Enabling Sustainability-Aware Process Mining: A Systematic approach for Measurement and Registration of Sustainability Data

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Abstract. Organizations are becoming increasingly aware of the environmental impact of their daily operations, raising concerns about their business practices. Consequently, they are seeking to incorporate sustainable practices to mitigate this impact while improving their business processes. Process mining is a key enabler in this context, supporting evidence-based process analysis and improvement. Although sustainability measures for business processes have been proposed and some approaches include sustainability attributes in event logs, it remains unclear how to systematically capture and derive sustainability data from process execution for process mining analysis. In this paper, we propose a systematic approach that includes specific sustainability measures with concrete formulae and required parameters, a method for registering and capturing such values in event logs within a XES extension for sustainability, and a measurement taxonomy differentiating between estimated and measured values. We evaluate the approach by presenting its practical application as a proof of concept, with results indicating that it can support organizations in the systematic registration and evidence-based analysis of key business processes sustainability dimensions.

Keywords: business process sustainability, sustainability measures, sustainability data, process mining for sustainability

1 Introduction

Business processes are at the core of the organization's business, defining the activities needed to achieve a business objective [23]. Organizations are becoming increasingly aware of the environmental impact of their daily operations, raising concerns about their business practices. Consequently, they are seeking to incorporate sustainable practices to mitigate this impact while improving their processes. Sustainability can be defined as the ability to use any resource in the present without compromising the use of that resource to meet the needs of future generations, while also ensuring a balance between economic growth and social and environmental well-being [5]. Green BPM (Green Business Process Management)[4] has emerged in the last decades to provide organizations with a vision in which sustainability is considered to be a business objective. Several sustainability measures and categorizations has been proposed, referring to the three dimensions from the Sustainable Development Goals (SDGs) from UN [5]: environmental, economic, and social. In the first one, which is our focus common categories are energy, emissions, waste, water and material [15,24].

Despite advances in business sustainability, few approaches address specific sustainability measures within business processes [19,20], particularly those analyzable through process mining [13,12]. This gap hinders data-driven sustainability assessment, making process mining [1] a key enabler in this context, providing the basis for evidence-based process analysis and improvement. Although sustainability measures for business processes have been proposed and some approaches include sustainability attributes in event logs, it remains unclear how to systematically capture and derive sustainability data from process execution for process mining analysis. Existing proposals typically embed the resulting values of such measures as event log attributes (XES or object-centric), most without clearly explaining how these values are registered or calculated, nor distinguishing between estimated and actually measured data, which undermines the transparency required in a field as critical as sustainability.

In this paper, we propose a systematic approach detailing specific sustainability measures, their formulae and required parameters, a method for registering and capturing both estimated and actual sustainability values in event logs with a defined sustainability XES extension and a measurement taxonomy that explicitly differentiates between estimated and measured values. We evaluate the approach by presenting its practical application as a proof of concept supported by a purpose-built sustainability library, a services calculator, and a dedicated analysis dashboard. The results indicate that our approach can support organizations in the systematic registration and evidence-based analysis of key sustainability dimensions of their BPs. However, only measuring certain indicators does not automatically lead to a meaningful improvement of a business processes environmental impact [17,22,24]. Organizations need to undertake previous stages of process lifecycle in order to identify and define sustainability measures that apply to each process, that can be integrated, monitored and assesed using our approach, and define the corresponding improvement actions for key measures.

The remainder of the paper is structured as follows. We discuss related work in Section 2. In Section 3, we present the proposal. Then, in Section 4, we present an example of application of our approach. Finally, in Section 5, we provide conclusions and an outline of future work.

2 Related work

Literature reviews such as [15,7] and more recently [24] present sustainability categories and measures within the three dimensions: environmental, economic, and social. In the environmental dimension sustainability measures are reported for categories such as energy, emissions, waste, water and material [15,24], while sub-classifications can also be added as: pollution, natural habitat conservation, land use [15]. Few approaches address specific sustainability measures within business processes [19,20], particularly those analyzable through process mining [13,12]. In [19] gamification is applied within business process management systems (BPMS) and to improve their sustainability. A set of sustainability measures specifically tailored to BPs is presented, building on existing proposals [15]. In a similar way [20] includes sustainability measures in event logs associating them with different tasks and providing an extension to BPMN and a dashboard for analysis. We based our sustainability measures in [19] explicitly indicating the source and method of registration and calculations for them, also for different types of activities as in [20].

An approach is presented in [12] specifically for object-centric event logs [2] within industrial BPs, in which sustainability measures are calculated based on values registered in an inventory for the elements supporting the BPs. It also lacks of a clarification on how the sustainabilty measures are integrated in the event log. Differently, our approach focus on BPs supported by information systems in organizations, providing clear means on how to register and calculate them, and an extension for the XES event log standard, which can be easily translated for object-centric event logs. Some commercial tools such as Celonis[3] are also including support for sustainability within process mining. From a methodological perspective, [10] introduced sustainability analysis patterns that extend traditional BPM techniques with environmental and social performance assessment. Other studies focus on challenges and potential solutions for applying process mining to sustainability monitoring [16].

3 Sustainability-aware Process Mining proposal

For organizations to be able to integrate, calculate and analyze the results of sustainability measures with process mining, guidelines and support to register and get sustainability data from process execution are needed. In this section, we present our systematic approach detailing the elements it comprises.

3.1 Systematic approach for sustainability measurement

Our proposal is focused on organizational business processes whose execution is supported by information systems, both traditional or process-aware ones such as Business Process Management Systems (BPMS). An overview of our systematic approach is presented in Figure 1 exemplified with a BPMS as support for BPs execution. The main components of the proposal are: (a) the information system and databases that support the BPs execution, in this example, a BPMS; (b) the tools for sustainability data registration component, which is invoked by tasks to support such registration, (c) the sustainability calculator component,

[3] https://www.celonis.com/solutions/sustainability

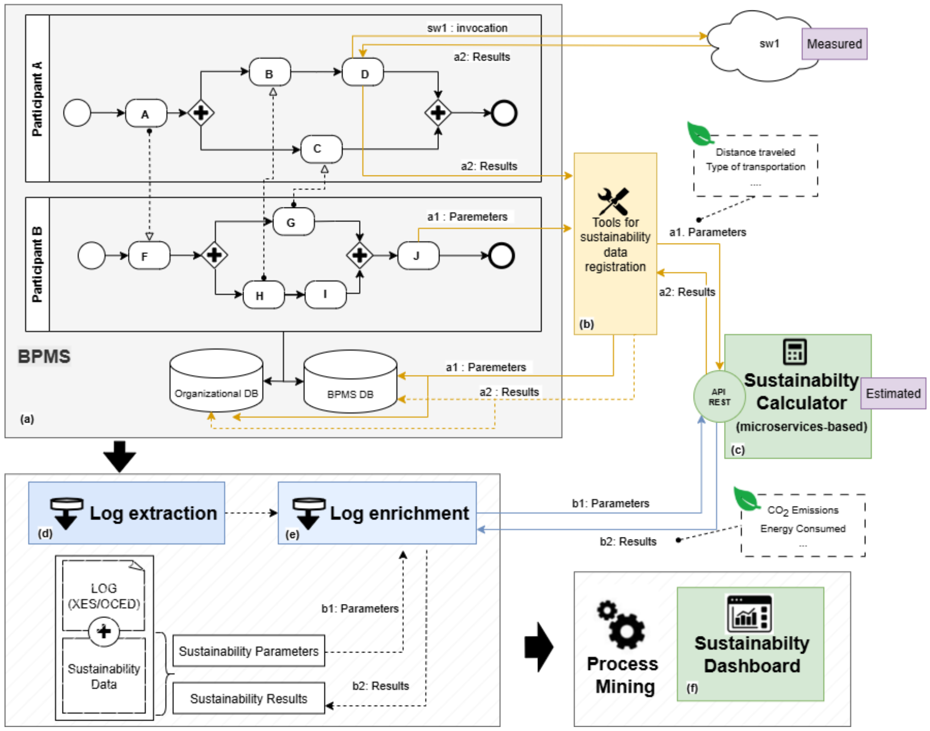

Fig. 1: Systematic approach for sustainability-aware Process Mining

microservices-based with an API REST, for runtime or off-line sustainability measures calculation, (d) the log extraction component, to generate the event log with sustainability attributes and values, (e) the log enrichment component to add missing measures results in the event log attributes with post processing in an off-line way, if needed, and (f) the sustainability dashboard, which presents sustainability measures data and process mining results.

Within business processes execution, different types of sustainability data can be registered, for example, to calculate the energy consumption of each task. This data can refer to specific elements of the software which executes the task e.g. the implementation language used within the system, the OS or the database used, or can refer to elements of the hardware (infrastructure) where the system is executing e.g. the type of CPU or the RAM of the computer or server. Sustainability data can also refer to other elements of the process that are used/managed by each task e.g. paper waste, CO_2 emissions, etc. For each sustainability measure to be calculated for the BP, the corresponding task where the sustainability data must be collected is identified, and the recording of sustainability parameters and measure values is ensured. An example BPMN process in a BPMS showing this is depicted in Figure 1 (a).

The tools for sustainability data registration component is shown in Figure 1 (b), which is invoked by tasks to support such registration. This component receives the sustainability data to be registered (parameters), and registers it within the BPMS database (optionally also in the organizational database). This would allow sustainability data registration to be integrated even into existing business process already implemented, by integrating this connection.

Sustainability data registration in its basic form refers to only registering the parameter values within that task execution, which are needed to calculate the sustainability measure e.g. for CO_2 emissions per kms, the fuel type, fuel consumption and distance in km (c.f. Sub-section 3.2). This allows to mantain the original sustainability values in the event log from tasks execution for traceability. In this case, the event log entry will initially include only the attributes with the parameter values of the sustainability measure, and the event log requires post-processing to add the result value of the sustainability measure (see log enrichment component).

The sustainability calculator component, which is a microservices-based with an REST API, shown in Figure 1 (c), is provided to calculate measures or by invoking existing calculators e.g.[4] [5] using as input in both cases, the corresponding parameters. This calculator allows only for estimated sustainability measures result values (c.f. Sub-section 3.2).

We also provide support for a more advanced sustainability data registration in the event log in which both the parameter values and also the calculated result values for the sustainability measure are registered during runtime. For this, the sustainability calculator is invoked during runtime with the corresponding parameters, and the measure value is obtained. In this case, the event in the event log will include the attributes corresponding to the sustainability measure parameters values, and also, the attribute corresponding to the sustainability measure result value.

Finally, we also allow for the integration of actual measurement of sustainability data (using specific devices) (c.f. Sub-section 3.2) in the event log, for tasks that include execution in specific contexts e.g. a specific hardware measuring instrument as is the EET (Energy Efficiency Tester) we used in [8] that can be connected to an application backend server and measure software execution in real time. In this case, the associated event in the event log will only include the attribute corresponding to the sustainability measure result value, which is returned by the measurement execution.

The log extraction component provides support for collecting process execution data from the databases, and generate the event log including the sustainability attributes and corresponding values that were registered during runtime as described above. This is shown in Figure 1 (d). The log enrichment component is defined for post processing the generated event log and find events where measures results values are missing (only sustainability parameters values were registered), adding such results by invoking the sustainability calculator off-line.

[4] `https://www.carbonfootprint.com/calculator.aspx`
[5] `https://co2.myclimate.org/en/car_calculators/new`

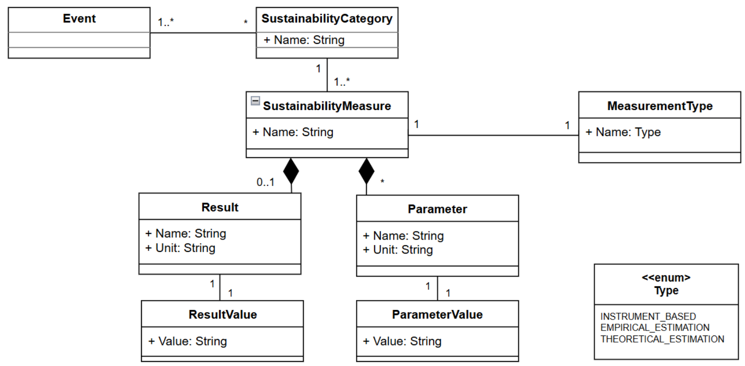

Fig. 2: Sustainability measures and measurement metamodel of XES extension

We defined a specific extension for sustainability data registration in XES event logs shown in Figure 2, which can be directly translated to object-centric event logs. An event can include an attribute for a sustainability category which has a name and can contain a list of sustainability measures for such category. Each sustainability measure has a name and includes a list of sustainability parameters, each one has a name and a parameter unit and value. Each sustainability measure can include a result with a name and a result unit and value. A sustainability measure has a measurement type which can be of one of the three types: instrument-based, empirically estimated or theoretical estimated.

The final event log for analysis with process mining will contain for all the sustainability measures identified for the business process, attributes and values in the corresponding events with parameters and measures results. This event log is then processed with process mining (e.g. discover the process model and show per activity the registered sustainability data, parameters and results, and per case, among others), and presented in the sustainabilty dashboard, which is shown in Figure 1 (f). The dashboard allows different diagrams visualization of all measures results, by category, among others.

3.2 Sustainability measures and measurement taxonomy

We integrate sustainability measures for BPs as defined in [19] and [15]. In the environmental dimension, in which we focus, we include as categories energy, emission, material, water, waste and software. We extended them by adding the concrete formulae and parameters needed for calculation, for each considered measure, and with measures related to BPs execution in an information system, such as the language of implementation e.g. Java, Python, etc, the CPU, cloud, among others, which can be estimated based on existing reference data, such as CO2 emissions. Depending on the availability of specific hardware sustainability measures can be actually measured within the BP execution. In Table 1 we present an excerpt of BPs sustainability measures for the defined categories.

Table 1: Excerpt of sustainability measures for BPs extended from [19,15].

Sust. Category	**Sust. Measure**	**Meas. Type**	**Parameter (Unit)**	**Formula**
Energy	Energy consumed (J)	EE	P: power (Watts) T: time (Seconds)	$P \times T$
	Energy consumed by device (J)	EE	DT: Device type (String) B: Brand (String) M: Model (String) T: time (Seconds)	$f(DT, B, M)(Watts)$ $\times T$
	Energy consumed by Cloud (J)	TE	P: provider (String) I: instance (String) R: region (String) T: Time (Seconds)	$f(P, I, R)(Watts)$ $\times T$
Emisions	CO2 emissions per kms (kg)	EE	Q: fuel consumption (L) T: fuel type (String) K: Kms (Int)	$f(Q, T)(Kg)$ x K
Material	Kg of paper consumed (kg)	EE	N: number of sheets (Int) A: area per sheet (m^2) G: Paper weight (kg/m^2)	$N \times A \times P$
	Fuel consumed per time (L)	EE	Q:volumetric flow rate (L/s) T: time (Seconds)	$Q \times T$
Water	Liter of water consumed (L)	IB	N/A	-
Waste	Recycled (L)	IB	N/A	-
Software	Energy consumed per CPU Usage (J)	TE	M: CPU Model (String) T: CPU time (Seconds)	$f(M)(Watts) \times T$
	Energy consumed per sw execution (J)	IB	N/A	
	Energy consumed per Language (J)	EE	L: programming language (String) T: time (Seconds)	$f(L)(Watts) \times T$

IB: Instrument-based Measurement, EE: Empirical Model-based Estimation,
TE: Theoretical Model-based Estimation

To clarify the different types of measurements, we propose a measurement taxonomy that adapts and generalizes existing frameworks [21] [14], focusing on differentiating approaches by their degree of empiricism—i.e., how they derive impact values from observable evidence, distinguishing three main categories:

Instrument-based Measurement. These approaches capture environmental data directly through instrumentation, offering the highest degree of empiricism and often serving as benchmarks for validation. They include: (i) hardware instrumentation (e.g., power meters, gas analyzers, DAQs); (ii) domain-specific sensors deployed in real-world environments (e.g., CO_2, particulate, or noise sensors); and (iii) platform-integrated monitoring (e.g., CPU thermal/current sensors in IoT devices [14]). While precise and traceable, these methods are often intrusive, costly, and less scalable in distributed contexts.

Empirical Model-based Estimation. In this category, impact is inferred from operational data (e.g., telemetry, logs) combined with empirically validated models or conversion factors, rather than direct measurement. Examples include: (i) utilization-based models using CPU/memory traces or tools such as perf, RAPL [21], or server profiling [18]; (ii) empirically calibrated analytical models linking parameters such as TDP or voltage to energy estimates [6]; and (iii) hybrid approaches multiplying observed activity (e.g., kWh) by emission factors (e.g., gCO_2/kWh) [3], as seen in travel CO_2 calculators or language-based software energy coefficients [11]. These methods strike a balance between accuracy and feasibility but depend on robust data and calibration.

Theoretical Model-based Estimation. These approaches rely on static assumptions, literature-based coefficients, or expert knowledge, and are typically applied when runtime data is unavailable. Examples include fixed grid emission factors or design-time mappings embedded in process models (e.g., "report generation consumes 0.2 kWh"), analogous to early-stage cost estimation models such as COCOMO. While lightweight and easy to apply, they are less reliable.

4 Example of application

In this section we present an example of application which serves as proof of concept of the approach, based on the BP from [19] for picking up patients from care homes for the elderly to take them to the hospital, shown in Figure 3.

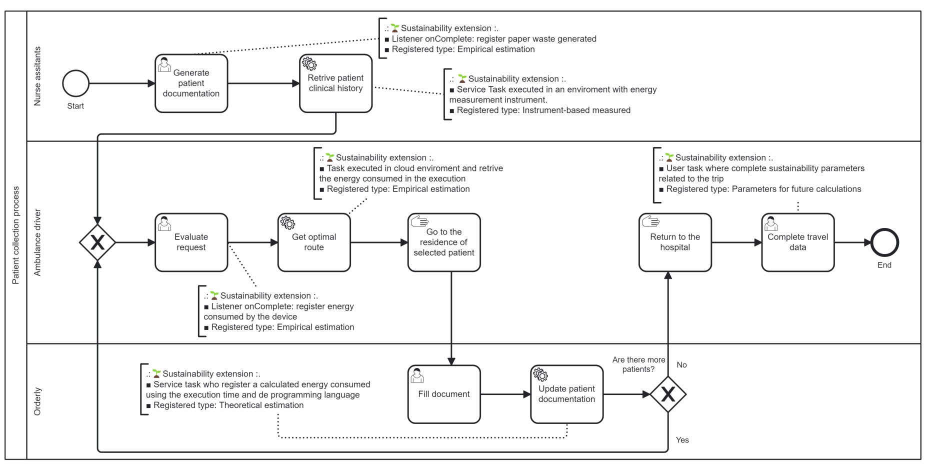

Fig. 3: Process model for picking up patients from care homes adapted from [19]

The process comprises nine distinct tasks, of type user, service, and manual, with three main participants: nurse assistants, ambulance driver, and the orderly.

Table 2: Selected measures registered in the process.

Task	**Measure**	**Calculation time**	**Calculation type**
Generate patient documentation	Paper waste generated (kg)	Runtime	calculator implemented
Retrive patient clinical history	Energy consumed per software execution (J)	Runtime	Measurement invoked
Evaluate request	Energy consumed per device (J)	Post processing	calculator implemented
Get optimal route	Energy consumed in cloud services	Runtime	calculator invoked
Update patient documentation	Energy consumed per programming language (J)	Runtime	calculator implemented
Complete travel data	Emissions per kms ($kgCO_2$)	Post processing	calculator invoked

The process starts when patient transportation is required. The nurse assistant generates and prints a patient list with basic information for the ambulance driver to pick up each patient based on an optimal route calculation. Finally, the driver completes travel details for each transfer and ambulance used. The business process is implemented using Camunda 7 as the BPMS, the microservices-based calculator and the analysis dashboard are implemented with Python[6].

The implemented process extends the BPMS with additional capabilities for capturing parameters and measures at different execution stages, for example, during task start or end events, or throughout the task execution itself. The parameters and measures can be recorded automatically, or parameters can be asked to be manually input by the user e.g. for tasks carried out outside the system. A purpose-built sustainability library -implementing the tools for sustainability data registration component- includes operations to add this capabilites to Camunda BPMS. Table 2 summarizes the measurements associated with each event, as well as the timing of their calculation.

We integrate automatic energy consumption logging for all user tasks. The measure result is estimated based on the programming language, using the average consumption rates per execution time from [11] as a reference. Additionally, for tasks executed in the cloud, such as "Get optimal route", we log energy consumption using existing online calculators. The system also supports direct, instrument-based measurements when the runtime environment provides access to energy or resource consumption data. This approach is exemplified in the "Retrieve patient clinical history" task, which simulates such an interaction. In contrast, the "Complete Travel Data" task uses a form to collect input parameters manually entered by the user. This data is then used in post-processing to calculate the corresponding CO2 emissions, again leveraging online calculators.

[6] `https://gitlab.fing.edu.uy/open-coal/pm-sustainability-approach`

The sustainability calculator as defined is a microservices-based component, with a set of REST services, each dedicated to a specific type of measurement (e.g. energy consumption per programming language or CO2 emissions per kms). These services follow a common interface, ensuring consistent parameter input and result output formats across all calculations. Two types of microservices implementation are provided: i) with own calculations based on the formulae and parameters defined, ii) invoking online existing calculators with parameters defined. Data acquisition from the BPMS and the generation of the XES event log extended with sustainability data, both registered during runtime and with post-processing calculations using registered parameters, are implemented.

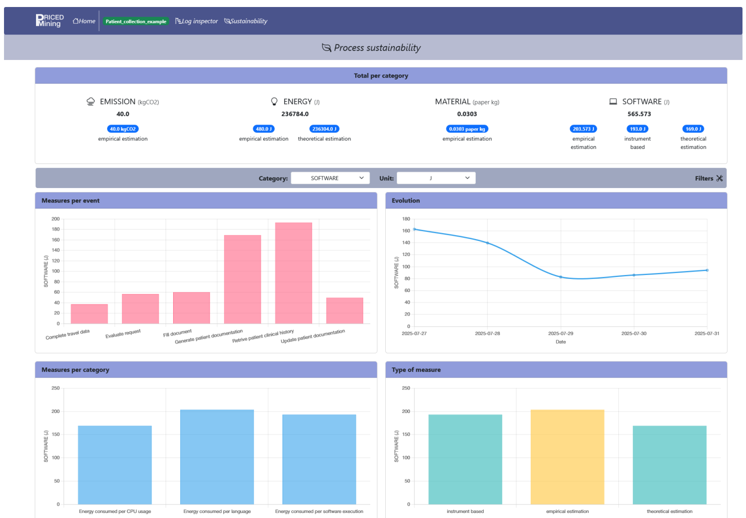

Fig. 4: Process sustainability dashboard

The sustainability dashboard shown in Figure 4 enables exploration of the recorded data, that goes beyond conventional monitoring. It links emissions, energy, material, and software indicators to the proposed taxonomy, offering impact breakdowns by measurement type. Furthermore, it incorporates process mining perspectives to analyze recorded data, which is key in our proposal.

5 Conclusions

In this paper we have presented an approach for systematically integrate sustainability data to business processes execution to be analyzed with process mining. We defined key conceptual components and guidelines to integrate the approach to BPs execution within supporting BPMS platform or traditional information systems. The elements defined within the approach and described in the paper are meant to be easily integrated into BPs implementations for sustainability-aware process mining. We evaluate the approach by presenting its practical application as a proof of concept, instantiating the proposal for a specific BP with selected sustainability measures, providing registration, calculation, XES event log generation and visualization of sustainability results. The results indicate that our approach can effectively support organizations in the systematic registration and evidence-based analysis of key sustainability dimensions of their BPs. Information regarding the type of measurement supporting the sustainability measures results is also provided for organizations to be aware of the scope of such results. Future work includes adding support for other sustainability measures, also translating the registration and extension method to objec-centric event data [9], as well as the visualization of results for such perspective.

6 Acknowledgments

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