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ReThink Your Processes! A Review of Process Mining for Sustainability

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***Abstract*—The transition towards more sustainable practices requires companies to assess their impact on the social and ecological environment and establish new processes in complex inter-organisational systems. Process mining is a collection of data-driven techniques to visualise, analyse and improve business processes. Its potential to increase sustainable business processes has been acknowledged by academia and industry but not systematically reviewed. This work analyses process mining's application for sustainability by conducting two consecutive literature studies – the first on the broad domain of sustainability, and the second on the circular economy, a widely accepted approach for pursuing sustainability. Results show the potential of process mining for assessing and analysing sustainability in business processes, allowing for data-driven decision support and targeted improvement. They also show that process mining has yet to reach the sustainability domain. To enable collaboration between both communities, we present PM4S, a framework for applying process mining for sustainability.**

***Index Terms*—process mining, sustainability, systematic literature review**

I. Introduction

Every year, tonnes of waste are created, an increasing amount of emissions are released into the atmosphere, and the global distribution of wealth and health becomes increasingly unbalanced [25]. These practices impact future generations' quality of life [47] – for example, by exploiting scarce resources and creating a climate crisis. With the United Nations' 2030 Agenda, the global society agreed to strive for sustainable development (SD) [69]. In 2016, industrial processes and transportation were responsible for 45.6% of global emissions [61] and, therefore, strongly affect the success or failure of SD [44]. To eliminate this tremendous impact, organisations must realign their business models [6], supply chains (SC) [23] and organisational practices [25].

Business Processes (BP) form the "arterial systems" of organisations [12], thereby being the critical element of its contribution to SD [66]. Business process management (BPM) must, therefore, incorporate sustainable objectives. As BPM substantially impacts industrial operations, an increasing amount of research is put into "Green BPM" [30]. However, BPM's contribution so far is mainly of conceptual and qualitative nature [20]. To provide more concrete and scalable support for more sustainable BP, this work evaluates how process mining (PM), the quantitative branch of BPM, can contribute to SD. PM is a relatively new discipline considered to *X-ray business processes* [70]. PM uses the data logged by IT systems when used in a business's day-to-day life to identify and visualise the relationship between the different activities [71]. The resulting *process model* is then used to analyse and identify the potential for improvement in the BP. PM techniques enable the automated identification of deviations from a benchmark process and extensive process analysis under the consideration of additional business data [74]. As PM offers a holistic view of as-is end-to-end processes, it has received increasing attention in academia [22] and industry [21] to support processes in a variety of domains, such as healthcare, manufacturing and financial auditing.

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In related work, scientists and practitioners have already noted PM's potential to drive sustainability. PM's potential as an auxiliary technique to support carbon accounting was assessed in [7], and the application of PM has been recognised as a technique supporting the assessment of a product's impact on its environment [20], [50]. Additionally, [59] provides an overview of the status and future of PM, naming sustainability as an essential domain PM can contribute to, by supporting the efficient utilisation of scarce resources. PM software vendors have started considering the impact of PM on sustainability and begun integrating SD perspectives into their tools [5], [56]. Celonis, one of the leading PM tools according to Gartner [34], has cooperated with a provider of emission data to integrate the consideration of emissions into their tools and applications [78].

In general, PM's potential contribution to SD is considered broad – from supporting the assessment of the sustainability of business practices to actually contributing by automating activities. Although the potential of PM for SD has been recognised, its potential has only been analysed for selected elements, such as impact assessment and emissions. Neither academia nor industry considers the full potential of state-of-the-art PM techniques, limiting consideration to process discovery and conformance checking and only focusing on PM for individual processes instead of process networks.

In the past, PM techniques have proven highly beneficial to objectives such as the reduction of cost, an improved understanding of end-to-end processes and an increase in overall performance [59]. In this work, we discuss the application of

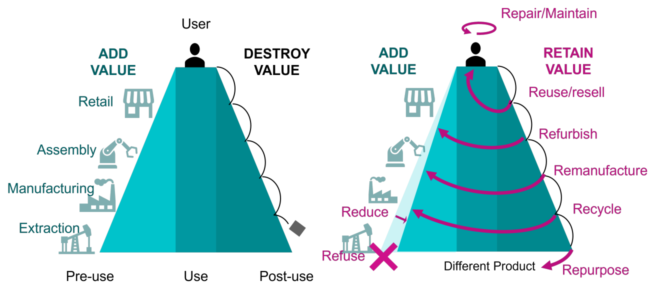

Fig. 1: Principle of the circular economy (based on [2]), linear economy (left) and CE (right).

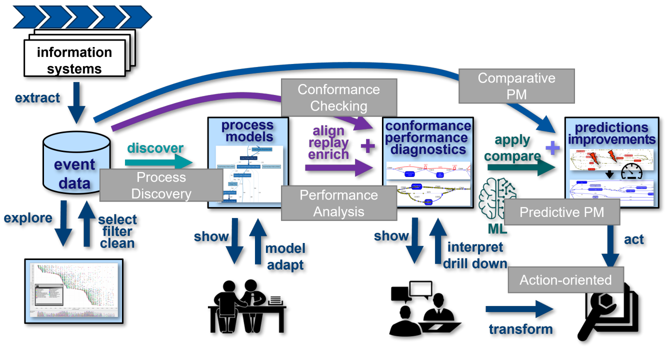

Fig. 2: Frequent types of process mining [74].

PM techniques to SD and investigate the following research questions: (RQ1) How can PM contribute to driving SD? (RQ2) How must PM be applied to be most beneficial for SD? (RQ3) What further research is required to make PM techniques more effective in driving SD?

The remainder of this work is structured as follows: We introduce SD, the circular economy (CE) and PM in Section II. In Section IV, PM's connection to the broad domain of SD is assessed and discussed with a systematic literature review (SLR-1) [37]. Based on the findings of SLR-1, we conduct a second review (SLR-2) to analyse the application of PM to the targeted and process-related field of the CE in Section V. Finally, we create a framework for applying PM for sustainability (PM4S) in Section VI. Section VII concludes this work.

II. Background

To ensure a common understanding for all that follows, we provide some background information on SD, the CE and PM.

A. Sustainable Development

The term *sustainable development* was coined in 1987 as economic growth through "development that meets the needs of the present without compromising the ability of the future generations to meet their own needs" [47]. It is commonly agreed [55] that SD encompasses three *pillars*: economic prosperity, social equity, and environmental quality [14]. Economic prosperity focuses on the increase of performance and the strengthening of markets, and social equity deals with the increase of human well-being and the development and strengthening of societies [35]. The regeneration of nature, the circulation of products and materials, and the elimination of waste and pollution increase environmental quality [15].

B. Circular Economy

The circular economy (CE) is a widely accepted approach to pursue mainly environmental SD [27]. The underlying idea is to move away from the "end-of-life" concept, in which material is sourced, and value is added to create products which are then used and eventually disposed of. In the CE, processes support material and energy regeneration by creating material and energy loops [35]. The CE describes a "system in which resource input, waste, emission, and energy leakage are minimised by slowing, closing and narrowing material and energy loops" [24]. The principles of CE can be described by ten so-called R-imperatives [57], which address different phases of a product's life cycle [2], see Figure 1.

Before beginning a product's life cycle, there is the option to refuse (R0) using hazardous or virgin material. After raw materials are sourced, smart manufacturing and targeted material use [54] support the reduction (R1) of input resources, waste, emissions and energy leakage [25]. Material loops can be slowed by following strategies to extend product life [2]: While a product's value is still high, it can be reused (R2), maintained or repaired (R3). When functions remain intact, but minor components must be replaced, they can be refurbished (R4). Remanufacturing (R5) describes a process in which all defective parts are replaced. If the original added value cannot be restored, products and materials can be repurposed (R6) – used for something other than originally intended [57]. After all added value is depleted, material loops can be closed by retrieving end-of-life materials [54]. This involves recycling (R7), where the product completely loses its structure, so merely the material itself and none of the added value is reused [27] and the recovery (R8) of energy trapped in the product or material. Materials can also be re-mined (R9) from a landfill when new options for material usage are found [57]. Apart from designing products for long life and life extension [6], the transition to the circular economy requires the introduction and management of processes supporting these practices [77]. Additionally, circularity [10] and the environmental impact of existing processes [29] must be assessed. Life cycle assessment (LCA) is a standardised method of quantifying a product's or service's emissions, material consumption, impacts on health and the environment, and natural resource depletion issues throughout its life cycle [16]. Not only does the transition to the CE mean that products must be used as efficiently as possible [25], they must also be designed accordingly [6].

C. Process Mining

IT systems typically support business operations. These systems usually create an *event log* documenting every *event* that occurs. An event describes the execution of a specific activity at a certain point in time in connection to a certain *case*. For example, the activity "book incoming goods" executed at 2023-01-31 12:42 for the case "order 123-456" is an event. PM is a set of techniques that use these event logs to generate business intelligence and support the understanding, analysis and management of processes [71]. Figure 2 provides a conceptual overview of common types of PM as described in [74]. Process discovery comprises all PM techniques that are used to establish a connection between activities to generate an overview of BPs – a *process model*. These models are used as a basis for process analysis and process improvement. Using the process model and (enriched) event logs as input, processes are diagnosed in two ways. Conformance checking techniques identify and quantify the differences between an event log and a benchmark process model. They aim to show where the log and model disagree. Besides considering deviation between as-is and to-be, processes are diagnosed by applying performance analysis techniques. Performance analysis aims at uncovering problems within business processes by calculating performance indicators. These indicators help, for example, to uncover bottlenecks within a process. Process diagnostics support the assessment of processes and thereby enable data-driven decisions. Comparative PM uses event data and diagnostics from different procedures and detects differences and commonalities in their application in consideration of their outcomes. It helps uncover root causes and is a good tool for inter- and intra-organisational benchmarking. Predictive PM combines PM with machine learning (ML) techniques to answer forward-looking questions. It uses process data, diagnostics and additional (business) data to detect and analyse reoccurring anomalies in processes and enables the prediction and analysis of possible future scenarios and their impact. Action-oriented PM aims at automating actions based on process diagnostics of running processes. Apart from triggering activities according to business rules, Robotic Process Automation (RPA) is a technique in which repetitive, manual tasks are performed by a software that mimics a human clicking and entering data.

A relatively new area of PM is *object-centric* (OC) PM. Instead of considering a single case, OCPM allows the association of multiple *objects* to each event. Each object has a certain *object type*. Therefore, OCPM not only allows the analysis between activities but also considers the relationship between activities and different object types as well as between individual object types [73]. It uses an OC event log (OCEL) as input. The current OCEL standard, the common basis for OCPM techniques, assigns a single object type and attributes to each object. Every event is associated with an activity, event attributes and the objects related to its execution [17].

III. Methodology Literature Reviews

The application of PM techniques to SD is discussed based on the results of two SLRs performed after the framework of Kitchenham [37]. This section describes the methodology of these reviews, denoting the first review of PM in the broad context of SD as SLR-1, and the second specifically on PM and the CE as SLR-2. Attempting an exhaustive

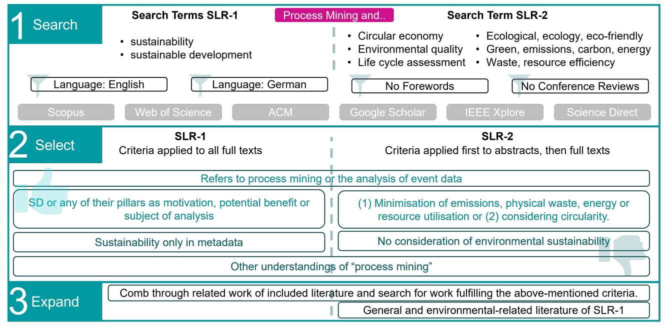

Fig. 3: Methodology of the two systematic literature reviews.

search of relevant work, the publication databases *Scopus, Web of Science, ACM Digital Library, IEEE Xplore, Science Direct* and *Google Scholar* were used. The search strings were applied to the title, and, where possible, to the abstract and keywords. Forewords and conference reviews were excluded, as well as any works without accessible full texts in English or German. The terms searched for can be found in Figure 3, where the methodology is depicted.

The search results were refined by applying the inclusion criteria to all 34 full texts in SLR-1 and the full texts of the publications remaining after abstract screening of the 120 search results of SLR-2. To be included, the publication was required to refer to the application of process mining or the analysis of event data in a manner described in Section II-C. So, any publications referring to the (qualitative) analysis of processes in the mining industry or using the term "process mining" in a different meaning were excluded. Additionally, addressing an increase in SD (SLR-1) or a contribution to the circular economy based on the definition presented in Section II-B (SLR-2) was required. Publications in which sustainability is merely mentioned in the metadata are also excluded. The details can be taken from Figure 3. Due to the few relevant search results found (14 each), no additional criteria that might reduce the number of findings were applied.

Attempting to add unidentified publications, the inclusion and exclusion criteria were applied to the references mentioned in the related work sections. All publications associated with environmental quality identified in SLR-1 were added to the analysis of SLR-2. Unfortunately, this did not increase the number of publications for SLR-1 and resulted in a final count of 22 publications for SLR-2.

Based on the understanding of SD and the CE presented in Section II, the addressed pillar and topic of sustainability are determined for each identified publication. We also distinguish whether SD is referred to directly or indirectly, e.g. by being mentioned as a potential benefit or motivation. Additionally, we categorise the publications as a publication describing a methodology (M), a case study (CS), or a survey/position paper (S/P). For the analysis of the papers, we also considered their year of publication, the publication's objective, the involved process and industry, and the purpose the PM

TABLE I: Relevant Publications of SLR-1 and SLR-2

References, Pillar (general SD, economic, social, environmental), Year, Type of Publication (Methodology, Case Study, Survey/Position), Relationship to SD (Direct, Indirect), Industry the publication refers to ("Industry" if not specified but private sector approved), Type of process addressed, Topic, PM's contribution, SLR-1 top, SLR-2 all general and environmental

Ref	SLR	Pillar	Year	Type	D/I	Industry	Process	Objective	PM Contribution	SD Aspect
[53]	1	soc	2021	CS	D	Industry	Occupational Safety	PM to improve health and safety	Identify and analyse process, organisational connections, and deviations	Health and Safety
[79]	1	soc	2014	S/P	I	IT Security	Data Flow	Improve control and transparency for information exchange	Identify data flow	Welfare and Security
[52]	1	soc	2015	S/P	D	Educational Management	Core Processes	Enable sustainable universities	Identify and analyse process, organisational Connections and deviations from regulations	Education
[36]	1	eco	2010	CS	I	Manufacturing	Core Processes	Increase organisational flexibility	Identify process, analyse different process outcomes	Performance
[81]	1	eco	2019	CS	I	Maritime Transport	Information Processes	Efficient freight export	Monitor process, detect deviations, identify weaknesses	Performance
[28]	1	eco	2016	M	D	Industry	Core Processes	Strengthen competitive sustainability	Monitor and analyse process, identify inefficiencies	Markets, Performance
[38]	1,2	eco, env	2022	M, CS	I	Manufacturing	Material Flow	Identify constrained resources	Monitor process, detect deviations	Performance, Resources
[62]	1,2	eco, env	2012	M	I	Industry	Core Processes	Support business network management	Identify organisational connections (social network analysis)	Performance, Sourcing
[49]	1,2	gen	2015	M	D	Industry	Maintenance	Sustainable maintenance through semantic PM	Monitor and assess maintenance performance, identify abnormalities	Availability, Efficiency
[48]	1,2	gen	2018	M, CS	D	Industry	Core Processes	Holistic corporate sustainability	Identify directly follows relation of activities	Waste, Emissions, Material Input
[65]	1,2	gen	2020	M	D	not specified	not specified	Automated compliance checking to SD targets	Monitor processes, detect deviations	SD Compliance
[60]	1,2	gen	2021	S/P	I	Manufacturing	Material Flow	Relationship process mining and process automation	Monitor and analyse production, Support Automation	Efficiency
[31]	1,2	env	2021	M	D	Manufacturing	Material Flow	PM for sustainable value stream analysis	Identify process, assses indicators	LCA
[1]	1,2	env	2022	M, CS	D	Manufacturing	Material Flow	Identify energy efficient disassembly sequence	Identify process	Energy, Remanufacturing
[32]	2	env	2014	M, CS	I	Manufacturing	Core Processes	Agile operations management for green factory	Monitor processes	Energy, Efficiency
[51]	2	env	2018	M	I	Manufacturing	Material Flow	Flexible CPPS with optimised parameters	Identify sequences of control methods	Efficiency, Energy
[41]	2	env	2020	M	D	Industry	Maintenance	Feasibility of PM for machine health	Identify healthy machine behaviour, monitor conformance, support root cause analysis	Energy, Availability
[64]	2	env	2020		D	Manufacturing	Maintenance	Optimal maintenance windows	Identify directly follows relation of activities	Efficiency, Availability
[50]	2	env	2021	S/P	D	Industry	Material Flow	Framework for LCA using PM	Monitor processes, assess indicators	LCA
[11]	2	env	2021	CS	D	Energy Systems	Maintenance	PM for maintanance of wind turbines	Identify and analyse process, bottleneck detection, conformance to benchmarks	Sourcing, Efficiency, Availability
[46]	2	env	2021		D	Energy Systems	Application Process	Assessment of suggested process changes	Identify process, analyse performance	Sourcing, Efficiency
[7]	2	env	2022	S/P	D	Industry	Core processes	PM for carbon accounting	Identify process, assess CO2 emissions, check SD compliance, simulate changes, identify reduction potential	Carbon Emissions
[13]	2	env	2022	M, CS	D	Aggriculture	Crop Rotation	Identify sustainable crop rotation strategy	Identify directly follows relation of crops	GHG Emissions, Sourcing
[20]	2	env	2022	S/P	D	not specified	not specified	Sustainable BPM for LCA	Monitor processes, assess indicators, detect deviations, root cause analysis	LCA
[39]	1,2	env	2022		I	Manufacturing	Core Processes	Framework for intelligent process automation	Monitor process, identify bottlenecks, detect deviations, root cause analysis, RPA	Waste, Resources, Efficiency
[19]/ [18]	2	env	2022/21	M,CS	I	Manufacturing	Material Flow	Data-driven simulation for digital twins	Monitor process, check conformance	Energy, Efficiency
[63]	2	env	2017	M	D	Manufacturing	Maintenance	Optimal maintenance windows	Identify directly follows relation of activities	Availability, Efficiency

application serves. Table I enlists the identified publications.

IV. Process Mining and Sustainable Development

This section considers the application of PM in the broad context of SD. We first present the connections between PM and SD established in literature and subsequently discuss how PM has been beneficial in driving economic prosperity, social equity, and environmental quality.

The fourteen publications related to SLR-1 can be found at the top of Table I. Eight of them address SD directly. A case study and two positions address the social pillar by aiming to improve health and safety [53], education [52], and welfare and security [79]. Two publications address SD at the macro level (social and educational infrastructure). All three publications show applications of PM to identify and analyse processes in specific domains (industry or process). Two of them involve the organisational perspective.

Five publications mention applications of PM for economic prosperity by increasing performance or strengthening markets through competitive advantage. Only one directly addresses this connection to the economic pillar. Three include a case study to improve performance and name sustainability as potential or motivation. The fourth describes a framework for sustainable competitiveness [28], and the last uses organisational process mining to increase performance by analysing business connections [62]. PM techniques are applied to the main processes and are used to detect, investigate and monitor processes, thereby using continuous analysis.

Two publications address SD as a general concept, and two explicitly mention all three pillars of SD [48], [49]. All four were, therefore, not linked to a specific pillar of SD but assigned to a *general* category. Three of these general publication's topics directly address SD - one by creating a tool evaluating the compliance of processes to SD goals and regulations [65], one by calculating the sustainability of processes and detecting gaps to a pre-defined benchmark [48] another by enabling decisions concerning all pillars of SD in maintenance processes [49]. The potential for SD through an increase of process automation achieved by PM is seen in [60]. In all these publications, PM is applied to assess the current status and support business decisions for more sustainability.

Four publications belong to the environmental pillar, all describing methodologies. In all of the introduced approaches, PM is combined with other methods such as optimisation techniques [1], the BPM-cycle [62], simulation models [38], or value stream analysis [31].

A. Discussion SLR-1

Despite PM and SD being topics of increasing interest in academia and industry, only fourteen publications refer to both PM and SD directly, with four relating to a general concept of SD. This can have various reasons, such as the absence of a conceptualisation of SD scholars agree upon [20], the benefits of PM not directly considered in the context of SD or the lack of support PM techniques can provide for SD. All of the presented case studies name the analysis of data-driven performance and support in identifying improvement potentials due to the application of PM techniques. This indicates that PM, at least, supports economic prosperity. The understanding that increasing performance contributes to economic prosperity is supported by [9]. The underlying sample of social sustainability indicates that the benefit of PM to the social pillar lies in the application of PM to a specific, human-centred domain and the consideration of the organisational perspective. Following this, we confirm the increasing application of PM fields such as healthcare [43] and smart cities [8] – two topics addressing SD on a macro level. PM techniques are also known for analysing social networks [75]. Besides a targeted choice in the domain, the consideration of social aspects is a dedicated topic in recent PM research. *Responsible PM* is a new area of a PM that addresses fairness, accuracy, confidentiality and transparency in the context of PM [72]. These examples and considerations show that there is research on the intersection of PM and social sustainability. Whether this implies the application of PM as a possibility to improve social equity has to be considered further. We see that all publications mentioning the environmental pillar propose methodologies. Additionally, the increase in publications in recent years could be interpreted as an identified deficit. Apart from three of the publications relating to the manufacturing industry, the publications do not indicate any other relationship in the application of PM, the SD-related topics they address or the purpose that is served (optimising disassembly [1], improving resource utilisation [38], assessing environmental indicators [31], and enabling the selection of responsible suppliers [62]).

We conclude that searching for an explicit connection between PM techniques and SD yields few results and offers only a partial overview of the potential of PM in SD. Over the last two decades, academia and industry focused on applying PM to improve the efficiency of processes [59]. Additionally, companies, which are the primary beneficiaries of PM, have an intrinsic interest in achieving economic prosperity. The application of PM to targeted domains and including the organisational perspective indicates benefits to social sustainability. The relatively new area of responsible PM may also contribute to social sustainability. However, many indicators for social equity are established using qualitative data [3]. PM, in contrast, is a set of quantitative techniques. According to the social life cycle assessment guideline, processes only cover about 10% of the scope related to social equity – compared to the roughly 60% of environmental sustainability [68]. Based on these insights and the indications of the ecological pillar and PM being the least developed pillar, we decided to narrow further analysis to contributions concerning PM and the CE.

V. Process Mining and the Circular Economy

As argued above, SD is a vast field, the analysis of which yields few results, suggesting a varying impact of PM's contribution to the different pillars of SD. We, therefore, narrow our field of interest from the broad area of SD to a more concrete

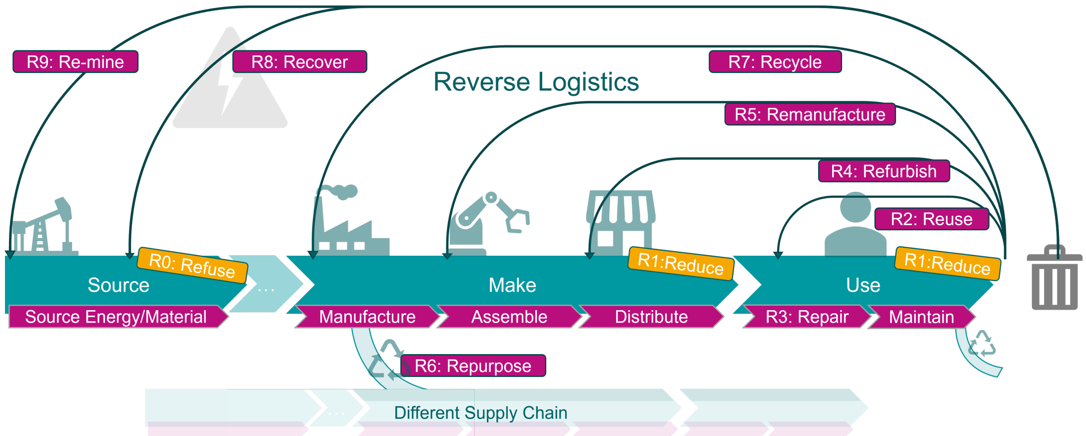

Fig. 4: Processes relevant to the CE.

field: The circular economy. In the remainder of this work, we want to identify (1) what PM can contribute to the CE and (2) how PM has to be applied to support the transition to and maintenance of the CE.

When considering the possible contributions PM can make to the CE, the obvious first step is identifying the processes of main interest to the CE. As the CE addresses the circulation of resources and energy, processes related to the traditional supply chain (SC), so sourcing, making, and distributing core products are relevant [4]. However, waste flows, product utilisation, and reverse logistics (RL) must also be considered [77]. RL includes all processes required to retrieve a product from a consumer to restore product or material value [33]. Based on these considerations, the R-imperatives and the relevant processes identified in [77] we summarised an overview of the relevant processes for the CE in Figure 4. The processes involved in sourcing, making and using products and energy form the heart of the CE. Working with circulated products or energy may offer different challenges (e.g. more variability in the control flow), but it involves the same SC and can, therefore, be integrated into the same supply system used to create products of virgin resources [42]. PM can be applied to a process system part of this SC or only affect individual processes, e.g. the disassembly of products.

In the following SLR, we look at the relevant publications from two different points of view: The associated processes of the CE and their contribution to the CE goals. By categorising the publications by processes, we want to assess the status and completeness of PM regarding the CE, whereas the specific application of PM techniques to support the goals of the CE is the latter's focus. We treat [19] and [18] as one publication, since [19] adds a case study to [18].

Sourcing of material and energy is addressed in four publications: Two present case studies in the renewable energy sector [11], [46], and [13] describes how PM can be applied to reduce greenhouse gases in agriculture. A fourth presents the application of PM to identify business networks, mentioning this as an opportunity for a more targeted selection of suppliers in terms of SD targets [62].

Production processes, so *making* products, is addressed by most publications. Six describe PM's part in some form of *smart manufacturing*, such as digital twins [19], [38], [39], production automation [32], [60] or cyber-physical production systems [51]. Two address the assessment of environmental impact [31], [50]. Two publications from the same authors optimise maintenance windows to increase production efficiency [63], [64].

Maintaining and repairing is the main concern of three other publications: One presents a case study demonstrating an improvement of managing maintenance jobs through PM [11], another proposes a methodology to support knowledge management for sustainable behaviour [49], and [41] applies PM to machine logs to support the detection of machine issues and root-cause detection. **Product distribution or utilising consumer goods** are not addressed to in any of the publications.

Reverse Logistics Processes are only directly referred to in one work – in [1] a method to identify the most energy-efficient disassembly sequence to support remanufacturing is presented. Additionally, integrating remanufacturing processes into production systems was mentioned as a requirement for the digital shadow presented by [19], and [48] describes a method to assess discrepancies to a benchmark of the utilisation of recycled material but does not detail on this.

Regarding the objectives of the CE, we see that most publications refer to smart manufacturing, leading to increased digitalisation. More digitalisation, in turn, increases process efficiency, which reduces material input, waste, emissions and energy consumption [40]. More concretely, efficiency is improved by automating parts of the process through RPA [39], [51], [60] or the creation of simulation models to compare alternatives and support decision-making [19]. The method in [38] monitors processes to identify constrained resources to support decision-making. A simulation model enriched with information on processed quantities and locations to support the material flow, which automatically creates and evaluates alternatives, is presented in [32]. Machine availability is optimised by generating a probabilistic prediction model to assign maintenance windows [63], [64]. Naturally, the previously introduced publications on maintenance and repair also contribute to the increase in resource availability.

Reducing resource input directly is achieved by remanufacturing [1] and the consideration of recycled material in [48].

Waste is mentioned in three of the publications: A framework for intelligent process automation is presented in [39]. PM is first used to identify the current practices, acting as a basis for the combination of RPA and an AI to operate a machine. This optimises material utilisation and a reduction in waste. In [48], waste is mentioned as an indicator, but no further information is provided. Publication [19] mentions the potential of integrating information on waste into a proposed digital shadow.

Emissions can be reduced by appropriate crop rotation strategies, according to [13], yet no integration of emission-related data is mentioned in the approach. The application of PM for carbon accounting is analysed in detail by [7] using interviews with professionals working on the topic. It concludes that it supports recognising, measuring, and monitoring CO2 emissions and checking compliance with targets. PM's potential for the simulation of process changes and their impact on carbon emissions and process performance and identifying CO2 reduction potentials is pointed out. Additionally, the utilisation of PM for the comparison of alternative practices is addressed. Unfortunately, the author does not detail any of this — we can only deduce that it requires information on carbon emissions per activity. Getting this data is, so the author, a problem to which the connection to emission databases via APIs might be an answer.

Energy consumption is addressed in several publications. In [1], the energy consumption per machine is analysed over time. The event log is enriched with information on the used machines. PM generates a process model, which is used to gain the precedence relationships among the activities. Combined with the energy consumption of these combinations are subsequently optimised to detect the energy-optimised sequence of activities. In other publications, energy consumption is added as an event attribute [50], [51]. A method in which the process model is enriched with information on machine setting parameters to determine the optimal energy-efficient process sequence and machine settings is presented in [51]. The framework of [50] describes accumulating a product's energy consumption throughout the process. Other publications only mention energy reduction as a consequence.

General contributions to the CE are addressed. One argues for using PM for LCA in production processes [31] – only a high-level framework is provided. A literature study on BPM the CE concludes that BPM has the potential to support LCA and considers PM a good option for operationalising LCA, detecting deviations from the planned path and supporting deviations via root cause analysis [20]. A third publication describes a high-level framework for integrating PM to LCA [50]. It discusses the ability of different discovery techniques for this task and mentions that discovery techniques have to be adjusted to provide information on cumulative energy consumption and display more details in process models. It mentions the requirement for a stronger focus on the material flow, the necessity of data the machines use and produce, and energy consumption. The framework presented in [49] should support decisions toward more sustainable practices by annotating the discovered process model with semantic information used for more detailed knowledge extraction and process analysis. Additionally, two works asses business processes' compliance to SD targets, policies and standards [65] or benchmarks [48]. For example, [65] proposes a translation of these sustainability constraints to formal logic, to which a compliance engine compares business practices based on event logs and additional business data. In general, all publications use PM to detect current practices. Nineteen publications describe leveraging PM's automatability to operationalise the described approaches – none explains how this is done in detail; conformance-checking of real-time data is assumed. Four only use PM to identify directly follows relationships [13], [48], [63], [64], and one performs social network detection [62]. Conformance-checking techniques are addressed for the detection of irregularities [11], [38], [41], monitoring processes [60], validating models and assessing model quality [19] and comparing practices to sustainability performance rules [7], [49] and sustainability targets [65]. Performance analysis techniques are mentioned for calculating performance indicators [11], [19], [39] and the detection of bottlenecks [38], [39]. Of the comparative PM techniques, only root-cause analysis is mentioned [20], [39], [41]. Only [19] uses PM techniques to create the simulation model, and RPA is mentioned in [60], and [39].

A. Discussion SLR-2

Considering the capabilities of PM and the processes mainly affected by the CE, it is not surprising that most publications describe the application of PM to increase efficiency and resource availability in a manufacturing context. Increasing efficiency and availability lowers the demand for additional resources and reduces waste, emissions, and energy consumption [25]. Many identified publications acknowledge the application of PM techniques for the holistic management of production systems due to their capability of end-to-end process analysis. As most publications relate to production management, we quickly see that the considered resources are those the manufacturing industry works *with*, not the products that are being worked *on*. This means that the main contributions to the CE the publications of SLR-2 describe are lowering demand for industrial goods and reducing excess emissions, waste and energy consumption of practices as they are. This undoubtedly contributes to the CE, yet its impact is limited as industrial goods have significantly less influence on environmental quality than consumer goods [80]. However, PM's capabilities to support rethinking BPs regarding energy efficiency, material input, emissions and waste production are also highlighted. Although most do not provide much detail on how this can be done, the overall tenor of all publications is that PM can support this transition. Based on this result, we can answer the first research question concerning PM's contribution to SD: PM supports **sustainability assessment and the management of relevant processes**. It also offers methods to detect the potential for improvement in sustainability, monitor processes about sustainability targets, compare the sustainability of different procedures, and identify drivers for high emissions, waste and energy consumption.

Regarding the processes mentioned in current literature related to PM and the CE, we see a heap around production management. The low coverage of consumer processes is expected, as PM relies on the analysis of event data of IT systems, and consumer behaviour regarding physical products is rarely logged and even rarer evaluated systematically. Only a single publication explicitly refers to a process not part of the traditional SC. The additional challenges related to reverse logistics, i.e., managing a material flow with high variance in required operations [26], are not addressed, despite PM's strength in supporting the management of less structured processes. Furthermore, the application of PM regarding intra-logistical or SC-related topics is not mentioned. This is unexpected, as logistical topics are highly relevant [33] and increased digitalisation and automation benefit the CE [40]. We also notice that only intra-organisational processes are mentioned, despite the CE and, with it, new laws and regulations emphasise the consideration of the entire SC and long product life. We see two likely reasons for the strong emphasis on production systems yet the near neglect of all forms of circularity, logistics and extended processes: (1) The CE concept is not well-established yet [45], so the processes PM could support may not be widespread enough. (2) Inter-organisational PM as a discipline is still in its infancy [76] and PM has mainly been adopted to increase the performance of a single organisation's [67] processes. Therefore, PM for **inter-organisational and logistical process analysis** form research gaps for PM in sustainability. Also, challenges arising from the new types of processes have to be analysed to support the development of targeted PM techniques.

Interestingly, the mentioned PM techniques and applications show that the full potential of PM is not used. For example, [38] neither applies nor discusses PM's techniques for identifying constrained resources, despite bottleneck detection being the objective of the presented work. The proposals for PM's application for carbon assessment [7] and LCA [50] also indicate that state-of-the-art PM has not been considered. Both enlist challenges that the application of OCPM could solve, such as PM's limitation to a single type of case, processes not representing the material flow but merely the control flow and the required addition of resource data to each event. This, as well as the few search results, leads us to conclude that knowledge about state-of-the-art PM has yet to reach the domain of SD.

VI. Process Mining for Sustainability

Exploring the current use of PM for sustainability helped us identify the processes relevant to the CE that must be supported and the contributions PM can provide. However, discrepancies in the identified potential of PM on the one hand, and its described application on the other have become apparent. We, therefore, map the contributions to SD mentioned in the results of SLR-2 to the different areas of PM to provide a structured answer to RQ1 before going into more detail on how this could be realised. Table II summarises PM's contributions PM to SD. PM techniques support detecting and monitoring current practices using business data and establishing a direct connection to SD assessment. To do so, different elements of the process have to be considered and depicted in the discovered models. This allows companies to use PM techniques to keep track of SD regulations, goals, benchmarks and standards. While driving sustainability, the toolset for performance analysis can be used to establish a lever between process performance and sustainability. Additionally, PM can be used for comparisons of alternatives and to identify the causes of high environmental impact. These results can support business decisions, model the impacts of consumer behaviour or product life extension strategies and increase digitalisation and automation.

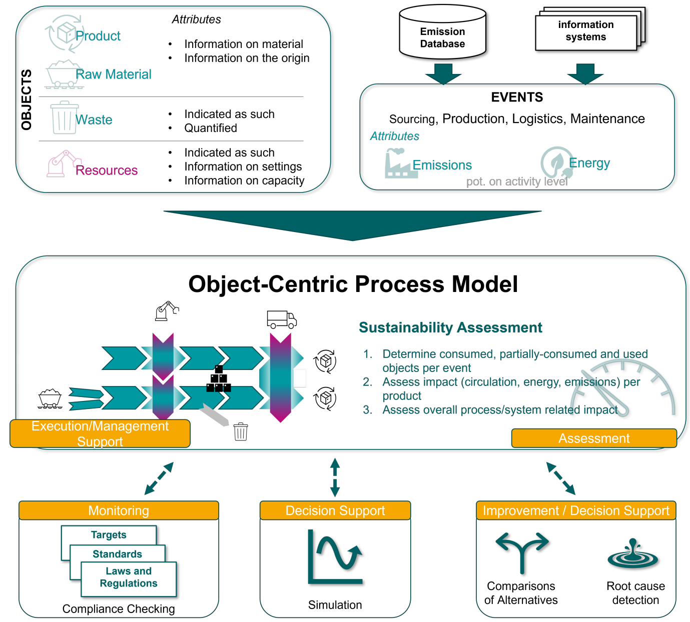

Fig. 5: Summary of the basic PM4S framework as basis for additional process analysis to increase SD.

To guide existing research in applying PM for sustainability and target gaps more effectively, we introduce the *Process Mining for Sustainability* (PM4S) framework as an answer to RQ2. The main principles of the CE are the efficient use of resources, the extension of product life and the valuable application of materials in end-of-life products [54] as well as the reduction of emissions and energy consumption [24] throughout the entire product life cycle [16]. We first consider the processes and perspectives PM techniques must capture and suggest a framework for assessing the environmental sustainability of processes before stringing it together in VI-B.

TABLE II: PM's contribution to sustainability based on the results of SLR-2.

Discovery	Raw Material and Components Intermediate and final Products Process Ressources Wastes
Conformance Checking	Impact of Abnormal Behaviour Checking Compliance to SD Goals
Process Analysis	Impact and Circularity Assessment Performance Analysis Bottleneck Detection
Comparative PM	Comparison of Alternatives Trade offs between SD aspects Root Cause Analysis
Predictive PM	Predict the Impact of Behaviour Predicting Goal Achievement Simulation
Action-oriented PM	Automation

A. Perspectives

The flow of all raw materials, intermediate products, final products, and waste lies at the core of the CE. The processes relevant to the CE were introduced in the previous section and are displayed in Figure 4. Currently, PM techniques are mainly applied to analyse and support value-adding processes, such as order management [58]. Additionally, the two SLRs have revealed PM's potential for maintenance processes. To assess sustainability PM techniques must be applied to processes including all relevant activities, including waste management and logistical operations such intra- and intra-organisational transportation and inventory management [77].

This means, the log must include events and objects associated with the raw materials, intermediate, final, and waste products. As the material flow of these products is interdependent due to logical dependencies, shared resources or batching PM4S requires OCPM, as only considering a single case does not allow for a realistic analysis of the involved system's complexity. The current OCEL standard requires each object to have a unique identifier, and PM techniques focus on "tracking" individual objects through the process. For PM techniques to be more helpful to logistical processes, they have to allow the consideration of object quantities instead of object identities and collections of interchangeable objects. To consider inter-organisational processes, the data silos from all involved parties must be broken down to create and analyse a joint process model.

As process resources strongly impact the environment, e.g. through produced emissions and their own life cycle, their utilisation, as well as their own lifecycle, has to be captured. We see two possibilities for including process resources in OCPM: They can be added to the event log as an event attribute or considered objects. Adding them as event attributes neither allows a direct connection to additional information, such as their settings, nor enables the consideration of maintenance and repair processes. Modelling resources as objects overcomes these obstacles, yet the current OCEL standard does not allow object attributes to change over time, which would support the energy efficiency analysis of machine configurations similar to the one described in [51]. Additionally, the resulting models could lack conciseness and potentially include many loops if an activity requiring the resource is performed several times. Process resources could be considered as a second, separate class of objects with a process relating to the resource status (similar to [41]) associated with the control flow of objects. As the options in line with the current OCEL standard seem unsatisfactory, yet the consideration of process resources is essential to sustainability, we consider the integration of process resources into PM4S as a potential for further research.

B. Sustainability Assessment

The aim of PM4S is not to merely increase process efficiency, which consequently leads to greater sustainability, but to increase the sustainability of BPs themselves. Therefore, assessing SD indicators through PM is not only an anticipated benefit of applying PM (see SLR-2) but forms the main contribution of PM4S. The environmental impact of a process can only be monitored and considered in process changes if incorporated into process management. Below, we consider how the assessment of material input (i.e. circulation of a product), emissions, energy consumption and waste can be included in PM. There are several ways of measuring the circularity of a product [10] – all of which require additional information on the involved components, for example, toxicity, scarcity, whether it is recycled material or the members of already replaced. This information has to be added to the event log, for example, as attributes to each object entering the considered system. In the publications of SLR-2, emission data is considered per event. The produced emissions per event must be extracted from business data or collected via an API to emission databases. The data can also be collected per activity and added as an event attribute in the preprocessing of the event log. If all data for the API calls are available in the OCEL, adding the emission data to the individual activities or events can also be integrated to process discovery techniques. The same holds for energy data. The waste assessment is only possible if each waste object is indicated as such by an object attribute and its quantity (potentially as a fraction of the input) is given in the object attributes. Using this information, slightly adapted discovery techniques, as suggested in [50], or an additional pre-processing step for other event attributes allows the consideration of the progression of SD indicators throughout the process. Their assessment requires the consideration of inter-attribute dependencies. Figure 6 depicts an example illustrating these dependencies. Event 1 occurs before Event 2, each describing the produced emissions and consumed energy as attributes. Leaning on LCA, we introduce counters for each object, describing the energy consumed and emissions created so far. Event 1 works on object a-b-c, subsequently used in event 2. As event 1 produces emissions, the amount of created emissions associated with object a-b-c when consumed for event 1 is higher than before event 1 was performed. Apart from object a-b-c, event 2 consumes object

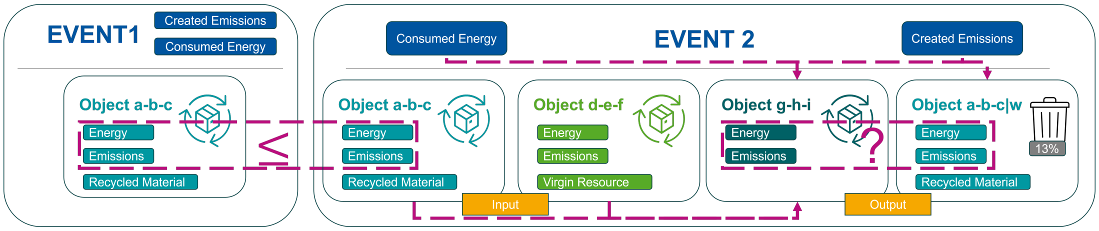

Fig. 6: Example for the assessment of environmental sustainability factors per object.

d-e-f, producing a waste object of the same type as object a-b-c and a product called object g-h-i. The emissions associated with product g-h-i depend on the emissions produced during event 2 and the counter of its components. The fact that object a-b-c was not fully may also be taken into account. Similarly, counters for circularity indices and energy consumption could be computed.

This consideration requires some additional concepts for the resulting PM techniques. For example, the described approach requires distinguishing whether an object associated with an event is merely used, (partially) consumed or created in the event. As the individual objects are only assigned to events without qualifying their relationship, the distinction could be made by considering previous and future events. Also, rules for calculating the sustainability indicators considering conversion and division of products and waste creation. As we can see, PM offers the possibility of creating these assessments, yet the specific details on how these counters must be calculated and integrated into PM techniques require further (interdisciplinary) research.

C. PM4S Framework

After deriving the contributions PM can make, the perspectives that must be captured and the assessment of the fundamental sustainability factors, we now combine them into a framework as depicted in Figure 5. As pointed out above, object-centricity is vital to PM4S. The event log has to capture all involved material flows (incl. waste), the involved process resources, value-adding as well as logistical activities. Additionally, each event requires attributes on created emissions and energy consumption. Apart from the event data, the objects have to be enriched with further details, such as information on materials, origins, information qualifying objects as waste/resources and the settings of process resources. Using this data, an object-centric process model can be created, including basic information on the system's and every object's emissions, energy consumption, and degree of circularity. The resulting model and the sustainability assessment can then be used as a basis for standard PM techniques focussing on performance and improvement as well as new techniques checking a process' compliance to benchmarks, targets etc.

VII. Conclusion

Business processes are the backbone of any organisation and impact environmental, social, and economic sustainability. When considering the application of PM for SD, we see that the support for social equity is limited, yet the application to human-centred processes is beneficial. For environmental quality, we identify a strong focus on the manufacturing industry and increasing efficiency. The identified publications mainly provide high-level descriptions. We recognise that PM techniques are not used to their full potential and conclude a lack of knowledge of the application and benefits of state-of-the-art PM techniques. Based on these SLRs, we have derived a PM4S framework for the application to increase SD in business processes. In this framework, the processes and process elements essential to environmental sustainability, as well as additional relevant information is used to build an object-centric process model enriched with environmental impact assessment metrics. This model is used as the basis for additional process analysis and improvement, to ensure that sustainability lies at the heart of all process changes. PM4S' main contributions lie in its ability of shedding light on increasingly complex business processes, enabling end-to-end process management and assessing process sustainability. It supports decision-makers in comparing alternative practices, enables simulations and digital shadows and highlights deviations to given benchmarks.

OCPM is a novel branch of the fast-growing and fast-developing discipline of PM [74], and PM4S poses an important use case to this new branch underlining its necessity. However, as shown in the previous section that the ignorance between the PM and SD domains is mutual – the requirements for assessing and improving sustainability highlight certain research gaps. On the one hand, we identify further research in the support of logistical process management (i.e., regarding federated PM and requiring unique, non-changing object identifiers) and the consideration of process ressource management. On the other hand, the capabilities of integrating and using additional information on events, qualifying objects and considering changing attributes need to be refined. The intersection between the two domains is still a scientific void offering much potential for additional, interdisciplinary research.

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