)	1	8	4	2	1	1	0	5.2	1.29
	3 (*)	3	11	1	2	0	0	0	5.9	0.86
	4	0	0	0	0	4	5	8	6.2	0.83
Perceived ease of use	5	0	0	1	3	6	6	1	4.2	1.00
	6 (*)	4	8	2	2	1	0	0	4.7	1.20
	7	0	0	1	1	7	4	4	4.7	1.10
	8 (*)	2	8	5	0	0	1	1	4.3	1.60
Intention to use	9	0	0	0	0	6	6	5	5.9	0.83
	10	0	0	0	3	6	7	1	5.4	0.86

The *Intention to Use* the guidelines is relatively high, but adoption challenges include costs and the framework's complexity. While the detailed guidelines enhance usefulness, they can increase implementation costs, particularly for IT systems for sustainability metrics and API licenses. Despite these barriers, the guidelines align with sustainability strategies and are expected to integrate well with current methods.

The evaluation shows that PMG3 is generally considered useful, with interest in adopting the guidelines. However, ease of use (EoU) received lower and varied scores, likely due to differences in seniority, technical skills, and sustainability knowledge. The need for clearer instructions on selecting emission factor databases and additional sustainability training was noted. Data validation challenges, especially when mapping internal data to third-party emission factors, highlight the importance of basic sustainability knowledge. Challenges in adopting the guidelines align with findings from the literature review, particularly regarding data availability and ERP systems' capacity to store sustainability data. Respondents also stressed the need for strategic alignment, as financial goals often overshadow sustainability objectives.

6 Conclusion

Despite growing interest in Green BPM, the use of process mining for sustainability and carbon accounting is underexplored. Process mining typically focuses on financial goals and lacks real-life applicability for sustainability. Frameworks like PM4S introduce OCPM for tracking GHG emissions, energy consumption, and waste but struggle with data availability and quality issues [1]. To address these gaps, we developed guidelines following design science research, focusing on GHG emissions in response to evolving sustainability regulations like the CSRD. Our literature review and exploratory interviews identified key challenges—such as data availability and process complexity—and success factors like system integration and management support. These insights shaped the development of the objectives of the solution and its design.

The guidelines consist of five steps essential for successful implementation. A business case comparing CO_2e emissions of two product alternatives demonstrated the need for contextual data, such as waste and inventory data, for effective decision-making. Evaluation through focus groups and surveys confirmed the guidelines' utility and ease of use, though challenges remain, particularly in data maturity and strategic alignment. This research contributes by developing and demonstrating the applicability of guidelines for process mining projects focused on GHG emissions. These guidelines provide detailed instructions for data requirements definition, process data retrieval, contextual data enrichment, and analysis. The artifact supports process mining practitioners in implementing sustainability projects, addressing data challenges, and ensuring accurate reporting. The demonstrated application in a business case adds to previous research by proving the guidelines' practical utility. Moreover, the research offers concrete examples of measuring and calculating sustainability KPIs, expanding process mining techniques to sustainability use cases, and aiding practitioners in meeting emerging legal requirements for sustainability reporting. Further research is needed to refine team roles, skills, and organizational attributes necessary for successful sustainable development projects using process mining. Our research extends prior frameworks like [12] and [15], which lacked real-life testing, by providing evaluated guidelines demonstrated in GHG emission projects. The artifact addresses data quality challenges through comprehensive data pooling guidelines and is structured around a five-step process: defining business and data requirements, data pooling, process model mapping, and result analysis to formulate recommendations.

This research has limitations related to both the artifact and the research design. While the artifact generally applies to various processes, it does not fully develop the object-centric perspective, which is important for accurate sustainability reporting. Future research could enhance the guidelines by integrating OCPM techniques for a more comprehensive implementation. The business case's narrow geographical and industry focus limits the generalizability of the findings. Although the geographical scope aligns with European CSRD coverage, further research is needed to test the guidelines in other industries, particularly highly regulated ones like pharmaceuticals. Additionally, the artifact has not addressed the complexities of emissions tracking in service industries. The empirical nature of the study, with focus groups, interviews, and surveys involving only 17 respondents from the same organization, also presents limitations. The small sample size and the homogeneity in tenure of the respondents restrict the diversity of insights. Future studies should expand to multiple organizations and include more senior practitioners to provide a broader validation of the findings.

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