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A Life Cycle and Enabling Concepts for Green Business Process Management

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A Life Cycle and Enabling Concepts for Green Business Process Management

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***Abstract*—Business Process Management (BPM) provides organisations with a systematic approach to model, execute, analyse, and continuously improve their business processes. Traditionally, BPM practices focus on the economic performance of business processes. With the advent of Green BPM, environmental sustainability emerged as an additional performance dimension, allowing it to support organisations in achieving their sustainability goals. However, most existing Green BPM initiatives focus on specific phases of the BPM life cycle or particular environmental performance indicators. As a result, organisations only have a limited understanding of the sustainability of their business processes and lack the means to control their environmental impact during process execution. This paper proposes a Green BPM life cycle that integrates environmental sustainability into every one of its phases without being restricted to specific indicators. An extension of BPMN, one of the standard notations for modelling business processes, is defined to allow process models to capture the environmental performance indicators that should be monitored during process execution, together with target values that can optionally be specified for each indicator to control the environmental impact of the process. An architecture is further presented for integrating these indicators into existing BPM systems by connecting calculator services to the process life cycle events. As a first step towards achieving full life cycle coverage, a prototype modelling tool for the BPMN extension and a prototype calculator service for carbon emissions have been developed.**

***Index Terms*—business processes, green business process management, environmental sustainability, key environmental indicators, process adaptation.**

I. Introduction

Urgent social and environmental challenges are pressuring organisations to become more sustainable. According to Elkington [1], organisational sustainability includes economic prosperity, environmental quality, and social justice, the so-called triple bottom line. This concept implies that the performance of organisations should not exclusively be measured in terms of their economic achievements but that they should also account for their social and environmental impact. Environmental sustainability, in particular, is a growing concern for organisations as legislative, economic, and societal factors encourage and compel them to reduce the environmental impact of their organisational activities [2]–[4]. Motivated by global issues such as climate change, policymakers are developing new strategies that foster economic growth while, at the same time, protecting the natural environment [5].

This form of sustainable development is accompanied by additional rules and regulations, such as the Corporate Sustainability Reporting Directive (CSRD) [6] and the Ecodesign for Sustainable Product Regulation [7] implemented by the European Union as part of the European Green Deal [8], that require organisations to report on and make an effort to reduce their environmental impact. These new strategies also confront organisations with the cost of polluting the environment through, for instance, emissions trading systems [9], [10], motivating and obliging them to reduce their greenhouse gas emissions through a monetary incentive. At the same time, organisations recognise the potential economic benefits that can be obtained by becoming more environmentally sustainable [4], [11], as reducing the consumption of resources such as energy can result in substantial cost savings. Issues such as climate change are similarly raising awareness within society of the need for more environmentally sustainable practices, resulting in an increased demand for green products and services [4]. This societal pressure means that organisations must adapt to these changing market circumstances to keep their existing clients and customers, and they can even use it to gain a competitive advantage [11].

Business processes — sets of related activities that are performed collectively to achieve some organisational goal and generate value for an organisation [12] — constitute the core of any organisation and represent one of their principal sources of environmental impact [2], [13]. The field of Business Process Management (BPM) provides organisations with the concepts, methods, and techniques that they need to model, execute, monitor, analyse, and continuously improve their organisational business processes [12]. The applications of BPM extend beyond the conventional definition of business processes (e.g. the processes found in insurance companies or financial organisations) to, for example, processes with a more physical nature, such as those encountered in the manufacturing domain [14]. Traditionally, BPM practices focus on improving the economic performance of business processes in terms of time, cost, quality, and flexibility, expressed as Key Performance Indicators (KPIs) [15]. With the advent of Green BPM [16], sustainability — defined as environmental sustainability in this

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case — has emerged as an additional performance dimension along with so-called Key Environmental Indicators (KEIs) as a means to quantify the environmental performance of a business process, allowing it to support organisations in achieving their sustainability goals [2]. However, so far, most existing Green BPM initiatives and research only target specific parts of the BPM life cycle — mainly concerned with measuring the performance along the sustainability dimension — or concentrate their efforts on particular performance indicators such as energy consumption or carbon emissions [2], [17], [18]. As a result, organisations only have a limited understanding of the sustainability of their business processes and lack the means to control their environmental impact during process execution.

This paper works towards the goal of making environmental sustainability an integral part of the BPM life cycle, from process modelling and execution to analysis and improvement. It proposes a Green BPM life cycle that supports environmental sustainability at every phase of the life cycle in a generic way (i.e. without being restricted to a specific set of KEIs). This Green BPM life cycle enhances the extended BPM life cycle for flexible processes [19] and consists of the following phases: modelling, execution and monitoring, analysis, and adaptation.

For the modelling phase, an extension of BPMN [20], one of the standard notations for modelling business processes, is defined that allows process models to capture the KEIs that a compatible BPM system should monitor during process execution. Target values can optionally be specified for each indicator to control the environmental impact of the process, for example, by influencing the process flow, selecting resources based on their impact, and scheduling task execution. An architecture of a BPM system that can execute these extended process models, monitor the specified KEIs, and adapt processes based on detected or predicted KEI violations is also presented. Its design allows for the integration of sustainability indicators into existing BPM systems by connecting external calculator services to the life cycle events generated by a system through a specialised monitoring component. This approach minimises the changes that have to be made to the BPM system and, at the same time, allows the calculator services to be reused in, for example, process simulation and mining tools. As a first step in realising complete coverage of the proposed Green BPM life cycle, a prototype of a modelling tool for the BPM extension is described, along with a prototype of a calculator service for carbon emissions that is developed according to the suggested architecture.

The remainder of this paper is structured in the following way. Section II provides an overview of the related work, detailing previously defined Green BPM life cycles, BPMN extensions for carbon emissions, and the realisation of partial life cycle coverage for specific KEIs and domain-specific applications. Section III presents the Green BPM life cycle and discusses each of the phases. This discussion also covers the BPM extension and the architecture of the BPM system. The two prototypes are described in Section IV, and Section V discusses the results of this paper. Finally, Section VI concludes the paper and provides directions for future work.

II. Related Work

Green BPM adopts, extends, and repurposes traditional BPM methods, techniques, and tools to address the environmental sustainability dimension of business processes. Analogous to workflow patterns, green process patterns provide guidelines for improving the environmental sustainability of business processes during process design and reengineering by describing solutions to common problems. Many such patterns have been defined [21]–[25], along with approaches for the automatic identification of issues in process models [26], [27] and the application of specific green patterns to business processes [28]. While the use of patterns is an excellent way to avoid generic unsustainable practices, they do not support organisations in assessing the environmental sustainability of their business processes, which is essential for identifying more specific improvement opportunities and confirming that changes have the desired effect.

Nowak et al. [29] discussed some of the additional aspects that need to be considered at each phase of the BPM life cycle to enable the assessment and reduction of the environmental impact of business processes. The need for KEIs to capture the environmental performance as a counterpart to KPIs was stressed as being a central part of the transformation. They also presented an extended BPM architecture to support this Green BPM life cycle. Similarly, Gallotta et al. [4] proposed a conceptual framework for the implementation of sustainable practices into business processes, covering essentially the same BPM life cycle phases. The Green BPM life cycle presented in the current paper follows several of these ideas, including the use of KEIs to measure the environmental sustainability of processes. Additionally, it considers aspects such as detecting and predicting KEI violations and autonomic process adaptation by adopting parts of the architecture of Ghahderijani and Karastoyanova [30] for autonomic process performance improvement, neither of which were discussed by Nowak et al. and Gallotta et al.

Various extensions of BPMN and other notations have been proposed to model sustainability-related aspects of business processes [31]–[36], of which several also define methods to calculate the environmental impact of the process and its activities [31], [35]–[37]. Besides the fact that the majority of these approaches are specific to energy consumption or carbon emissions, they only cover one phase of the BPM life cycle — process modelling — and do not provide an implementation of a tool for modelling processes using the extended notation.

A general overview of the most relevant KEIs to include in a BPMN extension was compiled by van den Broek [38] based on a literature study. Using a case study, van den Broek compared several options for adding elements to a process model to visualise environmental performance data and demonstrated how including KEIs in a business process can support explicit decision-making during process execution, such as choosing the most optimal mode of transportation for delivering goods to a customer. Unfortunately, most of the work was primarily concerned with carbon emissions [38],

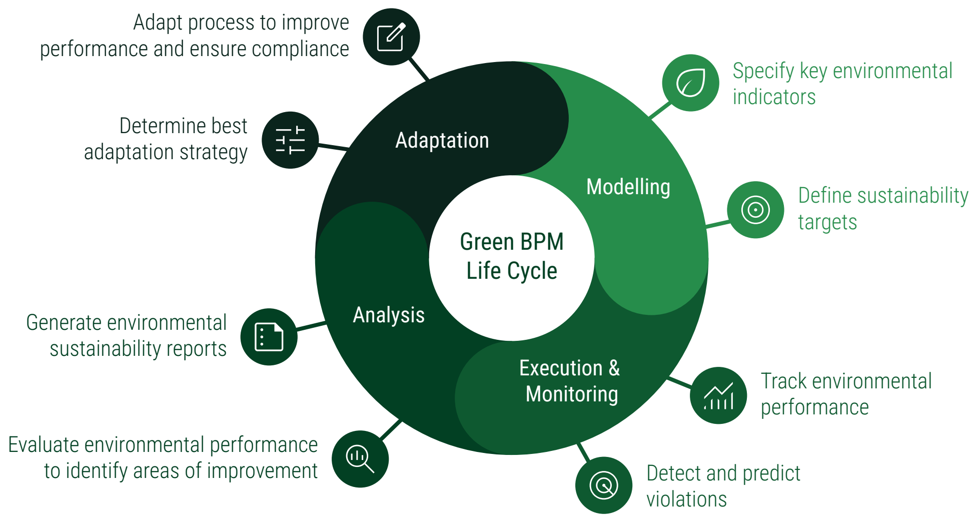


Fig. 1. The phases of the Green BPM life cycle along with the activities related to environmental sustainability performed in each of these phases.

which limits the applicability of many of the concepts to other KEIs, and integrating the indicators into the execution phase was accomplished by manually expanding the process model with tasks that present the environmental data to users and allow them to make decisions through forms.

Methods and systems that realise a partial or complete Green BPM life cycle focus their attention on specific KEIs: greenhouse gas emissions (mainly carbon emissions) [39]–[41], energy consumption [42]–[44], or both [36]. A number of these more extensive approaches [45]–[48] additionally focus on particular types of business processes or applications, such as the work by Vitali et al. [46], which is specific to cloud applications modelled as business processes. They propose a BPMN extension for adding annotations to process models that capture quality requirements, both traditional ones and requirements related to environmental sustainability, and allow application designers to mark certain parts of the process as optional and define variants for a task. However, this approach only supports adaptation by design using fixed adaptation mechanisms (e.g. skipping optional tasks and selecting different versions of a microservice to execute a task) and does not give process modellers control over the sustainability metrics that they are interested in, as energy consumption is implicitly assumed to be the exclusive driver for optimising execution. In contrast, the work presented in the current paper enables a more general type of environmentally aware process execution where the process modeller can select the relevant indicators for the tasks in a process.

Integrating existing sustainability analysis methods such as Life Cycle Assessment (LCA) into the BPM life cycle provides an alternative way to measure and improve the environmental performance of business processes [49]–[51]. LCA [52] offers a systematic, standardised method for holistically evaluating the environmental impact of products, services, systems, and even processes throughout their entire life cycle (i.e. cradle-to-grave). To date, the SOPA framework of Klessascheck et al. [49] is one of the leading examples of this integration: it employs a combination of LCA and activity-based costing to calculate the environmental cost of a business process and its activities, which it subsequently uses to analyse and redesign the process with the help of process simulation techniques. One of the main difficulties with LCA is the fact that it is a data-intensive process, making it a challenging, time-consuming, and costly study to conduct. For this reason, existing work, such as that of Klessascheck et al., assumes that the LCA data is available in some form, meaning they do not cover the entire BPM life cycle (collecting the data necessary to perform an LCA study is often done manually). The SOPA framework is also exclusively concerned with evolutionary changes, and the types of changes it supports are rather limited. Using KEIs can be considered somewhat similar to performing a life cycle inventory study [52] (omitting the last step of LCA) with a narrower scope, which could be mapped to specific environmental impact categories by, for example, using the technique of Hermann et al. [51]. There is also nothing that prevents these impact categories from being used as KEIs. Nonetheless, broadening the sustainability analysis to a complete LCA study is unquestioningly considered a worthwhile research direction, albeit one that is outside the scope of the current paper, which is concerned with integrating environmental sustainability into the entire BPM life cycle — including the execution and monitoring phases — without dictating the specific method that should be used to calculate the environmental performance of a process.

III. Green BPM Life Cycle

BPM has traditionally been concerned with the economic performance of business processes in terms of time, cost, quality, and flexibility [15]. Green BPM introduces environmental sustainability as an additional performance dimension.

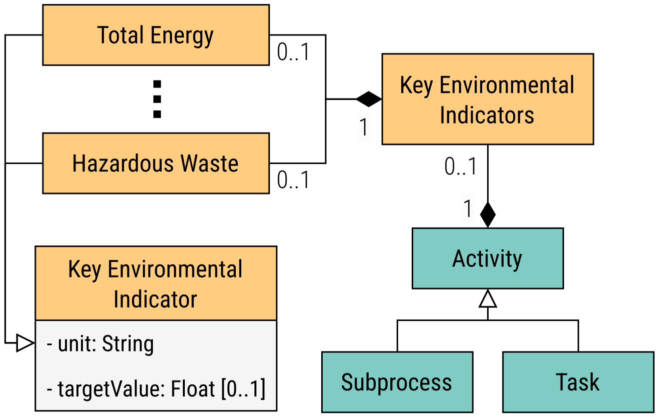


Fig. 2. The metamodel for the BPMN4ES extension. The green entities are part of the BPMN 2.0 specification [20]; the orange ones are part of the extended model.

The environmental impact of a business process, which stems directly from its tasks and subprocesses and the resources that execute them, can be subdivided into different measures related to distinct environmental concerns, such as greenhouse gas emissions, water pollution, and waste generation. KEIs offer a way to quantify this environmental impact, but which KEIs are relevant for an organisation is highly dependent on the domain in which the organisation is active, the types of processes it executes, and the individual tasks that make up these processes. It is also influenced by the overall organisational objectives, the environmental ambitions, and the rules and regulations that the organisation must comply with.

Given that there is not a single set of KEIs that is suitable for every organisation, this paper presents a Green BPM life cycle that supports organisations in making their business processes more environmentally sustainable by allowing for the continuous monitoring, control, and improvement of the environmental sustainability of business processes for a general set of KEIs. This Green BPM life cycle, which is shown in Fig. 1, enhances the extended BPM life cycle for flexible processes [19] and consists of the following phases: modelling, execution and monitoring, analysis, and adaptation.

A. Process Modelling

In the modelling phase of the Green BPM life cycle, process modellers have to complete one additional step besides the usual ones: attaching the KEIs that should be measured during process execution to the tasks and subprocesses of a process model and specifying the target values for these KEIs that should be enforced. Modelling these additional elements is completely optional, so organisations can gradually incorporate KEIs into their process models. Including the KEIs directly in the process model offers two notable advantages compared to documenting this information in a different place: it facilitates communication on environmental sustainability between stakeholders and allows for the automatic calculation and control of the KEIs in the execution and monitoring phase.

None of the existing standard modelling notations provide the means for defining the relevant KEIs for tasks and subprocesses. Given that BPMN [20] is nowadays the most widely used notation for modelling business processes, an extension of BPMN 2.0, called BPMN4ES, is created for this purpose. The extension consists of two parts: an extension of the BPMN metamodel, which adds KEIs as an additional modelling concept and allows them to be represented in the machine-readable format of a process model, and an extension of the notation to provide visual elements for KEIs that can be included in BPMN process diagrams.

Fig. 2 shows the extended metamodel. It defines the abstract *KeyEnvironmentalIndicator* type, which provides two attributes: the unit in which the values of the indicator are expressed and an optional target value that can be defined in case the goal is to enforce certain limits for the indicator during execution. Any concrete indicator must extend this abstract base type. There are no restrictions on the types of indicators that can be defined. As a starting point, the BPMN4ES extension includes some of the KEIs from the overviews that van den Broek [38] and Hernández González et al. [17] compiled based on a literature study. While these sets are by no means exhaustive, they should cover some of the more common indicators that organisations across different domains would be interested in. The indicators can be attached to tasks and subprocesses through the *EnvironmentalIndicators* container element, which can contain each of the KEIs zero or one time, allowing any combination of indicators to be created. This container element is associated with the abstract BPMN *Activity* class, which is extended by both the BPMN *Task* and *Subprocess* elements.

The extension of the metamodel is realised using the extension mechanism provided by the BPMN 2.0 standard [20]. This mechanism allows any subtype of the abstract *BaseElement* class, which includes the *Activity* element, to be assigned additional attributes and extension elements. Since the BPMN 2.0 specification already provides the option of adding extension elements, there is no need to modify the specification itself; it suffices to define the elements needed to capture the KEIs. The XML Schema of this part of the metamodel, which can be found on GitHub [53], defines the abstract *KeyEnvironmentalIndicator* type and the *EnvironmentalIndicators* element that contains all the indicators attached to a task or subprocess. The indicators are organised into groups, following the same classification as is used by van den Broek [38]. Additional indicators can easily be added to any of the existing groups or by creating new groups.

The notation used by the BPMN4ES extension for visualising KEIs in a process diagram is presented in Fig. 3. An indicator is represented by a distinctive icon, with a dashed line connecting it to the associated element (a task in the first two examples and an expanded subprocess in the last example). When a target value has been specified, the value appears underneath the icon of the indicator, as shown in the middle of Fig. 3. In a larger BPMN process diagram, each indicator attached to a task or subprocess is displayed

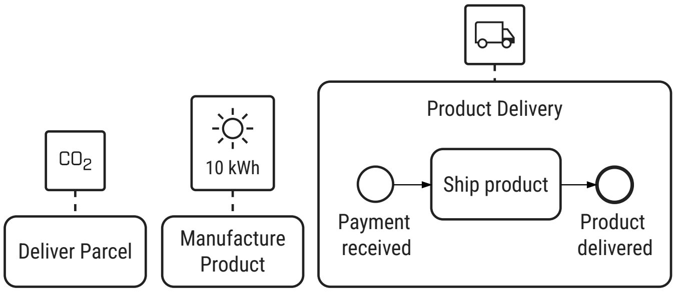


Fig. 3. The notation introduced by BPMN4ES for attaching key environmental indicators to modelling elements: (left) monitoring the performance for a task; (middle) enforcing a target value for a task; (right) monitoring the performance for an expanded subprocess.

separately, even if the same type of indicator already appears on a different task or subprocess, since the associated metadata may be different. This notation does not interfere with the visual appearance of the standard BPMN modelling elements, one of the requirements imposed by the BPMN specification for extensions. It can also handle multiple indicators attached to a single element.

B. Process Execution & Monitoring

Executing a business process that has been modelled with BPMN4ES and monitoring the KEIs that have been attached to its tasks and subprocesses requires a compatible execution and monitoring system. Fig. 4 presents a modular and extensible architecture for such a system that is based on the architecture created by Ghahderijani and Karastoyanova [30]. After a business process has been modelled and the process model has been refined into an executable model, it can be deployed to the BPM Enactment System, making it available for instantiation. This BPM system manages the process instances and the execution of their tasks by delegating the work to the appropriate services or people. The responsibilities of the BPM Enactment System can be fulfilled by any existing BPM system as long as it provides the functionality required by the Environmental Sustainability Monitoring Component and the Adaptation Component.

The Environmental Sustainability Monitoring Component relies on real-time event data from the execution environment, including events related to the life cycle of a process instance and its elements (e.g. tasks and subprocesses), to calculate the KEI values of tasks and subprocesses and monitor compliance with any target values defined in the process model. Calculating the KEI values is delegated to specialised calculator services, of which one or more may be available for each type of indicator. Various methods exist to calculate carbon emissions, for example, and each can have a dedicated calculator service, resulting in a highly modular design. Since many tasks in business processes involve physical resources that influence the environmental impact, the monitoring component may need additional information and data to calculate KEI values. This data can be obtained in real-time from sensors that provide measurements relevant for calculating a KEI, or they can be retrieved from a knowledge base containing historical data or other information that is available at design time.

The carbon emissions resulting from shipping a product are, for instance, dependent on the means of transportation that is selected for the task, which is something that may not be known until the process is executed. In this case, the characteristics of the mode of transportation (e.g. a vehicle) can be retrieved from the knowledge base and combined with task-specific information, such as the weight of the goods and the destination, to estimate the carbon emissions. For other KEIs, such as those related to energy consumption, the monitoring component may need real-time sensor data or data from external services (e.g. to obtain the emission factors based on the current energy mixture).

Besides storing the monitoring data in a database for analysis purposes, the Environmental Sustainability Monitoring Component also uses this data, combined with results from the process analysis phase, to monitor the environmental performance of the business process and detect and predict violations of the KEIs (and possibly other types of violations). When the monitoring component detects such a violation, it can trigger process adaptation in an attempt to improve the environmental sustainability of the process and correct or prevent the violation autonomously. In response to such a trigger, the adaptation component determines the optimal adaptation strategy in line with the types of adaptations supported by the BPM system, and it enacts the strategy by applying the changes to the process model or process instance. In case additional human involvement is desired, a predicted violation can also be communicated to a user (e.g. through a dashboard), who can then take the appropriate measures, including adapting the process.

C. Process Analysis

The availability of environmental performance data collected during process execution offers a wide range of possibilities for analysing the environmental sustainability of business processes. Techniques similar to process mining [54]–[56] can be used to assess the environmental impact of business processes for specific KEIs, determine which of the tasks of those processes are primarily responsible for this impact, find process instances whose environmental performance deviates considerably — either positively or negatively — from other process instances, and check that individual process instances conform to their corresponding process models. Based on these results, the processes on which redesign efforts should be focused can be selected, and potential areas of improvement can be identified. Process simulation techniques can assist in evaluating the environmental sustainability of alternative process designs [39], [57], allowing for the optimisation of certain KEIs or KPIs. To calculate the values of the KEIs, simulation tools can take advantage of the calculator services that the Environmental Sustainability Monitoring Component uses to measure the environmental performance of process instances during process execution. The effects of these redesign efforts, as well as the effects of other types of adaptations made

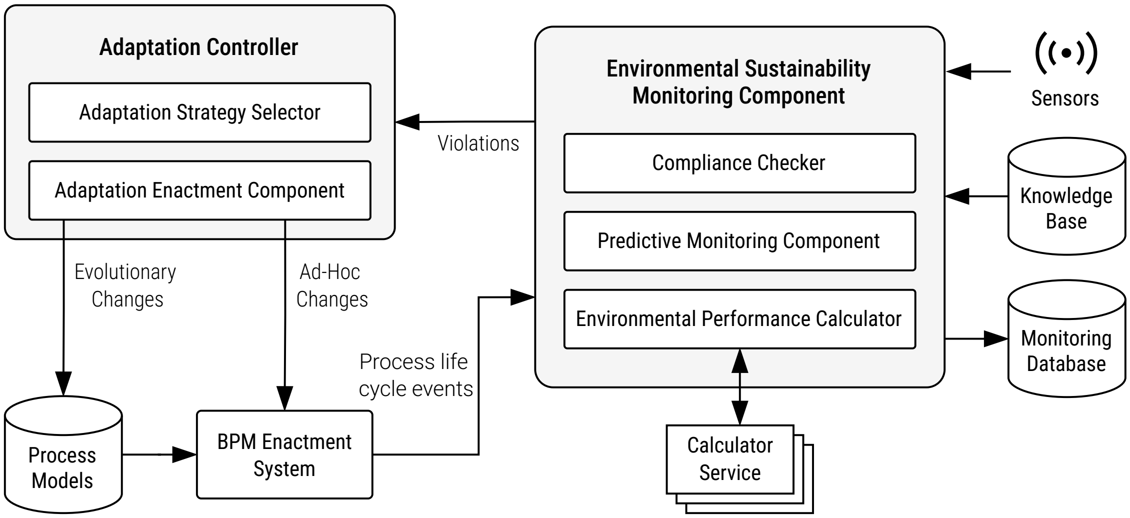


Fig. 4. The architecture of a BPM system that can execute process models specified using the BPMN4ES notation, monitor the values of the KEIs, and trigger process adaptations based on detected and predicted KEI violations.

during process execution, can be analysed to determine their efficacy and learn which types of adaptations produce the best results in which situations. Such insights are not only useful for human experts but also improve e.g. the decision-making of the autonomic adaptation system.

Compliance checking techniques can be applied to the data to verify that process instances comply with rules and regulations concerning environmental sustainability and targets set by the organisation on the KEIs [58]. Existing compliance checking methods [59] can be used for this purpose as long as the rules, regulations, and modelling elements related to KEIs can be translated into suitable representations. Finally, the environmental performance data can serve as the basis for generating reports on the environmental sustainability of the business processes of an organisation (which can, in turn, be included in reports on the overall environmental sustainability of the organisation). Internally, an organisation can, for example, use these reports to determine whether it meets its environmental sustainability goals and, if necessary, adjust its strategies. New legislation such as CSRD [6] is also increasingly obliging organisations to report on their environmental sustainability, and the ability to generate these reports automatically would greatly reduce the efforts that organisations need to spend on complying with such legislative requirements.

D. Process Adaptation

The adaptation phase deals with two types of changes: ad-hoc changes [60], which affect a single or a group of running process instances, and evolutionary changes [61], which target business process models. Ad-hoc adaptation is necessary whenever the environmental monitoring component observes or predicts a violation of one of the KEIs or non-compliance with environmental constraints related to rules or regulations during process execution. In case such a violation is detected, the best adaptation strategy must be determined, which can include selecting different resources (e.g. using a more sustainable transportation mode at the expense of increased cost or execution time), scheduling the execution of a task at a different time (e.g. when more renewable energy is available), skipping tasks that have been marked as optional, or making changes to the process model. For the latter, all types of adaptations that are available in the traditional BPM life cycle are allowed, such as adding or removing activities, combining activities to make their execution more efficient, and altering the sequence flow. It is even possible to combine different business cases (i.e. activity instances) in a batch [62], [63] to make their execution more sustainable, for example, by shipping multiple items together rather than separately.

Determining the best adaptation strategy and applying the necessary changes to process instances at runtime can be accomplished fully autonomously or with a human in the loop, depending on the level of control that is desired by an organisation and the time scale at which the changes need to be applied. For fully autonomous adaptation, the data collected during process execution and obtained in the analysis phase, including what has been learned from previous adaptations, can be used to determine the best adaptation strategy. More advanced techniques, such as planning, can also be used to synthesize alternative process flows, for which the environmental performance can be evaluated using simulation techniques.

When it comes to involving a human in the overall decision-making process, there are two extremes: semi-autonomous adaptation and manual control. With semi-autonomous adaptation, all a person has to do is approve an adaptation strategy pre-determined by the system or make the final decision as to which adaptation strategy to adopt from a limited number of options provided by the system that each make different trade-offs regarding the KEIs and potentially KPIs of the process. When manual control is desired, observed or predicted violations may be reported through a dashboard, after which it is entirely up to the user to determine the best course of action to correct or prevent the violation.

Evolutionary changes can, for the most part, be made with existing business process redesign techniques and tools [21], [60], [61] as long as they offer support for evaluating the impact on the relevant KEIs. Depending on the reason for changing a business process model, running process instances may have to be migrated to the new version, for example, when it concerns a new regulation that takes immediate effect. Multiple versions of a process model may also have to coexist, requiring an approach for keeping track of these different versions. All of these aspects of evolutionary changes can be dealt with using the same types of techniques that are used in the traditional BPM life cycle, as none of them are directly affected by the focus on environmental sustainability.

For both ad-hoc and evolutionary changes, the available adaptation strategies depend on the support provided by the BPM system. Moreover, the BPM system has to offer an interface through which the necessary changes can be enacted, and the execution of the process should temporarily be suspended to allow the best adaptation strategy to be determined. When an adaptation strategy is applied, the system must record the changes that are made to a process model or a process instance, along with the reason for making those changes, for auditing and provenance purposes and to allow the system to learn from those adaptations in subsequent iterations of the process analysis phase.

IV. Realisation

As a first proof-of-concept, two prototypes have been developed that cover parts of the Green BPM life cycle proposed in this paper. One is a modelling tool for creating diagrams using the extended BPMN4ES notation [53]. The other is a prototype of a calculator service that measures carbon emissions resulting from the fuel consumed by resources that execute the tasks of a process instance [64], [65].

A. BPMN4ES Modelling Tool

The prototype of the modelling tool for BPMN4ES is based on bpmn-js [66], a popular web-based modelling tool developed by Camunda for creating BPMN 2.0 process diagrams. Processes are modelled in the usual way, only now the modeller has the additional option of defining KEIs for the tasks and subprocesses, as shown in Fig. 5. The design of bpmn-js provides explicit support for extensions, making it relatively straightforward to add the components needed for including KEIs in the process diagram.

In line with the metamodel defined for BPMN4ES, the KEIs are added as extension elements to tasks and subprocesses. To allow bpmn-js to read, write, and modify these extension elements, the BPMN 2.0 metamodel is extended with a specific type for KEIs and a container element that stores the KEIs attached to a task or subprocess. This model extension is defined as a separate schema, similar to the XML Schema of BPMN4ES, in a format supported by bpmn-js.

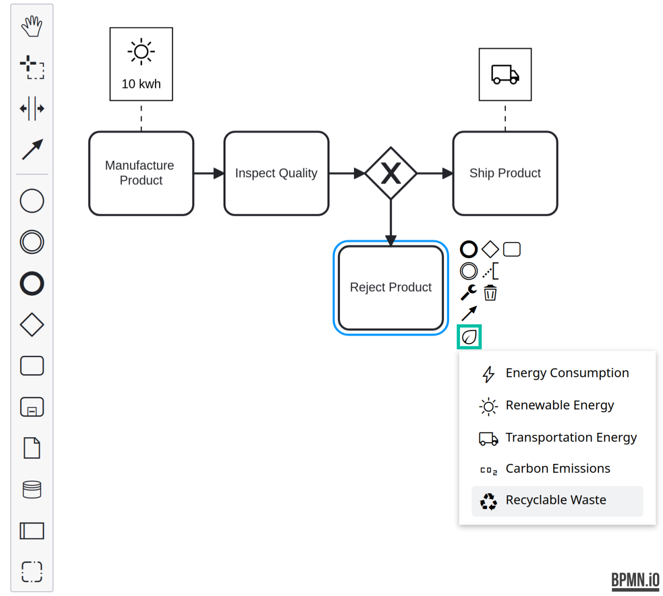


Fig. 5. A screenshot of the prototype modelling tool for BPMN4ES. Through an additional entry in the context menu, highlighted in green, the modeller can attach KEIs to the activities and subprocesses.

Additional controls are added to the user interface to allow process modellers to attach KEIs to the tasks and subprocesses of a process diagram. These options are included in the context menu, which becomes available when a user selects a particular element on the screen (as visible in Fig. 5) and provides various tools with which the selected element can be modified. Clicking on the KEI entry brings up a secondary menu from which the desired KEI can be chosen. When the user has entered all the relevant information, such as the optional target value, the corresponding extension elements of the task or subprocess are modified.

Besides modifying the extension elements to ensure that the KEIs appear in the process diagram when it is saved, the modelling tool also visualises them in the editor. For this part, the rendering component is extended. This new rendering component customises the way tasks and subprocesses are rendered on the screen. It relies on the logic of the existing rendering component to draw the visual elements of the tasks and subprocesses, as their visual appearance is not modified. In addition to this, the custom rendering component draws the KEI — consisting of the icon and the target value if one is specified — and connects it to the corresponding task or subprocess with a dashed line (following the BPMN4ES notation). Hence, the visual appearance of the indicator is directly tied to the task or subprocess.

B. Carbon Emissions Calculator Service

The calculator service for carbon emissions [64], [65] exemplifies the way in which the Green BPM life cycle supports the execution and monitoring of the environmental sustainability of business processes. It also provides a starting point for developing the monitoring and execution environment that

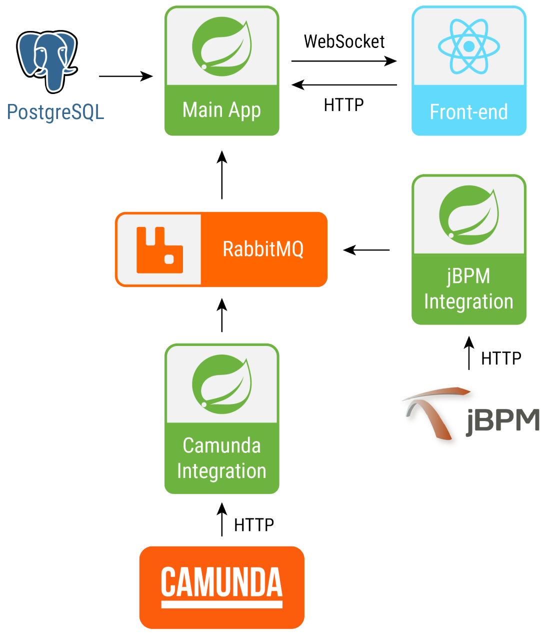


Fig. 6. The architecture of the calculator service for carbon emissions.

this phase requires. The architecture of the calculator service is shown in Fig. 6 and follows the reference architecture presented for the execution and monitoring phase. It has been integrated with two of the more widely-used BPM systems, Camunda 7 [67] and jBPM 7.74 [68], through an event-based integration layer that generates events whenever a process instance or an activity instance starts or finishes. For each process instance and each of its activity instances, the calculator service stores objects in a database to keep track of their carbon emissions. These emissions can be explored through a dashboard, where it is also possible to generate emission reports for processes.

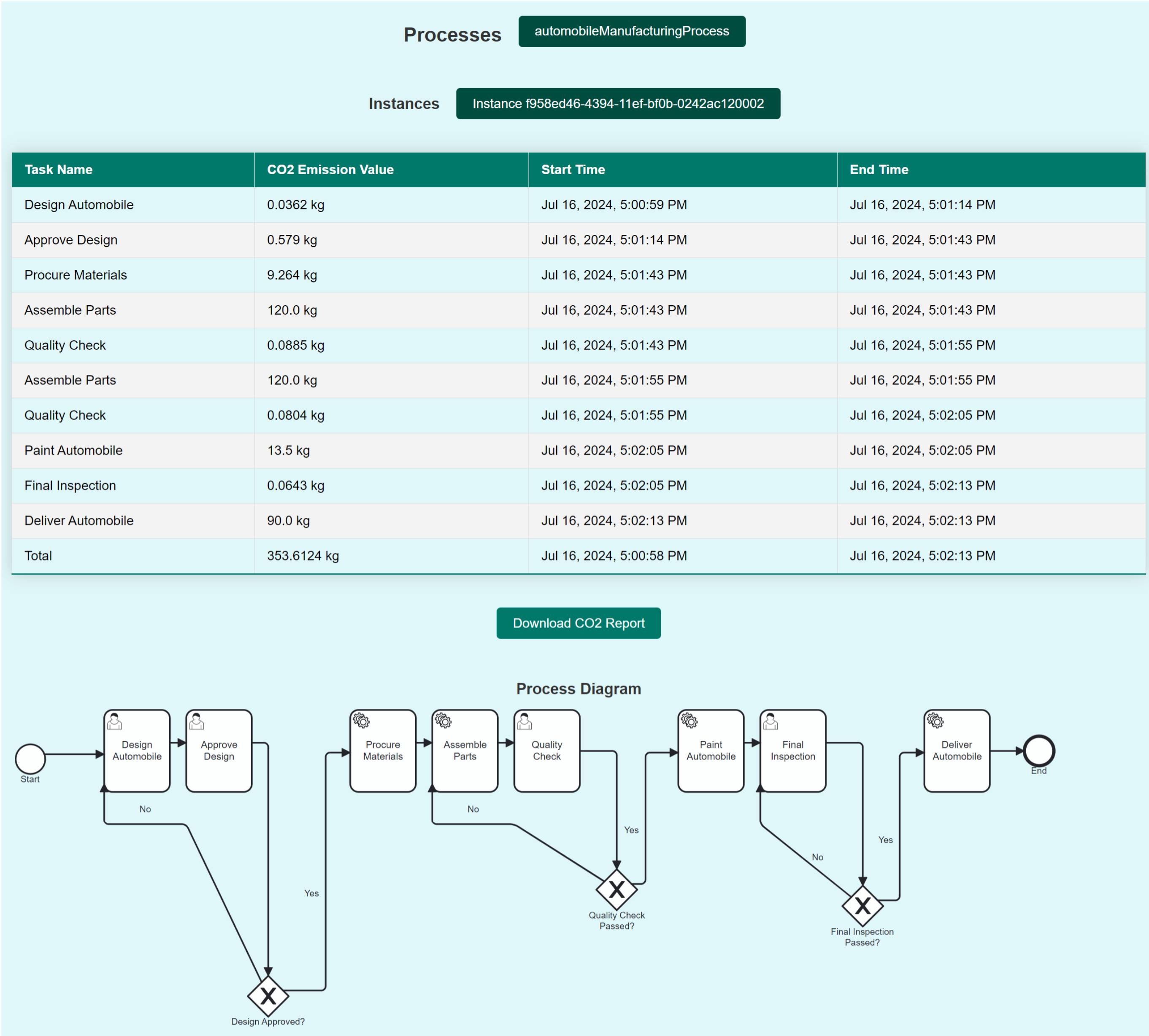
The current version of this service does not yet use the extension elements of BPMN4ES. Instead, carbon emissions are measured for all the tasks of a process instance based on the fuel consumed by their resources. This fuel consumption is specified separately through annotations along with the emission factors needed to estimate the corresponding carbon emissions. In future versions, this information would be included in the process model or retrieved from a knowledge base or third-party service. One set of annotations defines the types of resources that are used by a task and the characteristics of those resources, such as the type of fuel that they use and the amount of fuel they consume per unit of time. Other annotations define the emission factors for each type of fuel, providing the amount of carbon dioxide produced per unit of fuel (e.g. kilograms of carbon dioxide per litre of diesel). While the assumptions made by this approach arguably over-simplify the estimation of carbon emissions in a practical setting, the purpose of this prototype is to demonstrate the realisation of such a monitoring service and provide the basis for creating a service that can provide more realistic measurements in the future.

The steps that the calculator service performs to determine the carbon emissions of a process instance are illustrated using a greatly simplified example process from the automotive industry: the production of a car from its initial design to the final delivery. Fig. 7 shows an instance of this process, along with the carbon emissions produced by each activity, in the dashboard. During process execution, the service calculates the produced carbon emissions for an activity instance as soon as it finishes. This process starts by obtaining the relevant annotations for the activity instance from the database and calculating the amounts of fuel consumed by the resources based on their properties and the duration of the task. For some activities, such as manual ones, these durations are taken from the annotations to simulate tasks of various lengths. From these amounts and the emission factors, the calculator service can then estimate the amount of carbon dioxide produced by the execution of the task. All the calculations for all the resources and all the types of fuel are then summed up to obtain the total emissions for the task. When a process instance ends, the total carbon emissions are calculated by summing the emissions of all of its activities.

V. Discussion

The Green BPM life cycle proposed in this paper outlines a general approach for measuring, controlling, analysing, and improving the environmental sustainability of business processes. A BPMN extension for environmental sustainability called BPMN4ES, which introduces KEIs as an additional modelling concept, allows process models to specify the KEIs that should be monitored and controlled for the activities of the process during execution. Since the extension currently restricts the scope of the KEIs to activities (i.e. tasks and subprocesses), it is not yet possible to control the flow of a process based on sustainability-related information or to allow the process to react to sustainability-related events, which would, for instance, make it possible to model alternative paths to be taken whenever a process instance violates a KEI. For the same reason, defining a KEI for the entire process, either to monitor it for all the activities or to enforce a target value across the collective set of activities, is somewhat inconvenient. The extension supports these scenarios by wrapping all the activities in a subprocess or, specifically for monitoring, by attaching the KEI to every activity, but this method affects the understandability of the process model and increases the modelling effort, especially in the case of attaching KEIs to every activity, which results in an overwhelming number of additional elements in the process model.

The methodology behind the Green BPM life cycle is generalisable in the sense that organisations can, in principle, apply it to any KEI that may be of interest to them. Additional KEIs can easily be incorporated into the BPMN4ES metamodel, and the modular and extensible architecture of the execution and monitoring system makes it effortless to add calculator services. However, in general, to calculate the values of the KEIs, these calculator services depend on distinct data that cannot readily be provided by any generic execution



Task Name	CO2 Emission Value	Start Time	End Time
Design Automobile	0.0362 kg	Jul 16, 2024, 5:00:59 PM	Jul 16, 2024, 5:01:14 PM
Approve Design	0.579 kg	Jul 16, 2024, 5:01:14 PM	Jul 16, 2024, 5:01:43 PM
Procure Materials	9.264 kg	Jul 16, 2024, 5:01:43 PM	Jul 16, 2024, 5:01:43 PM
Assemble Parts	120.0 kg	Jul 16, 2024, 5:01:43 PM	Jul 16, 2024, 5:01:43 PM
Quality Check	0.0885 kg	Jul 16, 2024, 5:01:43 PM	Jul 16, 2024, 5:01:55 PM
Assemble Parts	120.0 kg	Jul 16, 2024, 5:01:55 PM	Jul 16, 2024, 5:01:55 PM
Quality Check	0.0804 kg	Jul 16, 2024, 5:01:55 PM	Jul 16, 2024, 5:02:05 PM
Paint Automobile	13.5 kg	Jul 16, 2024, 5:02:05 PM	Jul 16, 2024, 5:02:05 PM
Final Inspection	0.0643 kg	Jul 16, 2024, 5:02:05 PM	Jul 16, 2024, 5:02:13 PM
Deliver Automobile	90.0 kg	Jul 16, 2024, 5:02:13 PM	Jul 16, 2024, 5:02:13 PM
Total	353.6124 kg	Jul 16, 2024, 5:00:58 PM	Jul 16, 2024, 5:02:13 PM

Fig. 7. Part of the dashboard of the calculator service showing the carbon emissions for an instance of an example process.

and monitoring system, as collecting this data and making it available to the system requires specific components and infrastructure that are highly dependent on the organisational context. A manufacturing company may, for example, wish to monitor the energy consumption of the different tasks of one of its business processes. The data required to calculate this energy consumption may range from the overall characteristics of the machines involved in the manufacturing process to real-time data on their energy consumption. In the latter case, the company may have to install sensors to collect the necessary data — which may have to be repeated for each manufacturing line for which the KEI should be monitored — and this data must be made available to the monitoring system. The architecture of the execution and monitoring system includes components that facilitate the integration of these KEI-specific parts but cannot eliminate the need for an organisation to invest in the data collection process.

While achieving complete life cycle coverage is beyond the scope of this paper, initial efforts have been invested in this work to develop the technological support for the first phases of the Green BPM life cycle — modelling, execution, and monitoring — in the form of a modelling tool for the BPMN4ES extension and a prototype calculator service for carbon emissions. These proofs-of-concept demonstrate the feasibility of the architectural approach and differentiate this research from existing work describing generic Green BPM life cycles [2]–[4], which are all conceptual in nature. They also serve as the first step towards full life cycle coverage. At the same time, they do not yet provide all the functionality that these initial phases of the life cycle require, and the methods and tools for the remaining two phases, analysis and adaptation, also need to be developed to cover the entire life cycle and unlock its full potential.

As opposed to the traditional BPM life cycle, which is concerned with improving the economic performance of business processes, the Green BPM life cycle focuses on the environmental sustainability dimension. Ultimately, the Green BPM life cycle should enable the optimisation of multiple KEIs and even combinations of KEIs and other KPIs, such as those related to the economic performance of the process, as solely improving the environmental performance is generally not a realistic goal for organisations. Conceptually, the BPMN4ES extension allows more than one KEI to be attached to an activity, and monitoring multiple KEIs during process execution does not present any obstacles. The complexity arises during the adaptation phase when a process is optimised simultaneously with respect to multiple KEIs and KPIs. Attaching a single performance indicator to a task or subprocess simplifies the optimisation process since an activity does not directly influence the performance of other activities. As soon as multiple KEIs are attached to a single activity, or when other KPIs are also considered, the problem is transformed into a multi-objective optimisation problem for which it may not be possible to compute a single optimal solution.

Besides considering the direct environmental impact of the business processes of an organisation (i.e. the impact resulting from executing the activities), the Green BPM life cycle should ideally also account for any indirect impact resulting from, for example, the information technology that is necessary to execute, monitor, analyse, and adapt these business processes. Additionally, the environmental sustainability of the products and services on which an organisation relies should be reflected in the environmental impact of its business processes. Without considering the entire value network, optimising the environmental performance of a business process can potentially result in the environmental impact being moved outside of the scope of the organisation, such as by outsourcing activities with a large impact [69], [70]. In those cases, such changes would give the impression of improving the overall environmental sustainability of the organisation, while all they achieve is moving the impact to partners where it is not measured. That does not mean that outsourcing activities cannot be beneficial from an environmental sustainability perspective — an organisation that specialises in particular types of activities may be able to perform them more efficiently and deliver those services at a lower cost to the environment — but relying on other partners may just as well not have any impact or even increase the environmental impact of certain activities, especially when they are performed by organisations that are not bound by strict environmental regulations and that use a less optimal and more impactful process. As such, environmental sustainability should be approached from a holistic point of view that is not limited to the boundaries of an organisation so that organisations have a complete view of their environmental impact and can correctly assess the effects of any changes to their processes.

VI. Conclusion & Future Work

Through regulations, economic incentives, and societal pressure resulting from urgent environmental concerns such as climate change, organisations are forced to report on and reduce the environmental impact of their activities. With a focus on understanding, modelling, analysing, and improving the environmental sustainability of business processes, Green BPM can support organisations in achieving this goal. However, there is currently no integrated approach that covers the entire BPM life cycle and can be applied to all types of environmental indicators. This paper introduced a Green BPM life cycle that makes environmental sustainability a core part of an organisation by incorporating it into every phase of the BPM life cycle — modelling, execution and monitoring, analysis, and adaptation — without being specific to particular KEIs. An extension of BPMN, called BPMN4ES, was defined to allow process models to capture the KEIs, along with optional target values, that are relevant to the tasks and subprocesses of a business process. An architecture of a BPM system that can execute these process models, monitor the indicators during process execution, and trigger ad-hoc or evolutionary adaptations based on detected or predicted violations of KEIs has also been presented. Finally, a prototype modelling tool for the BPMN4ES extension and a prototype calculator service for carbon emissions have been described. These serve as a starting point for realising full life cycle coverage and demonstrating the feasibility of the architectural approach for extending existing BPM systems with environmental sustainability indicators.

There are many opportunities to develop the Green BPM life cycle further. The BPMN4ES extension can be enhanced by expanding the concept of environmental sustainability to other BPMN modelling elements, such as events and gateways, and by generalising the KEIs to pools, lanes, and even an entire process. Before organisations can fully utilise the Green BPM life cycle to measure, control, and improve the environmental sustainability of their business processes, it is also necessary to achieve complete life cycle coverage. This part consists of completing the realisation of the remaining parts of the proposed BPM system, designing the methods and tools that are needed to analyse the environmental performance of business processes, and creating novel adaptation strategies to allow the environmental impact of processes to be controlled through ad-hoc and evolutionary changes. An extensive empirical evaluation of the effectiveness of the proposed approach would additionally be required. Ultimately, the Green BPM life cycle should also enable the simultaneous optimisation of both environmental and economic performance measures. Finally, the environmental impact of the infrastructure that is required to execute, monitor, and adapt business processes has to be accounted for in the overall environmental assessment of an organisation, as these can contribute considerably to the overall footprint.

REFERENCES

[1] J. Elkington, *Cannibals with Forks: The Triple Bottom Line of 21st Century Business*, ser. Conscientious Commerce. New Society Publishers, 1998.

[2] J. Maciel, "The Core Capabilities of Green Business Process Management – A Literature Review," in *Proceedings of the 13th International Conference on Wirtschaftsinformatik*, Feb. 2017, pp. 1526–1537.

[3] A. Nowak, F. Leymann, D. Schumm, and B. Wetzstein, "An Architecture and Methodology for a Four-Phased Approach to Green Business Process Reengineering," in *Information and Communication on Technology for the Fight against Global Warming*, vol. 6868. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 150–164. [Online]. Available: https://doi.org/10.1007/978-3-642-23447-7_14

[4] B. Gallotta, J. A. Garza-Reyes, A. Anosike, M. K. Lim, and I. Roberts, "A conceptual framework for the implementation of sustainability business processes," in *Proceedings of the 27th Production and Operations Management Society (POMS)*. Production and Operations Management Society, May 2016.

[5] G. H. Brundtland, "Our Common Future—Call for Action," *Environmental Conservation*, vol. 14, no. 4, pp. 291–294, Jan. 1987. [Online]. Available: https://doi.org/10.1017/S0376892900016805

[6] European Parliament and Council of the European Union, "Directive (EU) 2022/2464: Corporate Sustainability Reporting," Dec. 2022. [Online]. Available: https://eur-lex.europa.eu/eli/dir/2022/2464/oj

[7] ——, "Regulation (EU) 2024/1781: A Framework for the Setting of Ecodesign Requirements for Sustainable Products," Jun. 2024. [Online]. Available: https://eur-lex.europa.eu/eli/reg/2024/1781/oj

[8] European Commission, "The European Green Deal," Dec. 2019. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2019:640:FIN

[9] European Parliament and Council of the European Union, "Directive 2003/87/EC: A system for greenhouse gas emission allowance trading within the Union," Oct. 2003. [Online]. Available: http://data.europa.eu/eli/dir/2003/87/2024-03-01

[10] Ministry of Ecology and Environment (China), "Carbon Emission Trading Management Measures," Feb. 2021. [Online]. Available: https://www.gov.cn/zhengce/zhengceku/2021-01/06/content_5577360.htm

[11] S. Ambec and P. Lanoie, "Does It Pay to Be Green? A Systematic Overview," *Academy of Management Perspectives*, vol. 22, no. 4, pp. 45–62, 2008. [Online]. Available: https://www.jstor.org/stable/27747478

[12] M. Weske, *Business Process Management: Concepts, Languages, Architectures*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2012. [Online]. Available: https://doi.org/10.1007/978-3-642-28616-2

[13] S. Seidel, J. vom Brocke, and J. Recker, "Call for Action: Investigating the Role of Business Process Management in Green IS," *All Sprouts Content*, vol. 11, no. 4, Apr. 2011. [Online]. Available: https://aisel.aisnet.org/sprouts_all/432

[14] K. Hoesch-Klohe and A. Ghose, "Environmentally Aware Business Process Improvement in the Enterprise Context," in *Harnessing Green It*. John Wiley & Sons, Ltd, 2012, ch. 13, pp. 265–281. [Online]. Available: https://doi.org/10.1002/9781118305393.ch13

[15] M. Dumas, M. La Rosa, J. Mendling, and H. A. Reijers, *Fundamentals of Business Process Management*. Berlin, Heidelberg: Springer, 2018. [Online]. Available: https://doi.org/10.1007/978-3-662-56509-4

[16] J. vom Brocke, S. Seidel, and J. Recker, *Green Business Process Management : Towards the Sustainable Enterprise*, ser. Progress in IS. Heidelberg New York: Springer, 2012.

[17] A. Hernández González, C. Calero, D. Pérez Parra, and J. Mancebo, "Approaching Green BPM characterisation," *Journal of Software: Evolution and Process*, vol. 31, no. 2, p. e2145, 2019. [Online]. Available: https://doi.org/10.1002/smr.2145

[18] S. R. Gohar and M. Indulska, "Business Process Management: Saving the Planet?" in *ACIS 2015 Proceedings*, 2015. [Online]. Available: https://aisel.aisnet.org/acis2015/51

[19] N. Soveizi, F. Turkmen, and D. Karastoyanova, "Security and privacy concerns in cloud-based scientific and business workflows: A systematic review," *Future Generation Computer Systems*, vol. 148, pp. 184–200, Nov. 2023. [Online]. Available: https://doi.org/10.1016/j.future.2023.05.015

[20] Object Management Group, "Business Process Model and Notation (BPMN)," Jan. 2014, version 2.0.

[21] A. Nowak, F. Leymann, D. Schleicher, D. Schumm, and S. Wagner, "Green business process patterns," in *Proceedings of the 18th Conference on Pattern Languages of Programs*, ser. PLoP '11. New York, NY, USA: Association for Computing Machinery, Oct. 2011, pp. 1–10. [Online]. Available: https://doi.org/10.1145/2578903.2579144

[22] A. Nowak and F. Leymann, "Green Business Process Patterns – Part II (Short Paper)," in *2013 IEEE 6th International Conference on Service-Oriented Computing and Applications*, Dec. 2013, pp. 168–173. [Online]. Available: https://doi.org/10.1109/SOCA.2013.11

[23] A. Nowak, T. Binz, C. Fehling, O. Kopp, F. Leymann, and S. Wagner, "Pattern-driven green adaptation of process-based applications and their runtime infrastructure," *Computing*, vol. 94, no. 6, pp. 463–487, Jun. 2012. [Online]. Available: https://doi.org/10.1007/s00607-012-0188-x

[24] P. Lübbecke, P. Fettke, and P. Loos, "Towards Ecological Workflow Patterns as an Instrument to Optimize Business Processes with Respect to Ecological Goals," in *2016 49th Hawaii International Conference on System Sciences (HICSS)*, Jan. 2016, pp. 1049–1058. [Online]. Available: https://doi.org/10.1109/HICSS.2016.134

[25] ——, "Sustainability Patterns for the Improvement of IT-Related Business Processes with Regard to Ecological Goals," in *Business Process Management Workshops*. Cham: Springer International Publishing, 2017, pp. 428–439. [Online]. Available: https://doi.org/10.1007/978-3-319-58457-7_31

[26] ——, "Towards Guidelines of Modeling for Ecology-Aware Process Design," in *Business Process Management Workshops*. Cham: Springer International Publishing, 2018, pp. 510–519. [Online]. Available: https://doi.org/10.1007/978-3-319-74030-0_40

[27] P. Lübbecke, A. Goswami, and P. Fettke, "A Method for Ecological Process Optimization Based on Compliance Checking," in *2018 IEEE 20th Conference on Business Informatics (CBI)*, vol. 01, Jul. 2018, pp. 119–128. [Online]. Available: https://doi.org/10.1109/CBI.2018.00022

[28] A. Nowak, U. Breitenbücher, and F. Leymann, "Automating Green Patterns to Compensate CO2 Emissions of Cloud-based Business Processes," in *Eighth International Conference on Advanced Engineering Computing and Applications in Sciences*, Aug. 2014, pp. 132–139.

[29] A. Nowak, F. Leymann, and D. Schumm, "The Differences and Commonalities between Green and Conventional Business Process Management," in *2011 IEEE Ninth International Conference on Dependable, Autonomic and Secure Computing*, Dec. 2011, pp. 569–576. [Online]. Available: https://doi.org/10.1109/DASC.2011.105

[30] A. Y. Ghahderijani and D. Karastoyanova, "Autonomic Process Performance Improvement," in *2021 IEEE 25th International Enterprise Distributed Object Computing Workshop (EDOCW)*, Oct. 2021, pp. 299–307. [Online]. Available: https://doi.org/10.1109/EDOCW52865.2021.00061

[31] J. Recker, M. Rosemann, A. Hjalmarsson, and M. Lind, "Modeling and Analyzing the Carbon Footprint of Business Processes," in *Green Business Process Management: Towards the Sustainable Enterprise*. Berlin, Heidelberg: Springer, 2012, pp. 93–109. [Online]. Available: https://doi.org/10.1007/978-3-642-27488-6_6

[32] C. Houy, M. Reiter, P. Fettke, and P. Loos, "Towards Green BPM – Sustainability and Resource Efficiency through Business Process Management," in *Business Process Management Workshops*. Berlin, Heidelberg: Springer, 2011, pp. 501–510. [Online]. Available: https://doi.org/10.1007/978-3-642-20511-8_46

[33] S. Betz, "Sustainability Aware Process Management using XML-Nets," in *Proceedings of the 28th EnviroInfo 2014 Conference*, 2014.

[34] X. Zhu, G. Zhu, S. vanden Broucke, and J. Recker, "On Merging Business Process Management and Geographic Information Systems: Modeling and Execution of Ecological Concerns in Processes," in *Geo-Informatics in Resource Management and Sustainable Ecosystem*, ser. Communications in Computer and Information Science, vol. 482. Berlin, Heidelberg: Springer, 2015, pp. 486–496. [Online]. Available: https://doi.org/10.1007/978-3-662-45737-5_48

[35] K. Hoesch-Klohe, A. Ghose, and L.-S. Le, "Towards Green Business Process Management," in *2010 IEEE International Conference on Services Computing*, Jul. 2010, pp. 386–393. [Online]. Available: https://doi.org/10.1109/SCC.2010.21

[36] A. Wesumperuma, A. Ginige, A. Ginige, and A. Hol, "Green Activity Based Management (ABM) for Organisations," *ACIS 2013 Proceedings*, 2013. [Online]. Available: https://aisel.aisnet.org/acis2013/144

[37] J. Recker, M. Rosemann, and E. R. Gohar, "Measuring the Carbon Footprint of Business Processes," in *Business Process Management*

Workshops, vol. 66. Berlin, Heidelberg: Springer, 2011, pp. 511–520. [Online]. Available: https://doi.org/10.1007/978-3-642-20511-8_47

[38] V. van den Broek, "Going greener through BPM: A method for assessing processes environmental footprint and supporting continuous improvement," Master's thesis, Einhoven University of Technology, Aug. 2015.

[39] A. Wesumperuma, J. A. Ginige, A. Ginige, and A. Hol, "A Framework for Multi-dimensional Business Process Optimization for GHG Emission Mitigation," *ACIS 2011 Proceedings*, Jan. 2011. [Online]. Available: https://aisel.aisnet.org/acis2011/91

[40] P. Hehnle, M. Behrendt, L. Weinbrecht, and C. Corea, "Carbon-Aware Process Execution for Green Business Process Management," in *26th International Conference on Enterprise Information Systems*, Sep. 2024, pp. 659–666. [Online]. Available: https://doi.org/10.5220/0012557100003690

[41] A. Ghose, K. Hoesch-Klohe, L. Hinsche, and L.-S. Le, "GREEN BUSINESS PROCESS MANAGEMENT: A RESEARCH AGENDA," *Australasian Journal of Information Systems*, vol. 16, no. 2, Mar. 2010. [Online]. Available: https://doi.org/10.3127/ajis.v16i2.597

[42] A. Nowak, T. Binz, F. Leymann, and N. Urbach, "Determining Power Consumption of Business Processes and Their Activities to Enable Green Business Process Reengineering," in *17th IEEE International Enterprise Distributed Object Computing Conference*, Sep. 2013, pp. 259–266. [Online]. Available: https://doi.org/10.1109/EDOC.2013.36

[43] J. Hermann, S. Rusche, L. Moder, and M. Weibelzahl, "Watt's Next? Leveraging Process Flexibility for Power Cost Optimization," *Bus Inf Syst Eng*, Aug. 2024. [Online]. Available: https://doi.org/10.1007/s12599-024-00888-1

[44] M. Reiter, P. Fettke, and P. Loos, "Towards Green Business Process Management: Concept and Implementation of an Artifact to Reduce the Energy Consumption of Business Processes," in *2014 47th Hawaii International Conference on System Sciences*, Jan. 2014, pp. 885–894. [Online]. Available: https://doi.org/10.1109/HICSS.2014.117

[45] O. Skarlat, P. Hoenisch, and S. Dustdar, "On Energy Efficiency of BPM Enactment in the Cloud," in *Business Process Management Workshops*, vol. 256. Cham: Springer International Publishing, Jul. 2016, pp. 489–500. [Online]. Available: https://doi.org/10.1007/978-3-319-42887-1_39

[46] M. Vitali, P. Schmiedmayer, and V. Bootz, "Enriching Cloud-native Applications with Sustainability Features," in *2023 IEEE International Conference on Cloud Engineering (IC2E)*, Sep. 2023, pp. 21–31. [Online]. Available: https://doi.org/10.1109/IC2E59103.2023.00011

[47] C. Cappiello, P. Plebani, and M. Vitali, "Energy-Aware Process Design Optimization," in *2013 International Conference on Cloud and Green Computing*, Sep. 2013, pp. 451–458. [Online]. Available: https://doi.org/10.1109/CGC.2013.77

[48] C. Cappiello, N. T. T. Ho, B. Pernici, P. Plebani, and M. Vitali, "CO2-Aware Adaptation Strategies for Cloud Applications," *IEEE Transactions on Cloud Computing*, vol. 4, no. 2, pp. 152–165, Apr. 2016. [Online]. Available: https://doi.org/10.1109/TCC.2015.2464796

[49] F. Klessascheck, I. Weber, and L. Pufahl, "SOPA: A framework for sustainability-oriented process analysis and re-design in business process management," *Inf Syst E-Bus Manage*, Jan. 2025. [Online]. Available: https://doi.org/10.1007/s10257-024-00695-x

[50] A. Fritsch, "Sustainability Analysis Patterns for Process Mining and Process Modelling Approaches," in *Process Mining Workshops*. Cham: Springer Nature Switzerland, 2025, pp. 725–737. [Online]. Available: https://doi.org/10.1007/978-3-031-82225-4_53

[51] B. G. Hermann, C. Kroeze, and W. Jawjit, "Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators," *Journal of Cleaner Production*, vol. 15, no. 18, pp. 1787–1796, Dec. 2007. [Online]. Available: https://doi.org/10.1016/j.jclepro.2006.04.004

[52] ISO, "ISO 14040: Environmental management — Life cycle assessment — Principles and framework," 2006.

[53] Michel Medema. (2025, Feb.) BPMN4ES. Version 0.1.0. [Online]. Available: https://github.com/michel-medema/BPMN4ES

[54] N. Graves, I. Koren, and W. M. van der Aalst, "ReThink Your Processes! A Review of Process Mining for Sustainability," in *2023 International Conference on ICT for Sustainability (ICT4S)*, Jun. 2023, pp. 164–175. [Online]. Available: https://doi.org/10.1109/ICT4S58814.2023.00025

[55] L. Brehm, J. Slamka, and A. Nickmann, "Process Mining for Carbon Accounting: An Analysis of Requirements and Potentials," in *Digitalization Across Organizational Levels: New Frontiers for Information Systems Research*, ser. Progress in IS. Cham: Springer International Publishing, 2022, pp. 209–244. [Online]. Available: https://doi.org/10.1007/978-3-031-06543-9_9

[56] C. Ortmeier, N. Henningsen, A. Langer, A. Reiswich, A. Karl, and C. Herrmann, "Framework for the integration of Process Mining into Life Cycle Assessment," *Procedia CIRP*, vol. 98, pp. 163–168, Jan. 2021. [Online]. Available: https://doi.org/10.1016/j.procir.2021.01.024

[57] P. Lübbecke, M. Reiter, P. Fettke, and P. Loos, "Simulation-Based Decision Support for the Reduction of the Energy Consumption of Complex Business Processes," in *2015 48th Hawaii International Conference on System Sciences*, Jan. 2015, pp. 866–875. [Online]. Available: https://doi.org/10.1109/HICSS.2015.109

[58] F. Klessascheck, S. A. Fahrenkrog-Petersen, J. Mendling, and L. Pufahl, "Unlocking Sustainability Compliance: Characterizing the EU Taxonomy for Business Process Management," Sep. 2024, arXiv:2408.11386. [Online]. Available: https://doi.org/10.48550/arXiv.2408.11386

[59] H. Groefsema, N. R. T. P. van Beest, and G. Governatori, "On the Use of the Conformance and Compliance Keywords During Verification of Business Processes," in *Business Process Management Forum*, ser. Lecture Notes in Business Information Processing. Cham: Springer International Publishing, 2022, pp. 21–37. [Online]. Available: https://doi.org/10.1007/978-3-031-16171-1_2

[60] B. Weber, S. Rinderle, and M. Reichert, "Change Patterns and Change Support Features in Process-Aware Information Systems," in *Advanced Information Systems Engineering*, ser. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer, 2007, pp. 574–588. [Online]. Available: https://doi.org/10.1007/978-3-540-72988-4_40

[61] F. Casati, S. Ceri, B. Pernici, and G. Pozzi, "Workflow evolution," in *Conceptual Modeling — ER '96*, ser. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer, 1996, pp. 438–455. [Online]. Available: https://doi.org/10.1007/BFb0019939

[62] L. Pufahl and D. Karastoyanova, "Enhancing Business Process Flexibility by Flexible Batch Processing," in *On the Move to Meaningful Internet Systems. OTM 2018 Conferences*, ser. Lecture Notes in Computer Science. Cham: Springer International Publishing, 2018, pp. 426–444. [Online]. Available: https://doi.org/10.1007/978-3-030-02610-3_24

[63] L. Pufahl and M. Weske, "Batch activity: Enhancing business process modeling and enactment with batch processing," *Computing*, vol. 101, no. 12, pp. 1909–1933, Dec. 2019. [Online]. Available: https://doi.org/10.1007/s00607-019-00717-4

[64] B. Popescu. (2025, May) Carbon Emissions Calculator Service for Business Processes. Version 0.1.0. [Online]. Available: https://github.com/bogdan9926/Environmental-Sustainability-Calculator-Service-for-Business-Processes

[65] ——, "Environmental Sustainability Calculator Service for Business Processes," Master's thesis, University of Groningen, Aug. 2024. [Online]. Available: https://fse.studenttheses.ub.rug.nl/id/eprint/34080

[66] bpmn.io. (2025, Jan.) Bpmn-js. Version 18.2.0. [Online]. Available: https://github.com/bpmn-io/bpmn-js

[67] Camunda. (2024, Apr.) Camunda Platform 7. Version 7.21. [Online]. Available: https://camunda.com/platform-7/

[68] KIE. (2023, Jul.) jBPM. Version 7.74.1. [Online]. Available: www.jbpm.org

[69] W. Klöpffer and B. Grahl, *Life Cycle Assessment (LCA): A Guide to Best Practice*, 1st ed. Weinheim an der Bergstrasse, Germany: Wiley, Apr. 2014. [Online]. Available: https://doi.org/10.1002/9783527655625

[70] A. Fritsch, J. von Hammerstein, C. Schreiber, S. Betz, and A. Oberweis, "Pathways to Greener Pastures: Research Opportunities to Integrate Life Cycle Assessment and Sustainable Business Process Management Based on a Systematic Tertiary Literature Review," *Sustainability*, vol. 14, no. 18, p. 11164, Jan. 2022. [Online]. Available: https://doi.org/10.3390/su141811164